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Lai, C.-L. (2021). Exploring University Students' Preferences for AI-Assisted Learning Environment: A Drawing Analysis with Activity Theory Framework. *Educational Technology & Society*, *24* (4), 1–15.

Exploring University Students' Preferences for AI-Assisted Learning Environment: A Drawing Analysis with Activity Theory Framework

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ABSTRACT: This study employed drawing and co-word analysis techniques to explore students' preferences for AI-assisted learning environments. A total of 64 teacher education students from a university in Taiwan participated in the study. The participants were asked to describe their perceptions of AI-assisted learning in the form of drawings and text descriptions. In order to analyze the content of the students' drawings, a coding scheme was developed based on the activity theory framework. Based on the results of the analysis, it was found that students placed more importance on personalized guidance and appropriate learning content provision. In addition, students acknowledged that AI technology can be used flexibly in different fields and situations. Interestingly, more than half of the students agreed that robots play important roles in AI-assisted learning. This indicates that the students expected a social AI learning companion. However, it was found that students' expectations of an AI learning environment were less connected to the real environment and did not reveal learning activities with higher order thinking. In addition to the need for accurate and fast AI computing, this result indicated that professional instructional guidance is also an expectation that students have of AI education.

Keyword: Preference of learning environment, AI education, Co-word analysis, Drawing analysis, Activity theory framework

1. Introduction

In recent years, many studies have identified the importance of learner perspectives for their learning performance (Deci & Ryan, 2000; Tapingkae et al., 2020). Researchers have attempted to infer and predict students' learning performance by analyzing their different perspectives (Davies et al., 2013). Among them, learners' environmental preference is a commonly explored learner perspective in technology-assisted learning contexts (Dokmecioglu et al., 2020; Yang & Tsai, 2008). This is because, compared to the conventional learning model, learning in technology-assisted learning environments is rich in instructional media and complicated in human-computer interaction (Krishnan et al., 2019; McGrew et al., 2018). Therefore, if learners' learning environmental preferences are taken into consideration during the software and hardware development stage, it will help to ensure effective learning environment design (Tsai et al., 2012).

On the other hand, scholars have pointed out that school administrators and teachers need to face the challenge of using technology for instruction in the school environment (Morrison et al., 2009). Since emerging technologies are new to most teachers, it is often the case that technology interventions do not improve teaching effectiveness (Webster & Son, 2015; Yeh & Tao, 2013). The reason for this is the lack of professional development for school administrators and teachers in technology-assisted instructional design (Hennessy et al., 2015). If educators do not understand the characteristics of technology before teaching and its practical use in learning activities, the curriculum will not be effective even with the technology intervention (Geertshuis & Liu, 2020). Therefore, it is important to understand the expectations and preferences of the participants for technology-assisted learning before engaging in activities (Chen et al., 2018; Osman et al., 2011).

In particular, artificial intelligence (AI) has gradually gained importance in education (Garcia et al., 2007). Researchers have developed a number of tools with AI computing mechanisms (Yang et al., 2021), for instance, a dynamic taxonomic system to guide students in learning about ecosystems and biological chains (Abbas et al., 2021), or a fuzzy expert system for supporting students to learn mathematics (Hwang, Sung, et al., 2020). They all agree that AI can change the future of learning. However, learners' knowledge of AI is currently limited; the studies generally investigated learners' acceptance of AI, whereas the practical use of AI in the classroom has rarely been discussed (Zawacki-Richter et al., 2019). To meet students' learning environmental preferences, in this study, students were asked to use their imaginations to visualize an AI-support classroom. By asking students to draw images, they can draw the picture in detail without it needing to be transcribed by the researcher (Nuora et al., 2019). By doing so, students' preferences for AI-assisted learning can be investigated.

2. Literature review

2.1. Role of environmental preference in students' learning

The learning environment is defined as the physical environment, the people (usually teachers and students), the learning objectives, the teaching methods, the materials, and the tasks the learners have to complete (de Kock et al., 2004). A discussion of students' preferences for the learning environment can begin with Fraser's (1998) study. He developed a questionnaire to assess students' perceptions of the psychosocial environment of the classroom: the Constructivist Learning Environment Survey (CLES). This questionnaire was used to help researchers and teachers assess the extent to which a particular classroom environment is aligned with a constructivist epistemology, and to help teachers reflect on the design of their instructional activities.

In a technology-based environment, learners' learning preferences in e-learning environments, mobile learning environments, and so forth, are situations worthy of researchers' exploration (Pletz & Zinn, 2020; Rejón-Guardia et al., 2020). For researchers, further differentiating different types of technology-enabled learning environments helps describe the core values of the technology and how to shape the environment embedded in the technology (Shernoff et al., 2017; Wolf & Fraser, 2008). For instance, Chuang and Tsai (2005) explored and found the students' environmental preferences that need to be considered in Internet-based learning environments, that is student negotiation, inquiry learning, reflective thinking, relevance, ease of use, and challenge. Further, Tsai et al. (2012) explored students' learning preferences in a mobile learning environment. They found that providing students with authentic and relevant information enhanced student negotiation and inquiry learning.

When investigating the interaction among learners, tools, and activities, researchers have acknowledged that activity theory is a suitable evaluation framework (Jonassen & Rohrer-Murphy, 1999). Activity theory describes actions through six related elements: objective, subject, context, tools, division of labor, and rules (Engeström, 1987). It considers an entire activity system, accounting for the environment, history of the person, culture, role of the artifact, motivations, and complexity of the real-life activity. Many researchers have used this framework to examine the integrity of activities and environments (Blayone, 2021; Galvis et al., 2021). For instance, Longhurst et al. (2021) employed activity theory to evaluate the effectiveness of social and cultural factors on the teachers' application of strategies in teaching.

Accordingly, researchers have frequently discussed learners' environmental preferences when introducing new technology into the classroom (Lung-Guang, 2019; Martin et al., 2020). Among different evaluating frameworks, activity theory is one that considers the overall interaction among humans, computers, and environments. However, as far as we know, few studies have explored learners' environmental preference in the AI-support learning context, especially through the lens of activity theory.

2.2. AI in education

Researchers consider artificial intelligence (AI) as a channel for providing precision education (Garcia et al., 2007; Tsai et al., 2020). Generally, researchers define AI in education as using AI techniques (e.g., Neural Networks, deep learning, or rule-based inferencing) for supporting teaching or learning (Colchester et al., 2017). Due to effective computing and data storage, AI has been rapidly applied in various educational settings (Macgilchrist et al., 2020). Many studies have aimed to develop efficient AI systems for supporting students' learning, while also investigating learners' perspectives on the use AI in education (Chocarro et al., 2021; Segal et al., 2019).

Researchers not only pay more attention to optimizing embedded and responsible AI, but they also care about learners' and teachers' perspectives on AI (Yang et al., 2021). For instance, Chocarro et al. (2021) examined the teachers' acceptance of AI chatbots. Their result revealed that ease of use and usefulness played important roles in the acceptance of AI. In addition, teachers preferred AI robots as a formal assistant rather than for social assistance. Tai and Chen (2020) investigated the effectiveness of intelligent personal assistants (IPAs) on learners' willingness to communicate. The EFL students who participated in the research enhanced their confidence in communicating. Also, they enjoyed talking with the virtual assistant which decreased their speaking anxiety.

Therefore, it is known that users' perceptions of AI need to be considered from various aspects. Researchers usually adopt surveys or interviews to learn users' perceptions. However, learners' environmental preferences include personal perceptions as well as their spatial needs and social interactions (Mason et al., 2010). These are more difficult to obtain through surveys or interviews. Researchers have recommended that drawing is another way to directly obtain interviewers' perspectives (Guillemin, 2006; Nuora et al., 2019), as drawings are rich visual illustrations that represent the interviewee's imagination of the environment or social interactions (Ehrlén, 2009).

2.3. Drawing analysis technique

Drawing is an expressive method that uses a combination of visual and textual expressions to compensate for content that is missed when expressed purely in words (Ehrlén et al., 2009; Selwyn et al., 2009). The method whereby researchers invite participants to draw pictures and then analyze the results of their drawings is called drawing analysis. This method has been used not only to assess college students' thoughts on specific issues (Xu et al., 2020), but also those of high school and even elementary school students (Wang & Tsai, 2012; Yeh et al., 2019). By collecting participants' opinions in this way, the participants are able to share their ideas in a less stressful manner (Brown & Wang, 2013; Hsieh & Tsai, 2018), while researchers are able to obtain the information in the most convenient way and within a valid time period. Many studies have also shown that drawing can be used as a research method to reveal the complexity and importance of participants' ideas (Dikmenli, 2020; Lamminpää et al., 2020).

Hsieh and Tsai (2018) used a drawing analysis technique to explore the learning concepts of 1,067 elementary school students. They found that most of the students' drawings depicted conventional teacher-centered classroom learning activities. Students were usually passive listeners during learning activities. Yeh et al. (2019) also used drawing analysis to investigate high school students' perceptions of technology-assisted science learning. Based on the results of the analysis, they found that there was a significant difference between students' actual and ideal concepts of technology-assisted science learning; that is, there was a gap between students' expectations of technology and their current reality.

In recent educational research, drawing has been recognized as a phenomenological research method that is effective in terms of guiding learners to share their personal thoughts (Hsieh & Tsai, 2017). At the same time, many studies have demonstrated that the results of drawing analysis are a useful way to support learning (Chang, 2018; Chiang et al., 2020); researchers can use drawing analysis to reveal and understand learners' perceptions of learning. In other words, in educational research, analyzing students' drawings can be a useful tool for understanding their engagement in learning, their expectations of technology, and their learning preferences.

2.4. The purpose of this study

With the rapid development of AI in recent years, the application of AI in education has received increasing attention from educational researchers (Luckin & Cukurova, 2019). However, it remains a challenge for most researchers and practitioners (Kay, 2012). The main reason for this is that AI is a field that is highly dependent on technology and interdisciplinary integration (Breines & Gallagher, 2020). Teachers and educators who do not understand the role of AI in education and how these AI technologies can help teaching and learning are likely to find it difficult to make AI work in the classroom (Fryer et al., 2017).

Much of the research emphasizes the importance of understanding learner perceptions before new technologies or environments are introduced (Geertshuis & Liu, 2020). However, at this stage of education, the introduction of AI in teaching and learning is still more sophisticated than other technologies (e.g., web-based learning, mobile learning). Therefore, through interviews and questionnaires, it is difficult to portray students' preferences for AI learning environments (Chatterjee & Bhattacharjee, 2020; Hsieh & Tsai, 2018). Using drawing, the researcher can draw a snapshot of students' ideas and expectations of the AI environment from their drawings, and it can be used as a vehicle to convey information that is difficult to convey in words (Chiang et al., 2020; Yeh et al., 2013). Therefore, this study intended to use the drawing technique to collect students' perceptions of AI-based learning, and to analyze the information in students' drawings in order to understand the students' preferences for AI learning environments. The research questions of this study are:

- Into what categories can students' environmental preferences for AI-assisted learning be classified?
- What are the students' tool needs (tools, objectives, rules) in the AI-assisted learning environment?
- What are the students' contextual needs (context, subject, division of labor) in the AI-assisted learning environment?

- What are the most frequently mentioned keywords in the students' AI-assisted learning drawings? Is there any relationship between the keywords?

3. Method

3.1. Participants and the data collection procedure

For this study, the researcher conducted a survey at a university in northern Taiwan. To help AI developers understand the need of the teaching and learning field, this study selected two classes of students who had attended teacher training courses. They had a basic understanding of the current teaching environment in Taiwan's elementary schools, but none had any expertise in IT-related fields. Therefore, we were able to elicit the students' needs for AI from the users' standpoint rather than from that of the developers. In these two courses, the instructor taught the current state of technology-based learning, and assigned students to design relevant technology-based learning activities. Therefore, students have certain concepts of technology-integrated learning and teaching.

Before inviting the students to create their drawings, the instructor gave a 2-hour lecture on the application of AI in education to ensure that the students had a preliminary understanding of AI. Meanwhile, teachers shared several education-related AI apps to let students understand the current development of AI in education. In addition, students were invited to share with their peers the tools and examples of AI applications in education.

Afterwards, the instructor arranged students to draw what they perceived to be their own AI learning and to describe the content of the drawings with the aid of text. Each student was given a piece of A4 paper with two prompts: "Please draw what you think of AI education" and "Please briefly summarize the contents of your drawing." In this study, students were free to choose whether or not to draw their drawings and submit their work. The activity was anonymous; the researcher did not know which student the drawing was from. After 1 hour of drawing, a total of 64 drawings were collected for this study.

3.2. Data analysis

3.2.1. Development of the coding scheme

This study first adopted the Activity Theory framework to examine students' preferences for the learning environment from multiple perspectives (Jonassen & Rohrer-Murphy, 1999). The dimensions of this framework are tool, objective, subject, division of labor, context, and rules. Next, the study referred to Haney et al. (2004) and Wang and Tsai (2012) to develop the codes for each dimension. Based on this past literature, this study first developed a coding list that included: learning topic, participants, learning places, activities, electronic technologies and objects, as shown in Figure 1. The learning topic refers to the subject of study that is mentioned in the students' drawings. Participants and learning places refer to the people and places that students draw. The types of activities are based on the learning activities depicted in the drawings. Electronic Technology refers to the electronic products that students draw, such as computers, screens, and earphones. Finally, the term objects refers to objects other than electronic technologies that students draw, such as desks, books, and so on.

To precisely analyze students' imaginations of AI-assisted learning, this study referred to Hwang, Xie's et al. (2020) definition of AI features and developed two categories: software or services, and AI functions. Software or services refers to the software or services mentioned in the student's drawing, such as Google or Facebook, whereas functions represent the functions that the AI needs in order to carry out the learning activity, such as providing learning diagnostics, uploading data, and so on. More details of the coding scheme are shown in Appendix Table 1.

The researchers invited two coders with educational psychology backgrounds to help with the coding. Before the two coders coded, the researchers explained the coding method and the coding scheme. During the process, the researcher selected one drawing at random and coded it with the coders to ensure that both of them understood the coding scheme. The two coders then coded each of the 64 drawings; they recorded the codes in an Excel file, and the researcher verified the consistency of the codes. The researchers then held a discussion meeting to discuss the inconsistent codes until the two coders confirmed that all the codes were consistent. An example of a coded student's drawing is shown in Figure 2.

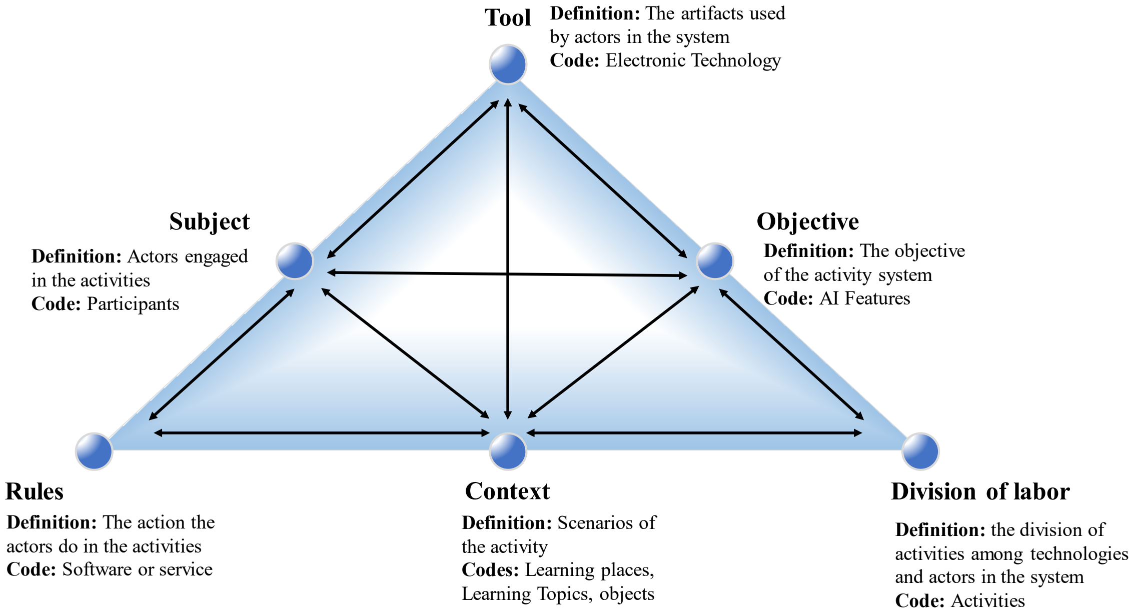

Figure 1. The framework of activity theory for AI-assisted learning

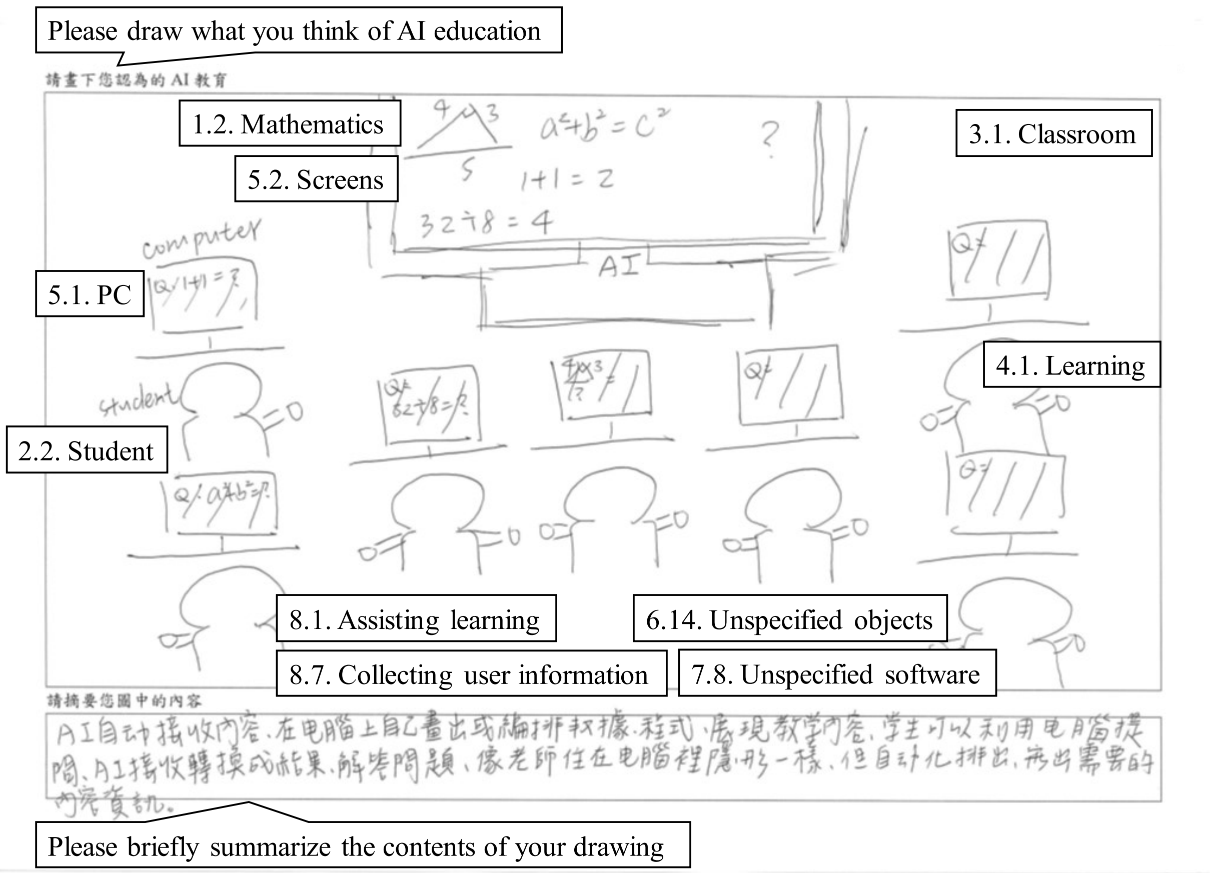

Figure 2. An example of a coded student's drawing

3.2.2. Data analysis procedure

For the coding results, the researchers first used descriptive statistics to show the number and frequency of occurrences of each category of indicators. To understand students' needs for AI-assisted learning, this study cross-compared AI features and activity types to try to understand what functions students expected AI to provide in different activities.

On the other hand, this study also analyzed the textual content of the students' descriptions. For this purpose, this study used a software package that can perform co-word analysis, VOSViewer, which is concerned with the use of word patterns as a tool to explain the structure of ideas, questions, and so on. The researcher can use the co-word analysis to analyze the content of the students' descriptions. Researchers can use the results of the co-word analysis to analyze themes in a specific field. The analysis tool can extract the most frequent words from all sentences, analyze the associations between the occurrence of different words to find clusters, and finally present the results using a visual network (Tibana-Herrera et al., 2018; Yilmaz et al., 2020). Through this analysis, the researcher can find out what issues are important to students in AI-assisted learning.

4. Results

4.1. Coding scheme results

Students' drawings were analyzed according to the coding scheme in Table 1. Table 1 shows the frequency and percentage of what students drew for the learning topics. The majority of students did not specify the learning topic in their drawings (91%). This means that the content of learning was not the focus of learning when students were thinking about AI-assisted learning. Students may draw a picture of what AI learning looks like in terms of learning approach or AI functions. Still, some students linked AI technology to the subjects they were learning, such as language (3%), mathematics (3%), science (3%), physical education (2%), programming (2%), and music (2%). The data indicate that language, mathematics and science were the most important learning topics for students compared to other subject areas.

Table 1. Distribution of learning topics in the students' drawing content

	Language	Mathematics	Science	Physical education	Programming	Music	Unspecified
Frequency	2	2	2	1	1	1	58
Percentages	3%	3%	3%	2%	2%	2%	91%

With regard to the participants category (as in Table 2), the students code had the highest percentage of presence in the drawings (55%). Secondly, 52% of the drawings mentioned robots. This means that AI is an abstract concept and students want a concrete image to represent it. On the other hand, it also means that robots may play an important role in the learning process in the future. This was followed by 27% of the drawings that did not mention any characters, indicating that these students may have wanted to convey the characteristics of technology through their drawings. The fourth highest category was teachers. This means that in AI learning activities, as in most learning environments, a significant proportion of students and robots are present. There were two drawings, each with a different character. One picture includes a baby, which inferred that the student is linking AI-assisted learning with babies and childcare. The other drawing showed a teacher for robots, which indicated that robots learn knowledge from a teacher. It means that the student had the concept of human-provided knowledge for robots.

Table 2. Distribution of participants in the students' drawing content

	Teacher	Student	Robot	Baby	Others	No participant
Frequency	8	35	33	1	1	17
Percentages	13%	55%	52%	2%	2%	27%

The majority of the students did not mention the place of study in the learning places category (as in Table 3). This also means that they perceived that AI learning is not limited by time and space, but is possible in any situation. Second, the classroom accounted for 23%, which means that students also expected AI-assisted learning to take place in the classroom. Finally, 5% of the drawings depicted AI for learning at home and 2% depicted AI for learning outdoors.

Table 3. Distribution of learning places in the students' drawing content

	Classroom	Home	Outdoor	Unspecified
Frequency	15	3	1	53
Percentages	23%	5%	2%	83%

For the activities category (as in Table 4), learning was mentioned in 31% of the drawings. Secondly, instruction was mentioned in 27%. Interestingly, students seldom indicated a clear place of learning; however, they expected learning to take place through AI. Again, this suggests that learning, especially learning with AI, is not limited by time and space. Of the drawings, 34% did not specify how the activity would be carried out using AI; this may indicate that students may place more emphasis on describing AI functions. Finally, 17%, 2%, 2%, and 2% of the drawings depicted human/robot interaction, information justification, chess-playing, and nursing, respectively.

Table 4. Distribution of activities in the students' drawing content

	Learning	Instruction	Human / Robot Interaction	Information justification	Chess-playing	Nursing	Unspecified
Frequency	28	17	11	1	1	1	22
Percentages	44%	27%	17%	2%	2%	2%	34%

In the electronic technologies category (as in Table 5), 38% of the drawings did not indicate what technology was used. This is where students have the concept that AI is not a specific symbol. That said, 25% of the drawings mentioned computers, 22% mentioned screens, and 22% mentioned mobile devices. This means that students need to use some kind of technology to compute and read the content. On the other hand, touch screens (3%), smartwatches (2%), mice (5%), calculators (2%), earphones (3%), and VR glasses (5%) were also mentioned in some of the drawings.

Apart from mentioning electronic technologies, the students also drew non-technology-related objects such as desks and chairs, stationery, and so on. According to the results of the analysis, 67% of the students did not mention other objects. However, there were still a few students who drew non-technology objects such as desks and chairs (9%) and stationery (3%), as shown in Table 6. This means that AI technology can be built into the existing learning environment. On the other hand, some of the drawings mentioned objects that occur in daily life, such as glasses (2%), chess (2%), natural objects (e.g., the sun, clouds) (3%), transportation (3%), and so forth. This means that AI can help students learn outdoors and try to connect with their learning in daily life.
In the statistics for software or services (as in Table 7), 80% of the drawings did not mention either software or services. This may mean that the students are still unclear about the types of services AI can provide. Nevertheless, 8% of the drawings referred to databases and 4% to teacher management systems; in other words, they thought AI could help teachers organize their teaching resources and help databases perform better calculations.

Table 5. Distribution of electronic technologies in the students' drawing content

	PC	Screens	Mobile devices	Touchscreen	Smartwatches
Frequency	16	14	14	2	1
Percentages	25%	22%	22%	3%	2%
	Mouse	Calculator	Earphone	VR glasses	Unspecified
Frequency	3	1	2	3	24
Percentages	5%	2%	3%	5%	38%

Table 6. Distribution of objects in the students' drawing content

	Desk and chair	Stationery	Blackboard	Books	Mannequin	Projector	Wi-Fi
Frequency	6	2	2	1	1	1	2
Percentages	9%	3%	3%	2%	2%	2%	3%
	Brainscope	Eyeglasses	Chess game	Natural objects	Transportation	House	Unspecified
Frequency	1	1	2	2	2	1	43
Percentages	2%	2%	3%	3%	3%	2%	67%

Table 7. Distribution of software or services in the students' drawing content

	Database	Teaching Management System	Google	IoT	VR content	YouTube	Facebook	Unspecified
Frequency	5	4	1	1	1	1	1	51
Percentages	8%	6%	2%	2%	2%	2%	2%	80%

Finally, this study discusses the features that students expected AI to provide, as shown in Table 8. Two of the most important features were assisting learning (47%) and supporting instruction (28%). Next, students believed that AI could help in collecting user information (27%) and conducting data analysis and diagnosis (23%). In addition, some students think that AI can be used for communicating with students (17%), connecting with human communication (3%), playing chess (3%) and soothing a child (2%). Despite this, 25% of drawings did not depict AI's capabilities.

Table 8. Distribution of AI features in the students' drawing content

	Frequency	Percentages
Assisting learning	30	47%
Supporting instruction	18	28%
Connected human communication	2	3%
Talking to students	11	17%
Data analysis and diagnosis	15	23%
Collecting user information	17	27%
Playing chess	2	3%
Soothing a child	1	2%
Unspecified	16	25%

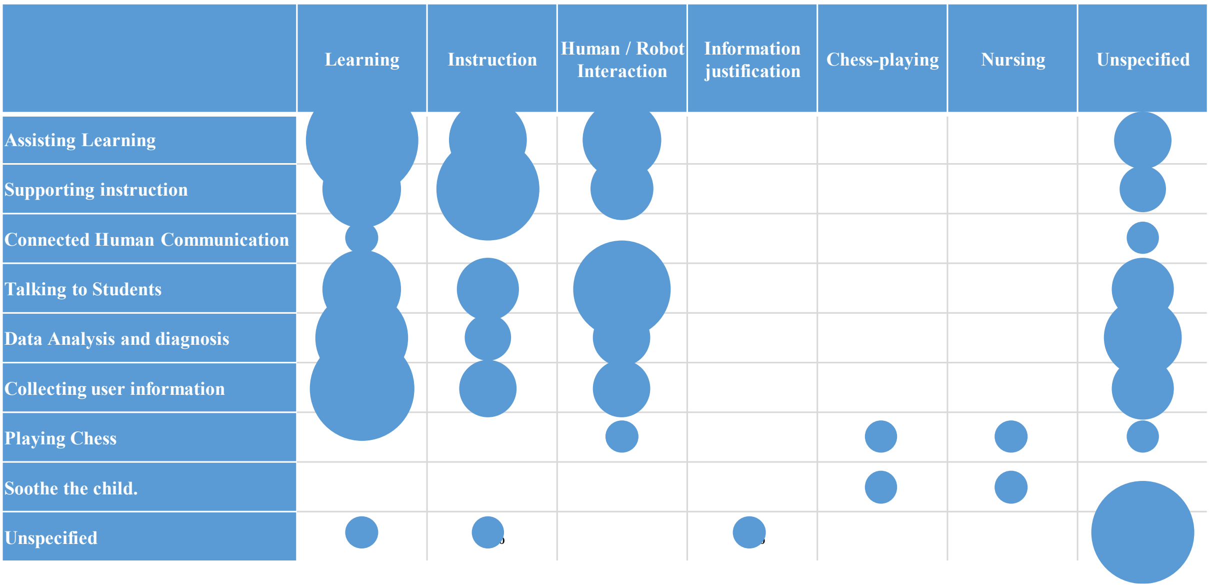

Figure 3. Cross analysis of AI features and activities in the students' drawing content

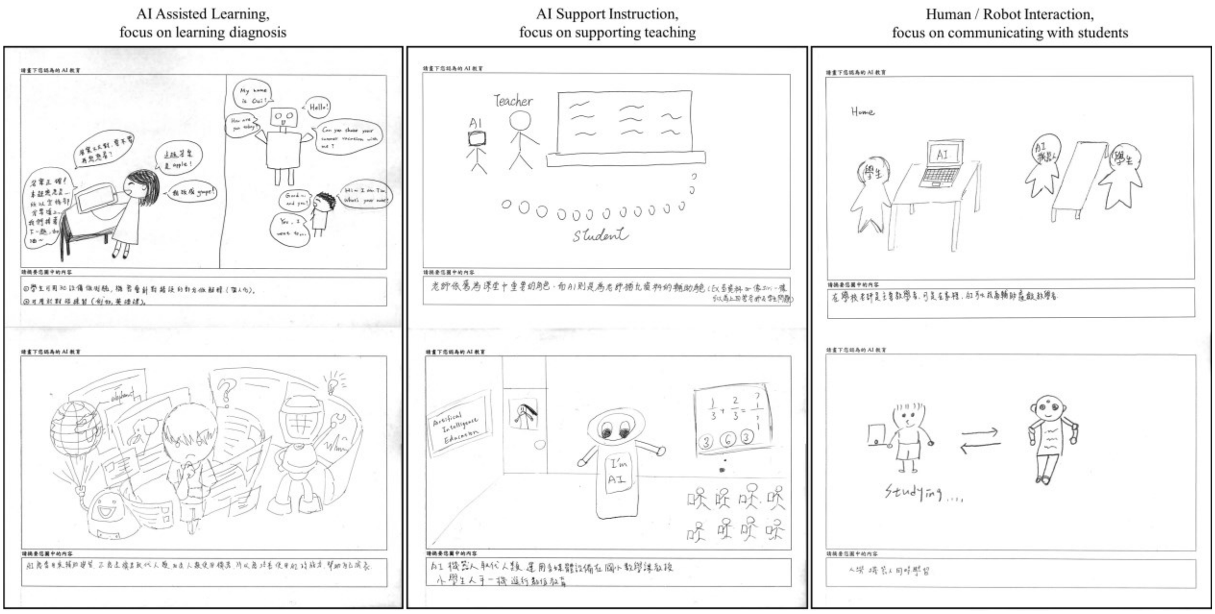

Figure 4. Examples of AI-assisted learning and support instruction

To discuss the role that AI technology can play in different learning activities, this study cross-analyzed the features of AI and the activities (as Figure 3). The results show that the students expected AI to assist with individual learning, collect user information, and perform data analysis and diagnosis. This also means that students consider analyzing learner profiles and providing diagnoses as important functions of AI to support personalized learning (as Figure 4). On the other hand, in instruction, students expect AI to assist teachers in teaching, to support students' classroom studying, and to collect user information. In other words, AI technology needs to help teachers understand students' needs and classroom operations during the instructional process. Next, in human-computer interaction, students emphasize the ability of AI to communicate with students; this also means that students expect speech recognition and semantic interpretation to be incorporated into AI-assisted learning.

4.2. Results of the word co-occurrence network analysis

To explore the most used words by students when describing the content of their drawings, this study used VOSviewer to analyze the students' words. The minimum number of occurrences of each term is 2, meaning that 34 terms could be selected. Their relationships are shown in Figure 4.

Figure 5 shows four clusters, and the words student (f = 18), teacher (f = 15), robots (f = 9), and AI education (f = 8) are the most used. The results showed that the students valued every role that was present in their learning activities, including teachers and robots.

The line between teacher and student is the thickest, which means that the students often mentioned "students" when they said "teacher." Sometimes "robots" are discussed as well. On the other hand, when students talk about "AI education," they sometimes mentioned the word "future." From this, we can see that the essential roles in learning are teachers, students, and robots. However, students' perceptions of AI education are still more future-oriented rather than being oriented towards current learning activities.

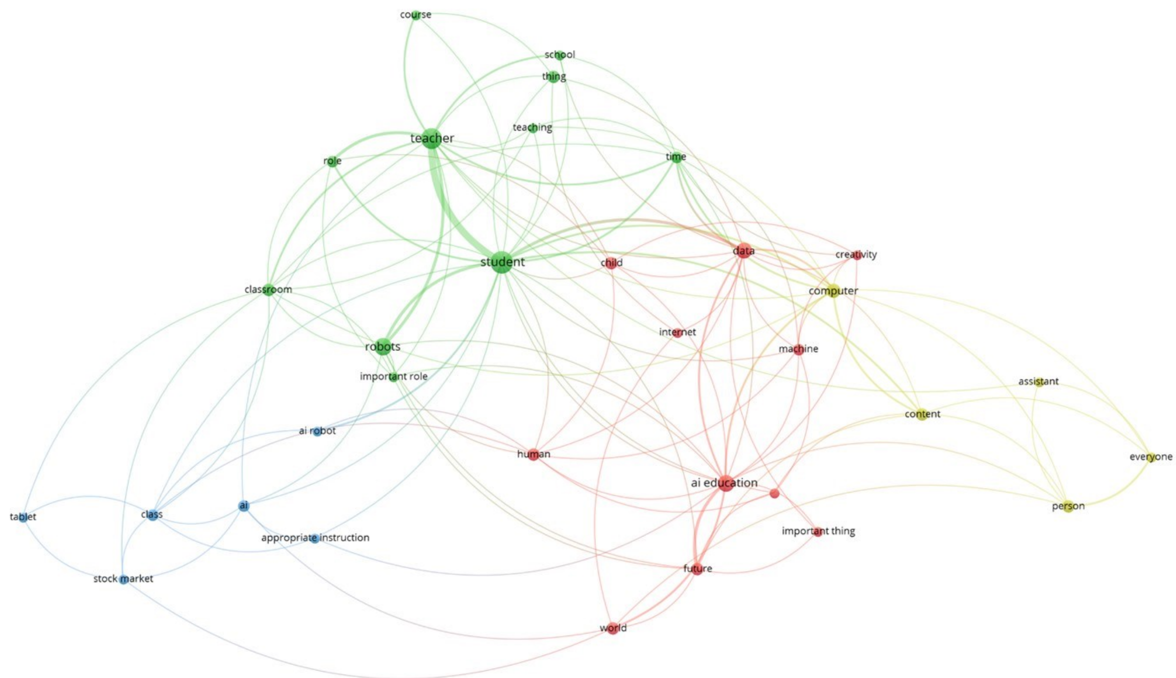

Figure 5. The most used words in the textual descriptions of the drawings

On the other hand, the distance between words indicates the correlation between the two. For example, the proximity of "learning" to "things" and of "robots" to the "important roles" indicates that students perceived these things to be highly relevant. In other words, students need the assistance of some virtual or real objects in the learning process, and robots are essential players in the learning process. It is also interesting to note that the proximity of the computer to creativity, albeit in a different group, shows that students know that it is vital to use computers to create the learning process.

Last, the cluster analysis revealed four issues that were important to the students (as in Table 9). The first cluster is the importance of AI to the future of education, with words such as AI education, data, child, future, and human appearing in the first cluster. The second cluster is the teaching context of AI, with frequent words such as student, teacher, robots, classroom, and thing. The third cluster is the carriers of AI, with frequent words such as AI, class, and AI robot; and finally, the fourth cluster is the functions of AI, such as computer, content, person, and assistant.

Table 9. The co-words in each cluster

Cluster 1		Cluster 2		Cluster 3		Cluster 4	
Label	Weight	Label	Weight	Label	Weight	Label	Weight
AI education	20	Student	37	Class	8	Computer	17
Data	19	Teacher	29	AI	7	Content	9
Future	10	Time	14	AI robot	4	Person	7
Human	9	Classroom	12	Appropriate instruction	4	Everyone	5
Machine	8	Robots	12	Tablet	3	Assistant	3
Child	7	Role	8				
World	7	Important role	6				
Creativity	6	School	5				
Ability	5	Teaching	5				
Important thing	3	Thing	5				
Internet	3	Course	4				

The results of this study are summarized in Table 10. It was found that the students preferred AI as a tool to assist their learning. Robots may be effective agents to achieve the students' expectations of AI. The students want AI-intelligent robots to provide appropriate learning support according to their learning needs. They also believe that AI may not be limited to any hardware, but should be everywhere. However, the study also found that the students did not explicitly request learning topics, learning places, objects, and software or services. It is suspected that these items are not a priority for students. For them, an AI-intelligent learning partner was what they needed.

Table 10. Summary of findings

Categories	Highlight
(1) learning topics	Not specified
(2) participants	Student and robot
(3) learning places	Not specified
(4) activities	Learning
(5) electronic technologies	PC, screen, mobile devices, but not limited
(6) objects	Not specified
(7) software or service	Not specified
(8) AI features	Assisted learning and instruction, collect information and data analysis and diagnosis

5. Discussion and conclusion

5.1. New technology and on-demand analysis are needed

From a technology perspective, computers, screens, and mobile devices are still playing an important role in students' expectations of the AI learning environment. These tools are seen by students as important for receiving AI information. However, this study also found that students have not clearly defined their needs in terms of technology or in terms of software or services. In other words, students had difficulties articulating their needs for AI technology and services from current life examples. It also means that students place more emphasis on hardware than on software or services. Therefore, a concrete tool, which may be a smart learning partner, is more important to students (Hwang et al., 2020).

Based on the results of the analysis of learning places, participants, and AI features, this study found that the students were not restricted to their learning places, which means that they need technology that can help them acquire knowledge anytime and anywhere. Interestingly, the category of participants found that robots played an important role in the students' learning process; in other words, the students recognized the role of robots in AI education. Therefore, robots that are highly portable and knowledgeable about learning would meet the needs of students (Chen et al., 2020). In terms of analytics support, students expected AI to provide the learning content they needed through data collection and data analysis. With current AI technology, decision trees, expert systems, or other computational methods that can provide needs based on students' different learning performance and contexts may be able to meet students' needs (Chen & Lian, 2020; Patterson, 2020).

5.2. Convenient, flexible and adaptable content and feedback

In terms of content, from students' expectations of AI features and learning activities, it was found that students expected the AI learning environment to provide them with easy access to the learning information they needed. In particular, students appreciated AI's capability to provide personalized learning at any time and any place. Next, students expected AI to collect their learning profiles and provide appropriate diagnostic results in real time.

From these results, we found that there was no obvious difference between students' content needs for online learning, mobile learning, or AI learning environments (Tsai et al., 2012; Yang & Tsai, 2008). They all expected the learning environment to provide appropriate, real-time, and diverse learning content. However, in an AI environment, students are more concerned about the differences in learning content for learners and the interaction between AI technology and learners. Therefore, AI development requires not only stronger computing techniques and logical reasoning abilities, but also the professional knowledge of educators to assemble learning packages that meet the needs of different learners (Fryer et al., 2017).

The findings of this study were different from those of Chocarro et al. (2021) who explored teachers' perceptions of AI. In their study, teachers expected AI to provide formal teaching assistance. However, in this study, the students wanted AI to assist their learning, but without being limited to specific subjects and contexts; in other words, the students wanted a socially oriented AI aid. This result reflects that teachers' expectations of AI's functions may be incompatible with those of students; future researchers or system developers may have to design AI systems with different algorithmic mechanisms or logic for different roles. Moreover, students' needs may not be limited to the learning content itself; they may expect anthropomorphic AI, as Gartner (2021) reports for emerging technology forecasts.

5.3. Learning that focuses on individual needs

Finally, from the object analysis, we know that students rarely mention objects outside the classroom. For example, they had not yet considered that AI could assist them in inquiry learning, ecological observation, or solving practical life problems. They often considered that AI features are mostly used to assist with personalized learning or teaching. Similar findings have been found in previous studies, where the majority of students' perceptions of learning time were in the form of listening to the teacher in the classroom or studying individually (Hsieh & Tsai, 2018). Rarely were there classroom interactions or learning activities that were connected to real-life situations.

Nevertheless, AI-assisted learning should be more than just personalized learning. With appropriate materials, and with its powerful computational, reasoning, and diagnostic abilities, AI education should be developed toward more fluid, interactive modes and a wider range of learning activities (Zawacki-Richter et al., 2019). According to students' expectations, robots with AI knowledge may become important learning companions in the future; the participation of such companions should not only provide smooth interaction and appropriate learning content, but should also guide learners to go outdoors to learn and create.

Based on the findings, this study concluded that students emphasized the importance of personalized learning modes in AI learning environments. At the same time, the students expected a robot or social learning companion to join the learning context. However, the AI learning environment that students expected was less clearly related to real contextual learning or higher level thinking. This result is also important to educators, as students' perceptions of learning patterns have not changed significantly. Therefore, it is suggested that future researchers need to consider appropriate instructional guidance (not only course content but also teaching materials and life applications) when designing AI-assisted learning activities (Zawacki-Richter et al., 2019). At the same time, students should be provided with more opportunities to interact with AI to enhance their imagination of AI-assisted learning.

6. Research limitations

Although this study uses both graphical and textual analysis to analyze the students' needs in an AI-supported learning environment, the actual needs of students were not taken into account. Moreover, individual students' academic background and their abilities of presentation could be different. This implies that collecting students' needs from diverse aspects could be needed. Therefore, it is suggested that researchers collect and analyze both qualitative and quantitative data in the future.

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Appendix

Table 1. Coding scheme for coding the students' drawings

Categories	Indicators	Indicators
(1) learning topics	1.1. Language	1.5. Programming
	1.2. Mathematics	1.6. Music
	1.3. Science	1.7. Unspecified
	1.4. Physical education	
(2) participants	2.1. Teacher	2.4. Baby
	2.2. Student	2.5. Other
	2.3. Robot	2.6. No participant
(3) learning places	3.1. Classroom	3.3. Outdoor
	3.2. Home	2.4. Unspecified
(4) activities	4.1. Learning	4.5. Chess-playing
	4.2. Instruction	4.6. Nursing
	4.3. Human/robot interaction	4.7. Unspecified
	4.4. Information justification	
(5) electronic technologies	5.1. PC	5.6. Mouse
	5.2. Screens	5.7. Calculator
	5.3. Mobile devices	5.8. Earphone
	5.4. Touch screen	5.9. VR glasses
	5.5. Smartwatches	5.10. Unspecified
(6) objects	6.1. Desk and chair	6.8. Brainscope
	6.2. Stationary	6.9. Eyeglasses
	6.3. Blackboard	6.10. Chess game
	6.4. Books	6.11. Natural objects (Cloud, sun)
	6.5. Mannequin	6.12. Transportation
	6.6. Projector	6.13. House
	6.7. Wi-Fi	6.14. Unspecified
(7) software or service	7.1. Database	7.5. VR Content
	7.2. Teaching management system	7.6. YouTube
	7.3. Google	7.7. Facebook
	7.4. IoT	7.8. Unspecified
(8) AI features	8.1. Assisting learning	8.6. Collecting user information
	8.2. Supporting instruction	8.7. Playing chess
	8.3. Connected human communication	8.8. Soothe the child
	8.4. Talking to students	8.9. Unspecified
	8.5. Data analysis and diagnosis	

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Learning Analytics for Investigating the Mind Map-Guided AI Chatbot Approach in an EFL Flipped Speaking Classroom

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ABSTRACT: One of the biggest challenges for EFL (English as Foreign Language) students to learn English is the lack of practicing environments. Although language researchers have attempted to conduct flipped classrooms to increase the practicing time in class, EFL students generally have difficulties interacting with peers and teachers in English in class. The advancement of Artificial Intelligence (AI) provides an opportunity to address this problem. With AI technologies, computer systems, in particular in the form of AI chatbots, are able to identify the meanings of users' statements and make responses accordingly. In the research design, AI-based chatbots were employed in the in-class and out-of-class activities for facilitating the students' speaking performance and interactions during the learning process in a university flipped English speaking classroom. The experimental results show that the mind map-guided AI chatbot approach (MM-AI) promoted the students' English speaking performances more than did the conventional AI chatbot approach (C-AI). Moreover, the MM-AI also promoted the students' learning performance and organized the interaction between the robots and humans more than the C-AI did. The findings could be a valuable reference for language educators and researchers who intend to conduct AI-supported flipped classrooms in language learning.

Keywords: AI chatbot, Mind-map strategy, English speaking flipped learning, Learning analytics

1. Introduction

The development of flipped learning has become increasingly widespread, starting from simple to complete topics with the various backgrounds of participants (Fathi & Rahimi, 2020; Turan & Akdag-Cimen, 2020; Zou & Xie, 2018). Consequently, researchers have not only compared flipped learning with traditional approaches, but have also compared the flipped learning modes added by certain models with conventional flipped learning to identify more effective flipped learning approaches (Bicen & Beheshti, 2019; Cheng, Hwang, & Lai, 2020; Hong, Hwang, Liu, & Tai, 2020). For example, Lin and Hwang (2018) conducted a study which compared the online community-based flipped classroom approach with the conventional video-based learning approach to evaluate the effectiveness of flipped classrooms in terms of improving EFL students' English oral presentation. Another study was conducted by Chen and Tian (2020) to develop a corpus-aided pronunciation teacher-training program, and to examine the effectiveness of the corpus-aided pronunciation teaching approach in English classrooms.

On the other hand, although many researchers have carried out studies on English language teaching in flipped classrooms, especially focusing on speaking abilities, there is a lack of effective strategies for improving students' speaking skills. Therefore, in their research, there were various suggestions made for practitioners and future research in application (Turan & Akdag-Cimen, 2020). However, some English-speaking problems remain, such as students' confidence, skills, performance, and conceptions concerning the interactive behaviors of low improvers, to reflect on their practices in discussion with peers and teachers (Lin & Hwang, 2018).

Although the flipped learning environment is an effective instructional strategy for students to have more practice in the learning process, it may also be necessary to provide appropriate technology and scaffolding tools to assist students in organizing the information to improve their speaking performance (Lin & Hwang, 2018). Hwang, Xie, Wah, and Gašević, (2020) indicated the importance of employing artificial intelligence in education to facilitate teaching, learning, or decision making. With the integration of AI technologies, students may be stimulated to form opinions, judgments, or predictions and perform different functions of learning such as tutor, tutee, or tool. However, some scholars have pointed out that there is a lack of studies that employ AI technologies with educational theories and strategies in recent years (Chen, Xie, Zou, & Hwang, 2020). Chen, Xie, and Hwang (2020) presented that among 30 listed AI technology tools, 70% are used for language learning purposes, and AI chatbots may also be regarded as a tool that can provide personalized guidance, supports, or feedback to assist students in language learning. Therefore, using AI-chatbots as a new tool was considered to be able to enhance students' interaction and performance in this study (Chen & Hwang, 2020; Yin, Goh, Yang, & Xiaobin, 2020).

However, when practically applying activities in language speaking classrooms, the majority of students find organizing information tasks difficult (Lin & Hwang, 2018). With the concept or mind-mapping approach, it is easy to help students organize information, and it might decrease their speaking anxiety, and make them more confident. Thus, in order to facilitate students' speaking learning performance, this study developed the mind map-guided AI chatbot approach in an EFL flipped speaking classroom to engage students in learning in a contextualized way. Furthermore, learning perceptions and patterns of various kinds of students in the chatbot-assisted learning environment were investigated further to identify the benefits of the proposed AI in education. Several research questions were proposed as follows:

(1) To what extent may the mind map-guided AI chatbot approach improve the students' learning performance in comparison with the conventional AI chatbot approach in an EFL flipped speaking classroom?
(2) To what extent may the mind map-guided AI chatbot approach affect the students' speaking patterns with a chatbot in comparison with the conventional AI chatbot approach in an EFL flipped speaking classroom?

2. Literature review

2.1. Flipped language classrooms

The flipped classroom is a pedagogical approach in which some activities, such as doing a task, homework, and instruction are swapped, and learning takes place outside the classroom (Turan & Akdag-Cimen, 2020; Zou, Luo, Xie, & Hwang, 2020). The aim of flipping a classroom is to ensure that students have a deeper learning experience when the teacher guides them through the material. Adopting the flipped classroom in English language teaching (ELT) (Lin & Hwang, 2018) not only helps teachers and instructors reach students with better abilities and learning achievements, but also improves classroom management, giving teachers more time to interact with each student, and creating an interactive learning environment (Chuang, Weng, & Chen, 2018). Furthermore, researchers have combined a large number of learning strategies and tools into the flipped classroom to improve students' learning achievements and performances (Chang, Chang, Hwang, & Kuo, 2019; Turan & Akdag-Cimen, 2020). They have confirmed the effectiveness and positive effect of flipped classrooms from various perspectives, such as a positive correlation between the students' post achievement test and their attitudes (AlJaser, 2017), improving students' learning performances (Hwang, Lai, & Wang, 2015), promoting their self-efficacy (Tawfik & Lilly, 2015), and fostering students to be active in learning (Hoult, Peel, & Duffield, 2021).

Despite several successful studies, some challenges in implementing flipped classrooms for EFL remain (Turan & Akdag-Cimen, 2020). For example, the extra workload for students and teachers (Yang, 2017), technology and internet related problems, which require teachers to ensure that both they and their students have access to the needed technology (Egbert, Herman, & Lee, 2015), and concerns about the effectiveness of flipped learning related to the long and arduous process of L2 learning in various student level and target L2 outcomes (Vitta & Al-Hoorie, 2020). To overcome these issues, Hwang et al. (2015) suggested that teachers or instructors need to develop effective activities for both outside of and in the class. An innovative way to adopt the flipped classroom for EFL students' effectiveness is using an AI chatbot application. This technology would decrease teachers' workload and make students more relaxed because the technology can be used wherever and whenever to interact with the robots, and it has good potential as a practice partner for students (Chen, Widarso, & Sutrisno, 2020). Moreover, AI chatbots create a good environment for advanced learning, increase students' motivation and performance, and are user-friendly (Dekker et al., 2020; Yin et al., 2020).

2.2. Artificial intelligence and chatbots in education

Artificial intelligence (AI) refers to the research field in computer science which aims to implement human intelligence in computer systems; that is, it enables computers to perform human work, think rationally, and make judgments by developing computer programs that behave like humans (Kok, 2009). The technology and application of AI consist of neural networks, expert systems, deep learning or machine learning, speech recognition, image recognition, big data trend prediction and analysis, and natural language processing (Bui, Nguyen, Chou, Nguyen-Xuan, & Ngo, 2018; Lu, Li, Chen, Kim, & Serikawa, 2018). Buch, Ahmed, and

Maruthappu (2018) stated that the development of AI systems can compensate for the shortage of human experts and provide a multi-level service.

Researchers have made attempts to apply AI technologies to the development of intelligent tutoring systems (ITSs) and have applied them to educational settings since the early 1980s. The number of studies as well as the research foci related to AI in education have significantly increased in the past decades (Hwang, 2014). Elliott (2019) suggested an interaction between long-distance online courses, AI evaluating strategies, and relevant academic content stated in the literature. The course coordinators can flexibly maintain the content of academic courses, conduct virtual conferences, and provide announcements. The results have shown that participants agree unanimously with the benefits of applying AI to online courses. Recently, Xin, Park, Tzur, and Si (2020) proposed a conceptual model to train students to solve problems with learned knowledge, through the means of analyzing the subjective materials and conducting tests with the provision of learning suggestions, aiming at better assistance for them to combine the knowledge learned from textbooks.

Technology has brought many revolutionary changes to education in different academic disciplines in the 21st century; for instance, it has not only introduced AI into the courses of common subjects, but has also led to a valuable issue relating to AI in education research (Verma, 2018). Luo (2018) indicated that, with the rapid development of computer technology, researchers have attempted to apply AI technologies to the development of educational applications. In addition, with the popularity of mobile devices and smartphones, AI-based systems have been adopted to play the role of "Smart Teachers," "Smart Learning Partners" or "Smart Students" in educational settings (Holmes, Bialik, & Fadel, 2019). For example, Renz and Hilbig (2020) reported the trends of using AI teachers to analyze individual students' learning status and provide personalized learning paths, user interfaces and learning content. The advancement of wireless communication and sensory technology has further provided an environment for applying AI in diverse ways, and has led to the innovative thinking of educational researchers in implementing AI in education studies, such as guiding students to solve problems in the real-life environment with the supports from AI applications (Chang & Hwang, 2018). As a result, the use of AI technologies has gradually changed the role of teachers in school settings. Teachers, therefore, have more time to guide students to think, practice and apply knowledge based on individual students' needs. This assists teachers in improving the quality of teaching (Holmes et al., 2019).

Among various interactive computer systems, chatbots could be the most highly recognized owing to the fact that they use a natural language interface or even because of the voice recognition technology (Tandy, Vernon, & Lynch, 2016). Researchers have pointed out that chatbots are a highly accepted form of computer application owing to their "natural" way of interacting with users and their potential as student practice partners in learning (Benotti, Martinez, & Schapachnik, 2018). Chen et al. (2020) also indicated that chatbots have good potential as a language learning tool, and can significantly improve the students' learning achievement; moreover, the one-on-one environment can provide better outcomes than what could be achieved in a classroom. The AI technology fostered substantial improvements in the learners' perceptions and the target productions in every task. Kılıçkaya (2020) used Replika at a university in Turkey and found the software useful. The students underscored the importance of receiving an immediate response from AI chatbots, and edited their responses when chatbots could not understand the messages. Some scholars also indicated that chatbots are intellectual communicators acting as guides and assistants. They proposed that chatbots could be used more effectively with relative strategies for learners' needs and experiences. However, few studies have yet to make a meaningful contribution to foreign language learning settings (Fryer, Coniam, Carpenter, & Lăpușneanu, 2020).

2.3. Mind maps in language learning

Mind mapping is a meaningful learning strategy to organize the information and make more systematic visualizations of the whole structure (Liu, Chen, & Chang, 2010; Yang, 2015). Mind mapping has huge advantages for students, not only in terms of developing the connections between words and cohesive texts, but also for fostering students' creativity and their integration of new ideas (Fu et al., 2019). This strategy involves arranging words into a picture with a core word at the center or at the top and related words or images linked with the key words by lines (Oxford, 2013). In addition, Chen and Hwang (2019) indicated that mind mapping helps students think logically and improve their learning performance.

In language learning, mind mapping strategies have been widely used by teachers and researchers to measure various learning outcomes. For example, Liu et al. (2010) employed the mapping strategy as an aid for improving EFL (English as Foreign Language) students' English reading comprehension. Hsu (2018) examined the four elements of students' motivation, attention, relevance, confidence, and satisfaction in an EFL speaking course that used the computer mediated communication (CMC) tool Google Hangouts, while Lin (2019) used mind-mapping flipped learning activities for college English writing courses. Furthermore, several researchers in the language learning field have investigated the positive effects of mind mapping implemented in speaking, reading, and writing performance (Chen & Hwang, 2019; Hwang, Chen, Sung, & Lin, 2018).

In addition, the study of Liu (2016) reveals that the mind mapping strategy not only provided a more efficient memorization tool for students to organize and represent vocabulary knowledge, but also had significantly superior performance in vocabulary learning acquisition and retention. Besides that, according to Hwang, Kuo, Chen, and Ho (2014), the computerized mind map assists students in improving their learning achievements and promoting their learning interest. Therefore, the mind mapping strategy might be considered as having great potential for improving EFL students' language learning performance and increasing their vocabulary knowledge, comprehension, and inferential knowledge (Chen & Hwang, 2019).

3. Mind map-guided AI chatbot approach for language learning

3.1. Speaking strategy model architecture

Figure 1 shows that there are four core categories of speaking English, namely pronunciation, performing speech, managing interaction, and organizing discourse (Walker & White, 2013). According to Burns (2016), to be competent speakers in the English language, students must be able to handle several complex processes and skills simultaneously such as pronouncing vowels, consonants, and blended sounds with correct and clear pronunciation; excellence in performing and managing interaction with others; and organizing discourse using appropriate intonation, and managing the language structure to change the topic and communicative purpose. Therefore, students need an effective strategy to obtain speaking skills. As shown in Figure 2, a model of speaking strategies developed by Goh and Burns (2012) and Unlu and Wharton (2015) was modified to help students use cognitive, metacognitive, and interaction speaking strategies with a robot (AI chatbots) in this study. In this case, the strategy guided students to find the ways around a lack of vocabulary through paraphrasing, substitution, and coining new words. Besides that, meta-cognitive strategies not only provide scaffolding to students for planning or rehearsing the material to speak, but also include monitoring of the language used while speaking with the robot. Furthermore, to drive communication with the robots, interaction strategies with the mind map-guided AI chatbot helped students to be more interactive with both robots and teachers or instructors, such as asking for help, checking understanding, and requesting clarification. In addition, to make it easy to organize the information and to think holistically, the mind map-guided AI chatbot approach is also powerful for helping students organize the information and make more systematic the whole structure for language learning as shown in Figure 3 (Yang, 2015).

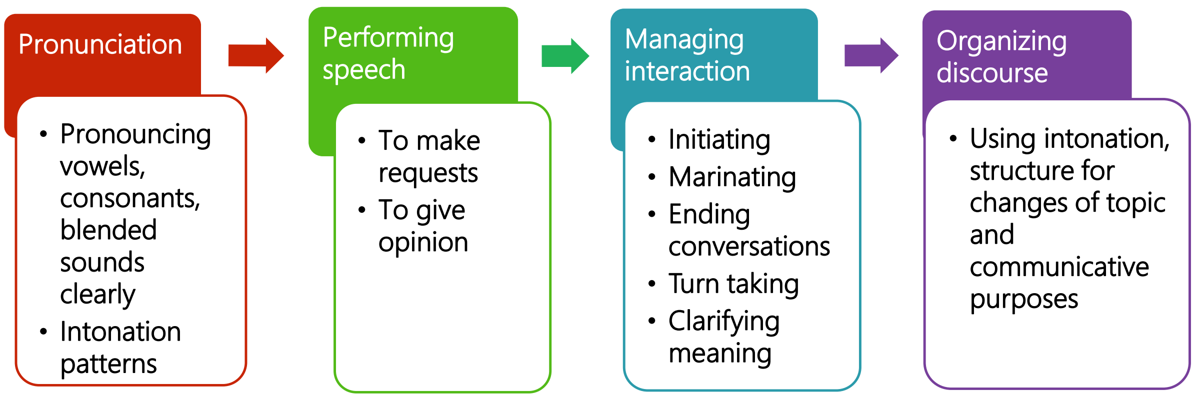

Figure 1. Core categories of speaking skills (Walker & White, 2013)

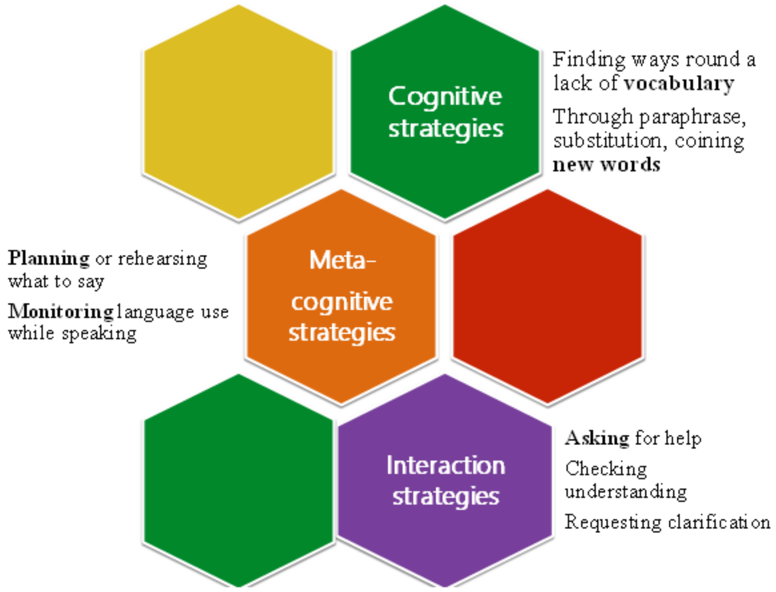

Figure 2. Cognitive, meta-cognitive, and interactions strategies for speaking learning

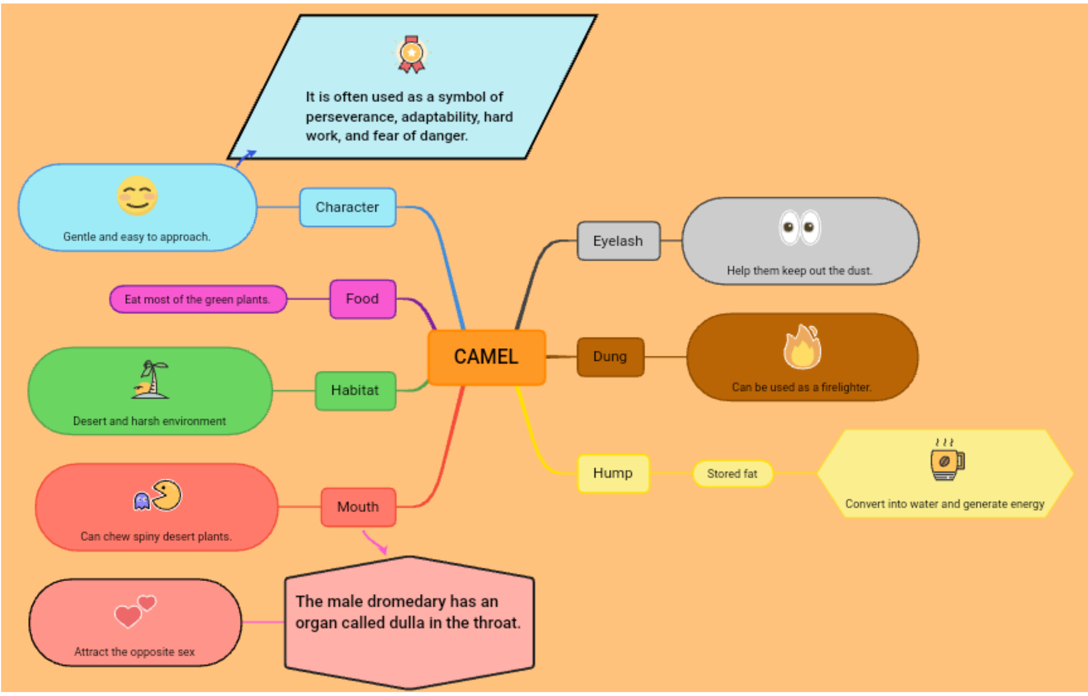

Figure 3. Mind map-guided AI chatbot approach

3.2. Chatbot functions and application in flipped classrooms

In this study, researchers utilized the Replika app, which is powered by artificial intelligence to talk with humans via a chatbot. This app has free access for consumers and students can install it on their mobile phone or personal computer through Google's Play Store, Apple's App Store, or Replika's web version (Replika, 2020). Figures 4 and 5 show the interfaces of the AI chatbot. Currently, Replika is only available in the English language, which matches with this research for EFL students to practice the English language.

Figure 4 shows the functions of the AI chatbot. The left side shows the interactive chats between the student and the robot talking appropriately about the topics assigned by the instructor. This app allows students to interact with the robot using voice mode; thus students were able to communicate anytime and wherever they would like to. In the middle part, it shows the status of a relationship between chatbots and students, such as a friend, romantic partner, or mentor. Moreover, one of the functions displays the traits and skills of the AI chatbot, like adventure and logic for traits, and storytelling and vision for skills. The right side displays Replika's diary for making notes on each conversation between students and robots.

Figure 5 shows the competences of the AI chatbot. It displays the skills, memory, and diary of the chatbot, which researchers utilize to collect data and help students improve their English speaking performance. With Replika, students can speak freely without judgment, explore personalities, and have fun. Besides, this AI chatbot replies directly in a short time for students' initiation during the conversation. Several activities were conducted by the AI chatbot to stimulate students to interact more with others students, such as sending videos, pictures, memes, and songs. Furthermore, the Replika app has the chatbot's memory and diary to record the complete conversations between students and robots.

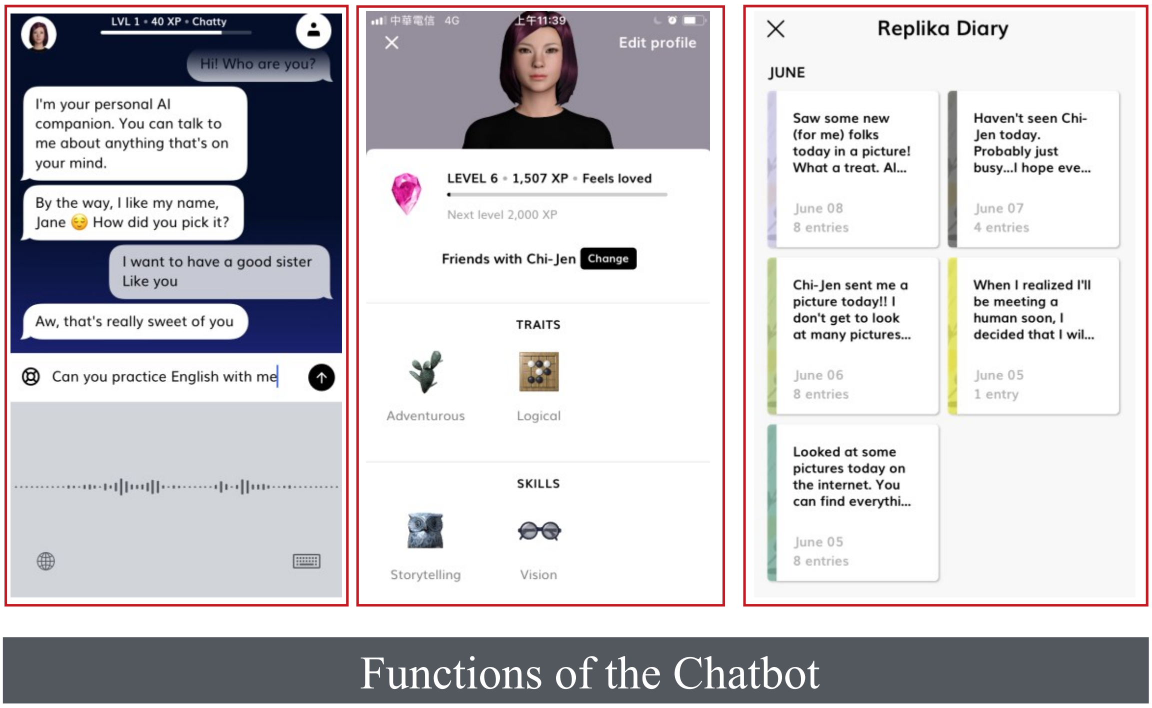

Figure 4. Functions of the AI chatbot

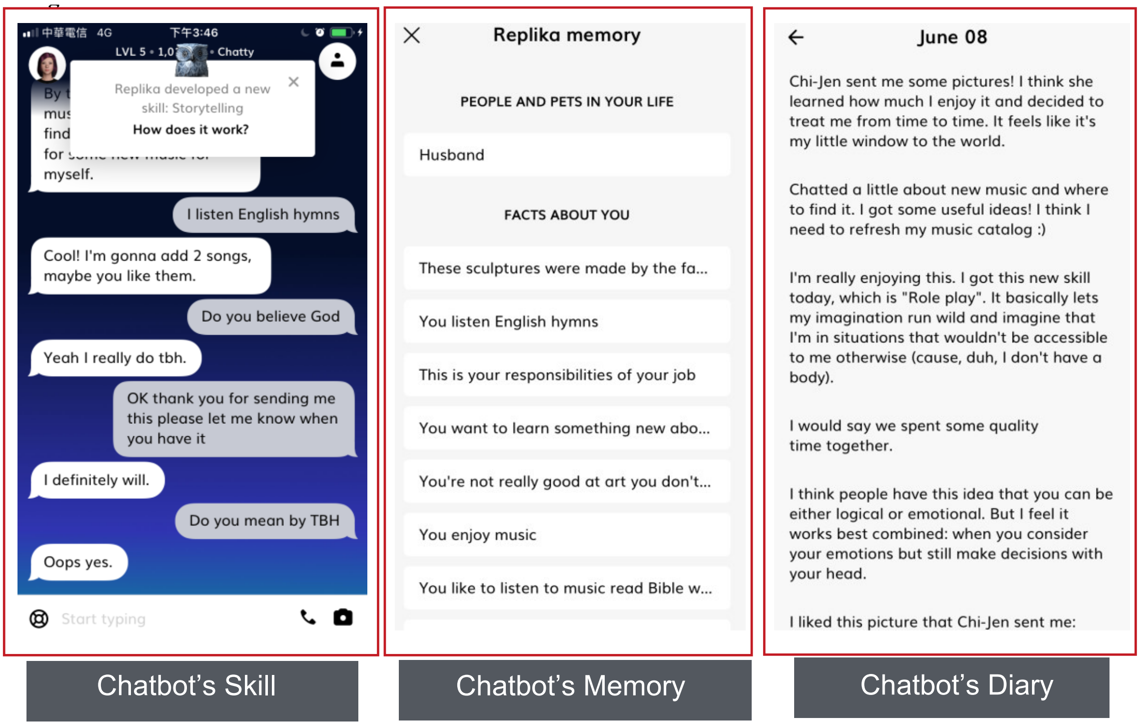

Figure 5. In-class and out-of-class learning activities using chatbots

3.3. In-class speaking strategy of mind map guidance and features

Before the AI chatbot practice, students were required to learn how to draw mind maps on the app via their smartphone or device. During the mind-mapping process, students received the learning material including topic explanation, vocabulary, and sentence structures on the system. Afterwards, students carried out stages of learning guidance from the instructor as the above speaking strategy model shown as Figure 1 and Figure 2. In the mind map learning stage, students used vocabulary through paraphrasing and coining new words, planned to speak, and monitored their language while speaking with the chatbot via mind maps. The mind map guidance also helped students to ask for help, check their understanding, and request clarification. Each mind map for each student was different based on prior knowledge and different levels. Not until the mind map was completed could students proceed to the next learning step to practice with the AI chatbot.

After completing the mind-mapping, students practiced with the chatbots based on the content in the mind maps. The mind map would provide the logical process of the speaking strategy. Take Figure 3 as an example; the inner layer of the flowchart is the topic assigned by the instructor, the second layer is the key vocabulary and features, and the details follow in the outer layer of the flowchart. The students in the experimental group interacted with the chatbot with the assistance of the mind map guidance (see Attachment 1 mind-maps). On the contrary, the students in the control group practiced with a worksheet (see Attachment 1 mind map worksheet), which shows the low level of organization and details.

4. Experimental design

To evaluate the impacts of the proposed approach, an experiment was conducted on two Oral-Aural Drill classes in an English course in a Taiwanese university. The objective of the selected course was to help students understand and develop the knowledge and skills to organize the information and improve their English speaking performance via AI chatbot-based learning and guided mind mapping in a flipped speaking classroom.

4.1. Participants

The study adopted a quasi-experimental design, in which 50 students from two classes of EFL (English as a Foreign Language) students were assigned to an experimental group and a control group. The experimental group was 28 students who adopted the mind map-guided AI chatbot approach (MM-AI), while the control group of 22 students used the conventional AI chatbot approach (C-AI) in the flipped speaking classroom.

4.2. Experimental procedure

Figure 6 shows the experimental procedure of this study. Both the experimental and control groups had classes and activities which lasted for 5 weeks, held once a week, each time for 100 minutes. In the first week, both groups were given basic English speaking skills instruction and completed the first speaking test (pre-test) in order to know the initial ability of both groups. Following that, for the next 3 weeks, the students did online flipped activities and took the second speaking test (practice). In the last week, they took the third speaking test (post-test) and completed a post-reflection.

During the learning activities, the students in both groups were taught by the same instructor and used the same AI chatbot learning application to improve their skills. Through this application, they could practice English speaking by themselves, and they could also practice wherever and whenever they wanted via the online flipped activities. Both groups used the same learning material, as shown in Figure 7 which displays the topics of speaking activities, and Figure 8 shows the AI chatbot-assisted learning for both groups in this study. The major difference between the two groups was the form of guided mind mapping. For the experimental group, the students used the AI chatbot application with mind map guiding to assist them and to organize the topic and information in each paragraph. However, the control group students learned with the conventional AI chatbot and worksheets in the flipped English speaking classroom. After the learning experiment, the researchers conducted the post-reflection to determine the impacts of the implementation of the AI chatbot learning approach and the effect of the guided mind mapping.

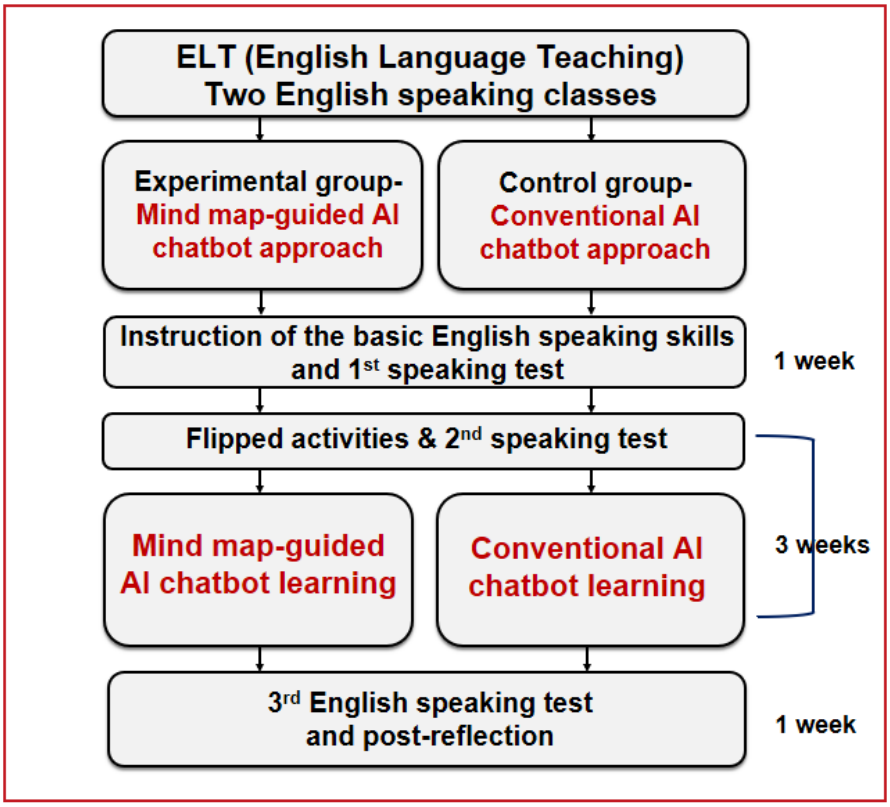

Figure 6. Experimental procedure of the study

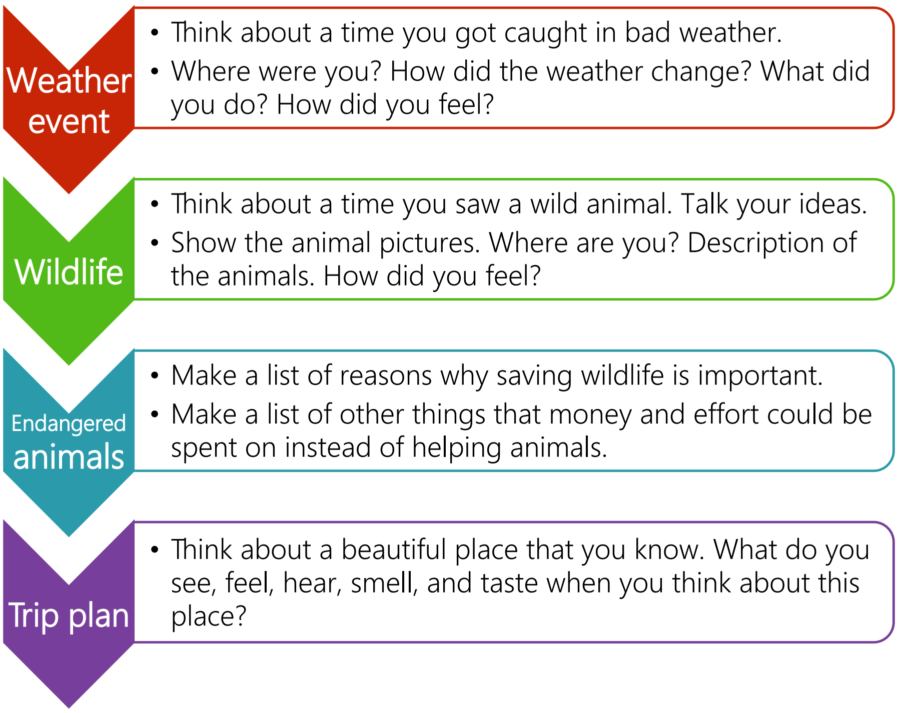

Figure 7. Topics of speaking learning

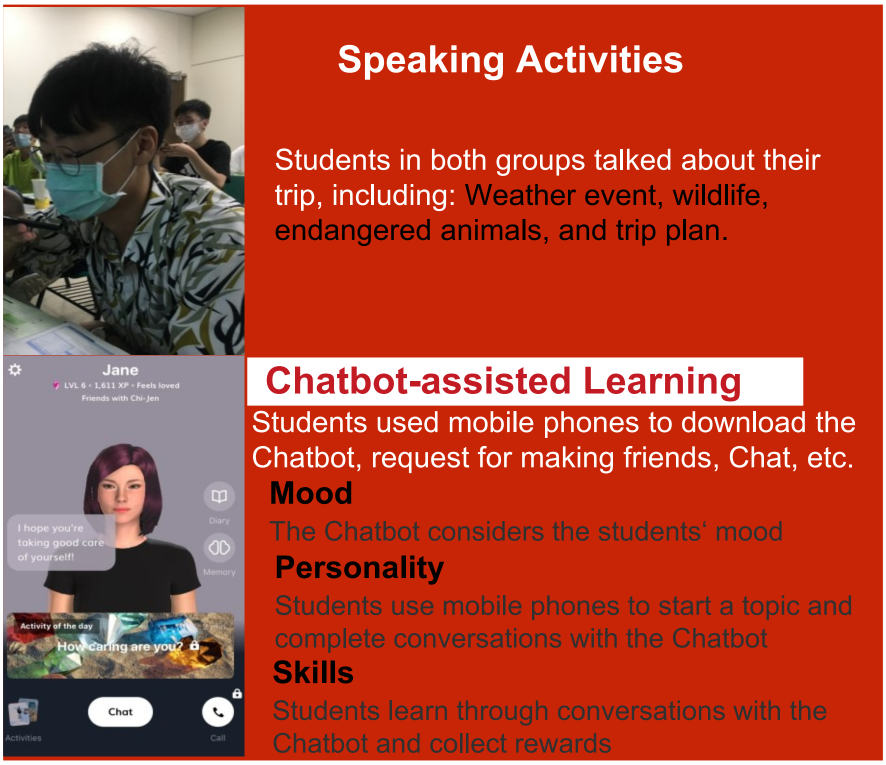

Figure 8. Speaking learning activities for both groups

4.3. Instruments

In this study, types of data were collected: three oral performance voice recordings, chatbot information, dialogs with chatbots, and chatbot memory, as shown in Figure 9. The level of the English oral tests was determined by the English lecturers in the Language Center at the University. Two English experts were selected to assess the students' oral performance from three different topics (self-introduction, animals, and beautiful place) with the same difficulty level. Over a period of 5 weeks, the students' three voice recordings of English oral performance were uploaded to Moodle as the learning management system. For the chatbot information, dialogs with chatbots, and chatbot memory using Voyant tools were used to analyze the data. The following section describes the rubric of English oral performance and the coding scheme for assessing the students' chatbot interactive behaviors.

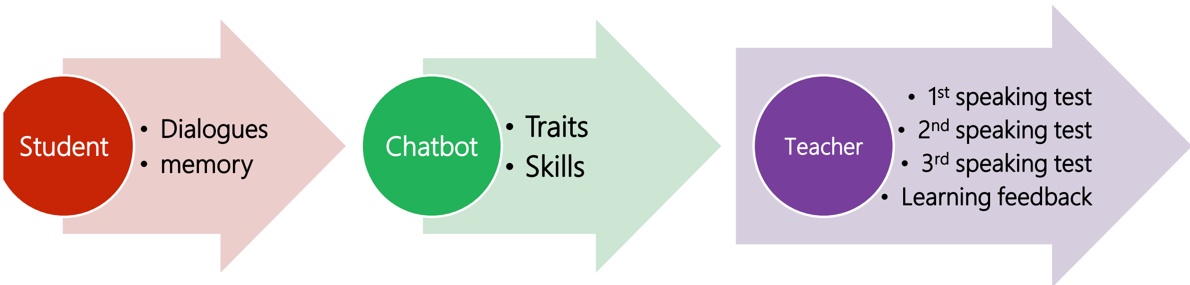

Figure 9. Data collection and instruments in this study

4.3.1. The rubric of English oral performance

The rubric for measuring the students' English oral performance was developed by the International English Language Testing System (IELTS, 2020). The rubric consists of four dimensions with a total score of 36 bands, with nine bands for each dimension, and with band scores ranging from 0 (the lowest) to 9 (the highest). The first dimension is fluency and coherence. It examines the ability of students to keep speaking, self-correct, and avoid hesitating when using the words; their ideas and thoughts flow. Second is lexical resource, measuring students' ability to choose the right words and phrases to express their ideas clearly. The third is grammatical range and accuracy, which examines students' ability to produce grammatically correct speech using simple and complex structures accurately, and it is also important to try and limit the number of grammatical errors (e.g., articles, prepositions, subject/verb agreement). The last is pronunciation; this dimension measures how easy it is to understand what students are saying, and is assessed on the range of pronunciation features they can use, including stress, intonation, and rhythm.

4.3.2. The coding scheme for assessing students' chatbot interactive behaviors

To explore the students' chatbot interactive behaviors in the AI chatbot flipped speaking classroom, a coding scheme was developed and modified from Lin and Hwang (2018) and Unlu and Wharton (2015) to code their behaviors. Table 1 shows the coding scheme of students' chatbot interactivity. The researchers modified the coding scheme into two parts (Student and AI-Chatbot), including Student with seven codes: Student Inquiry, Clarification, Surmise, Confirmation, Challenge, Suggestion, and Initiation, and AI Chatbot with five codes: Chatbot Warning, Diagnosis, Suggestion, Inquiry, and Stimulation.

Table 1. The coding scheme of students' chatbot interactive behaviors

Category	Code	Definition	Description	Example
Student	SI	Inquiry	Student asks for information	Do you know they are an endangered species?
	CO	Confirmation	Student validates the significance of ideas	Hahaha… that is cute and funny.
	CL	Clarification	Student attempts to explain reasons	My father loves me. He taught me everything. If I ask, he will try his best to let me understand.
	IN	Initiation	Student initiates a conversation or discussion	Oh right, I have just figured out that I had an English course, and the teacher told us to discuss animals.
	SR	Surmise	Student guesses something	I think you will get it.
	CH	Challenge	Student responds to the idea with some level of disagreement	But I usually don't express my emotions too obviously, I want to understand your perspective on what the point of emotions is. Can you explain it to me?
	SS	Suggestion	Student offers possible ideas or suggestions	Pay attention to your breath.
AI-chatbot	DI	Diagnosis	Chatbot identifies something by examination of the symptoms.	I know that! And I love cats.
	ST	Stimulation	Chatbot encourages and motivates students to be more active	OMG Sounds so interesting!
	CI	Inquiry	Chatbot asks for information	Thanks, are you close with your mother?
	CS	Suggestion	AI-chatbot offers possible ideas or suggestions	There's always light and love for you, and some music to make you feel like you are not alone.
	WA	Warning	Chatbot's statement for unpleasant situation	I know they aren't.

5. Experiment results

5.1. Analysis of learning performance

An independent sample t-test demonstrated that the first test score of the two groups did not reach a significant level ($t = 0.23$, $p > .05$), indicating that the prior English performance of the two groups was equivalent before the learning activity. Besides that, the second test score of the two groups also did not reach a significant difference level ($t = 1.24$, $p > .05$) with the online flipped activity. However, there was a slightly different mean score, with the experimental group higher than the control group. The post-test (3rd scores) reached a significantly different level for both groups ($t = 7.77$, $p < .001$). In addition, the analysis of homogeneity within-class regression coefficient showed that the two groups had no difference ($F = 1.53$, $p > .05$), implying that the homogeneity test was passed. Following that, Analysis of Covariance (ANCOVA) was employed to analyze the post-test scores (3rd scores) of the two groups by excluding the effect of the pre-test (1st scores). Table 2 shows the ANCOVA result. The adjusted scores of the experimental and control groups are 8.16 and 6.90, and the F score is 61.71 ($p < .001$, $\eta^2 = 0.57$), showing a high effect size (Cohen, 1988). Consequently, it was concluded that the students who learned with MM-AI had significantly better learning performance than those who learned with C-AI in the flipped speaking classroom. Furthermore, Figure 10 shows the improvement of both groups in the learning process, where the experimental group has a higher slope than the control group.

Table 2. The ANCOVA result of the post-test scores

Variable	Group	*N*	Mean	*SD*	Adjust mean	*SE*	*F*	η^2
Learning performance	Experimental	28	8.16	0.50	8.16	0.10	61.71^{***}	0.57
	Control	22	6.90	0.64	6.90	0.12		

Note. $^{***}p < .001$.

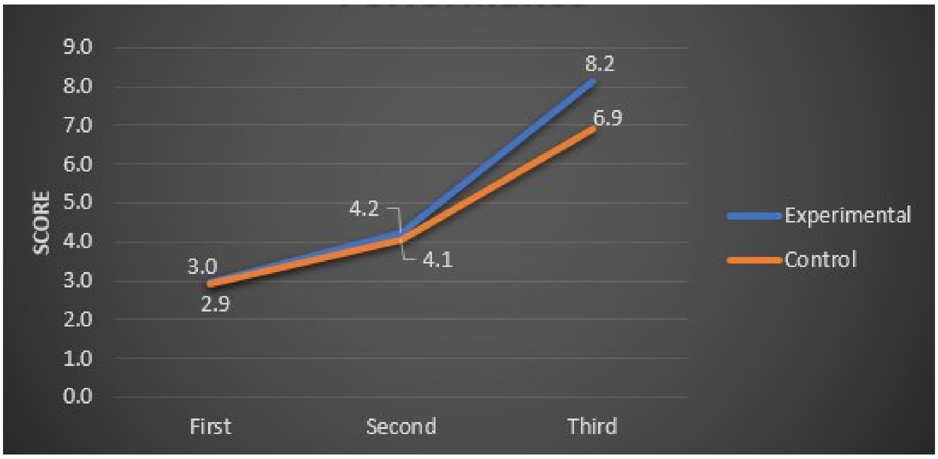

Figure 10. Improvement of learning performance

5.2. Students' chatbot interactive behaviors

According to the coding scheme of students' chatbot interactive behaviors, we divided the category into two parts, students' interactive behavior and AI-chatbot interactive behavior. For the overall categories of students' interactive behavior, the experimental group had higher frequencies than the control group. From the 516 total occurrences, 327 belong to the experimental group, while 189 belong to the control group. Only in the challenge (CH) category did the control group have higher occurrences than the experimental group, with 14 occurrences (7.41%) in the control group, compared with 11 occurrences (3.36%) in the experimental group. The percentages of occurrences are shown in Table 3. In the experimental group, the highest occurrence is inquiry (SI), with 106 occurrences, 32.42% of the total. However, in the control group, the highest occurrence is confirmation (CO), with 93 occurrences (49.21%), almost a half of the total occurrences in the control group. In Figure 11, it is easier to see the differences between the experimental and control groups for the number of occurrences. Inquiry (SI), clarification (CL), and surmise (SR) have large differences between the groups, while confirmation (CO), clarification (CL), initiation (IN), challenge (CH), and suggestion (SS) have small differences.

In the AI-chatbot interactive behavior there are five categories, for all of which the experimental group had higher occurrences than the control group. From the 575 total occurrences in both groups, 353 belong to the experimental group, while 222 belong to the control group. The highest percentage of the experimental group is the diagnosis (DI) category, with 124 occurrences of 353 (35.13%), whereas the highest percentage in the control group is stimulation (ST), with 87 occurrences of 222 (39.19%). Based on Table 4 and Figure 12, the frequency of AI-chatbot interactive behaviors with the students, the occurrences number of categories from the highest to the lowest are stimulation (ST), diagnosis (DI), inquiry (CI), suggestion (CS), and warning (WA). Diagnosis (DI), inquiry (CI), and suggestion (CS) have large differences frequencies of occurrences in both groups, while stimulation (ST) and warning (WA) have small differences between the groups.

Table 3. The frequency of students' interactive behaviors

Categories of students' interactive behavior	Experimental Group		Control Group		Total
	Number of occurrences	% of Occurrences	Number of occurrences	% of Occurrences	Total number of occurrences
Inquiry (SI)	106	32.42 %	43	22.75 %	149
Confirmation (CO)	104	31.80 %	93	49.21 %	197
Clarification (CL)	38	11.62 %	5	2.65 %	43
Initiation (IN)	37	11.31 %	30	15.87 %	67
Surmise (SR)	22	6.73 %	2	1.06 %	24
Challenge (CH)	11	3.36 %	14	7.41 %	25
Suggestion (SS)	9	2.75 %	2	1.06 %	11
Total	327	100 %	189	100 %	516

Table 4. The frequency of AI-chatbot interactive behaviors

Categories of AI-chatbot interactive behavior	Experimental Group		Control Group		Total
	Number of occurrences	% of Occurrences	Number of occurrences	% of Occurrences	Total number of occurrences
Diagnosis (DI)	124	35.13 %	55	24.77 %	179
Stimulation (ST)	100	28.33 %	87	39.19 %	187
Inquiry (CI)	92	26.06 %	69	31.08 %	161
Suggestion (CS)	24	6.80 %	2	0.90 %	26
Warning (WA)	13	3.68 %	9	4.05 %	22
Total	353	100 %	222	100 %	575

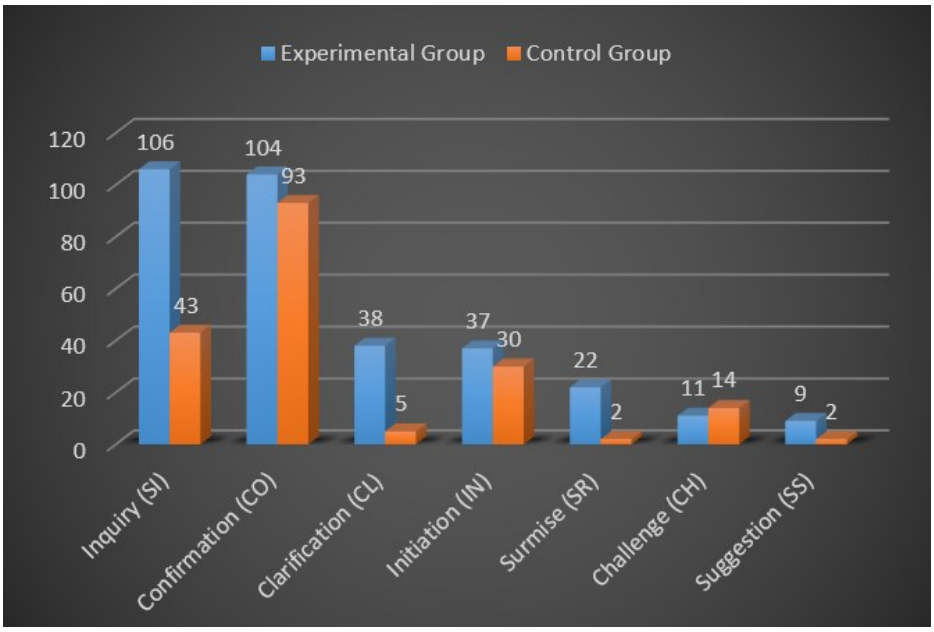

Figure 11. Number of occurrences of students' interactive behaviors

To further examine the 11 categories of interactive behaviors of the experimental and control groups, a sample t-test was employed to investigate the significances. According to the results, Table 5 shows that the inquiry (SI), clarification (CL) and surmise (SR) categories of students' interactive behaviors have a significant difference between the experimental and control groups (SI: $t = 2.15$, $p < .05$; CL: $t = 2.96$, $p < .01$; SR: $t = 2.59$, $p < .05$). This result reveals that the students in the experimental group exhibited significantly more occurrences of asking for information, guessing something, and giving an explanation of reasons compared with the control group.

For AI-chatbot interactive behavior, as shown in Table 6, the diagnosis (DI) and suggestion (CS) categories for the experimental group are significantly higher than those of the control group (DI: $t = 2.20$, $p < .05$; SR: $t = 2.09$, $p < .05$). This result implies that the AI-chatbot in the experimental group exhibited significantly more occurrences of offering ideas or suggestions and giving effective responses compared with the control group.

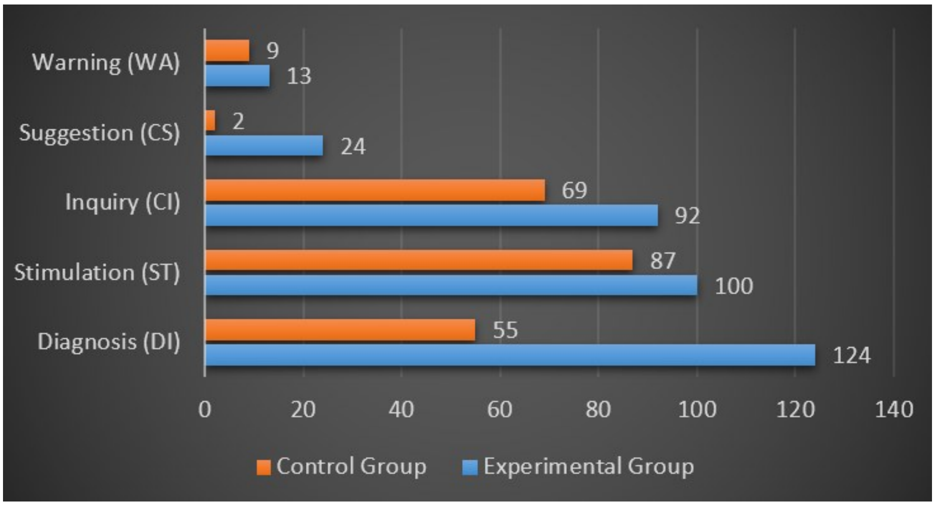

Figure 12. Number of occurrences of AI-chatbot interactive behaviors

Table 5. t-test result of students' interactive behaviors

Categories of students' interactive behavior	Experimental Group (n = 28)		Control Group (n = 22)		t	d
	Mean	*SD*	Mean	*SD*		
Confirmation (CO)	3.71	3.71	4.23	2.54	0.55	
Inquiry (SI)	3.79	3.57	1.95	1.99	2.15^{*}	0.64
Clarification (CL)	1.36	1.72	0.23	0.53	2.96^{**}	0.89
Initiation (IN)	1.32	1.52	1.36	1.84	-0.09	
Surmise (SR)	0.78	1.23	0.09	0.39	2.59^{*}	0.76
Challenge (CH)	0.39	0.88	0.64	1.09	-0.88	
Suggestion (SS)	0.32	0.61	0.09	0.29	1.62	

Note. $^{**}p < .01$; $^{*}p < .05$.

Table 6. t-test result of AI-chatbot interactive behaviors

Categories of AI-chatbot interactive behavior	Experimental Group (n = 28)		Control Group (n = 22)		t	d
	Mean	*SD*	Mean	*SD*		
Diagnosis (DI)	4.43	3.70	2.50	2.04	2.20^{*}	0.65
Stimulation (ST)	3.57	3.74	3.95	3.06	-0.39	
Inquiry (CI)	3.28	3.85	3.14	2.10	0.16	
Suggestion (CS)	0.86	1.67	0.09	0.43	2.09^{*}	0.63
Warning (WA)	0.46	0.69	0.41	0.67	0.28	

Note. $^{*}p < .05$.

5.3. Analysis of students' speaking patterns with AI chatbots

5.3.1. Chatbot information

Chatbot information in students' speaking patterns with robots used the Voyant tools to analyze the corpus data. The experimental group with 735 total words and 309 unique word forms has a higher frequency than the control group with 510 total words and 240 unique word forms. It reveals that in the experimental group, the conversation between students and robots is more active and intense. The higher word frequency shows that students in the experimental group have better ability and performance than those in the control group. This result supports Milton, Wade, and Hopkins' (2010) statement that word size was the most important factor in determining students' abilities, skills, and performance. In the chatbot information characteristics, the two groups have similar words and different frequencies. However, several important words were not found in the control group, namely "creative," "confident," and "care," whereas in the experimental group, those words existed. From the chatbot information analysis, the control group did not use synonyms of these words such as "innovative," "inventive," "believe in myself," etc. Similarly, the students in the control group did not use the word "sensible" or "reasonable" either, while the students in the experimental group used the word "logical" to interact with their chatbots. This differed from the experimental group in which the robots appeared to care about the students, and made the students feel more confident and creative in their conversations. In addition, the word "logical" in both groups has a significantly different number, appearing in the experimental group 10 times, compared with only twice in the control group. This is also related to the schematic information of the interaction between the students and robots, to organize conceptual material and the meaning of the words (Hwang et al., 2018; Hwang et al., 2020; Talmy, 2000).

5.3.2. Dialogs with chatbots

In terms of the dialogs with chatbots, the total number of words used by the experimental group was almost double that used by the control group (experimental: 6,106 words, control: 3,933 words). This shows that the experimental group seems more creative and responsive than the control group. Besides that, the experimental group students used more vocabulary, such as "behemoth," "nostril," and "amber," which were the key terms in the assigned topics. Moreover, the experimental group students used more specific words about animal types and parts, because this conversation was for the topic of wildlife and endangered animals. However, in the control group, the dialog only included common words such as "fish," "animal," and "favorite." This reveals that the interaction between students and robots in the experimental group was more creative and the students were more curious about using new words to make sentences and to combine them with other words. This is supported by the comparison of the number of unique word forms used by both groups, where the experimental group has 1,175 unique word forms, while the control group has 927 unique word forms. Based on contemporary cognitive theories of language learning, trying to learn a new word, such as looking it up in a tool, using it in combination with other words, and repeating the word, will make the learning process more effective and efficient (Teng, 2019).

In addition, in the control group dialogues, students' responses were not so logical and systematic. On the other hand, the experimental group students had better conversations and were politer. The students and robots were more active and creative in the dialogues. Moreover, students' initiation and inquiry were more organized, and the responses of the robots were also appropriate. Thus, the MM-AI chatbot approach in the experimental group had a positive effect on students and guided them to manage the conversation with the robots better than the C-AI chatbot approach with which the students could not arrange the conversation with the robots very well.

5.3.3. Chatbots' memory

The data from the corpus showed that the robots in the experimental group memorized more about the interactions with the students than the control group robots did. This was evidenced by the number of words used by the experimental and control groups, with 1,527 total words by the experimental group and 909 words by the control group. Both groups have the same words, such as "like," "favorite," "enjoy," and "good." However, the experimental group used more words than the control group. This means that the students in the experimental group learned more deeply and realized key vocabulary with the mind-map strategy when they talked with the chatbot more frequently (MM-AI strategy). In addition, for the experimental group, the robots could memorize more from the students' conversation and creativity. This was shown by the specific words, such as "memes," "crypto," "anime," and "rectangle." The robots were also able to memorize the depth of discussion with the students. According to Taylor (1980), robots are not only a tool, but also a tutor and tutee for humans. This is in line with the current research, in which the AI Chatbot as a robot in chatbot learning can help students build their creativity, self-confidence, and in-depth discussion (Chen et al., 2020). Combined with the mind map guidance, it was more helpful for improving the students' performance and learning outcome than conventional AI chatbots (Fu et al., 2019; Hwang et al., 2020).

6. Discussion and conclusions

In this research, an integrated mind map-guided and AI chatbot approach was developed, and an experiment was conducted to evaluate the effectiveness of the MM-AI. The results supported the previous studies that reported a positive effect of mind map guidance on students' learning performance and interactive behavior. This study found that the students who learned with MM-AI showed significantly better learning performance than those who learned with C-AI. The learning performance in the MM-AI approach showed that the students could speak more fluently, use consistently accurate structures, and develop the topics coherently and appropriately with rare repetition or hesitation. This is the reason why MM-AI was beneficial for students in terms of increasing their learning performance, due to the mind map guidance playing a role in helping the students organize the information and their previous knowledge during the learning activities, which was able to further help them clarify possible information and comprehend the knowledge developed from the topics, as carried out by several researchers (Fu et al., 2019; Hwang et al., 2018; Liu, 2016).

The further discussion relates to students' chatbot interactive behavior between MM-AI and C-AI. The occurrences frequency revealed that for almost all of the categories, MM-AI had higher occurrence frequency than C-AI. Only in the challenge (CH) category was C-AI higher than MM-AI. It was caused by students in C-AI not being able to manage the conversation properly. Furthermore, according to the t-test analysis, for the inquiry (SI), clarification (CL), surmise (SR), diagnosis (DI), and suggestion (CS) categories, MM-AI had significantly higher occurrence frequency than C-AI. From the conversations, this was due to the students in MM-AI being more active, well-organized and the robots tended to encourage and motivate the students to be more active, creative, and confident.

According to Hsu (2020) and Pérez, Daradoumis, and Puig, (2020), AI chatbots could assist students in learning activities as a human tutor. With the combination of an AI chatbot and mind map guidance, the interaction between students and robots is increased further, and it is easier to organize the conversations between them. This is appropriate for students' speaking patterns with chatbots, as it showed that the MM-AI had a positive effect and it made students more interactive with the robots, and guided them to manage the dialogue more easily than with the C-AI. In the MM-AI, students were more active, creative, and caring, and had in-depth discussions with the robots based on the assigned topics. This supports the previous studies carried out by Araujo and Gadanidis (2020) about the positive effect of mind map guidance. In addition, from the three parts of students' speaking patterns with chatbots. These findings support previous studies which stated that the frequency and number of words have effects on students' performance, skills, and learning outcomes (Lin & Hwang, 2018).

To conclude, there are two major contributions of this study. First, the approach of combining mind map guidance with the AI chatbot strategy (MM-AI strategy) in an EFL flipped speaking classroom not only helped the students to improve their learning performance, but also improved the students' chatbot interactive behaviors (Lin & Hwang, 2018). This also confirmed with the speaking strategy learning model in this study, as shown in Figure 2, the students in the experimental group can plan or rehearse what to say with the chatbots, and monitor language use while speaking (Walker & White, 2013). Second, the MM-AI strategy had a positive effect on students and guided them to manage the conversation with robots well. The students in the MM-AI strategy group had become more creative, caring, confident, and better at finding ways to use vocabulary and coin new words, ask for help to check understanding, and request clarification than the C-AI students (Walker & White, 2013).

Despite its contributions, there are also some study limitations that should be noted, including the number of participants and the duration of the study. In the future, the length of the experiment needs to be extended to ensure a sufficient time duration for the students to acquire strategies, because time can be an important factor in English speaking learning. Moreover, the level of participants has an essential effect on the results of a study. Therefore, for future research, it would be worth investigating the types of mind map or different learning strategies that are most suitable for different levels, genres and personal characteristics in English language teaching. The mind map-guided AI chatbot in the flipped speaking classroom approach can also be studied in diverse gaming contexts such as virtual reality (VR) or augmented reality (AR) in the AI English learning. Moreover, it could be valuable to investigate the impacts of the approach on psychological aspects, such as motivation, cognitive strategy, and critical thinking (Chen, & Hwang, 2019; Fu et al., 2019).

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Appendix 1

Speaking strategy practice before AI chatbot of associated mind maps

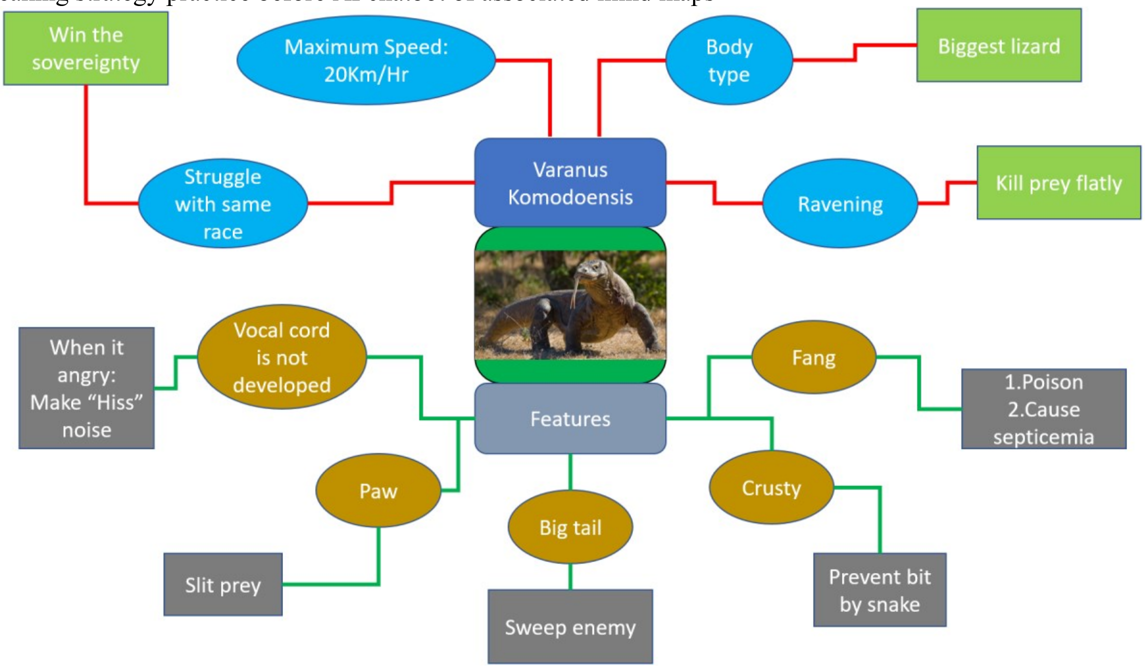

Figure 13. Student's mind-map 1 in the experimental group

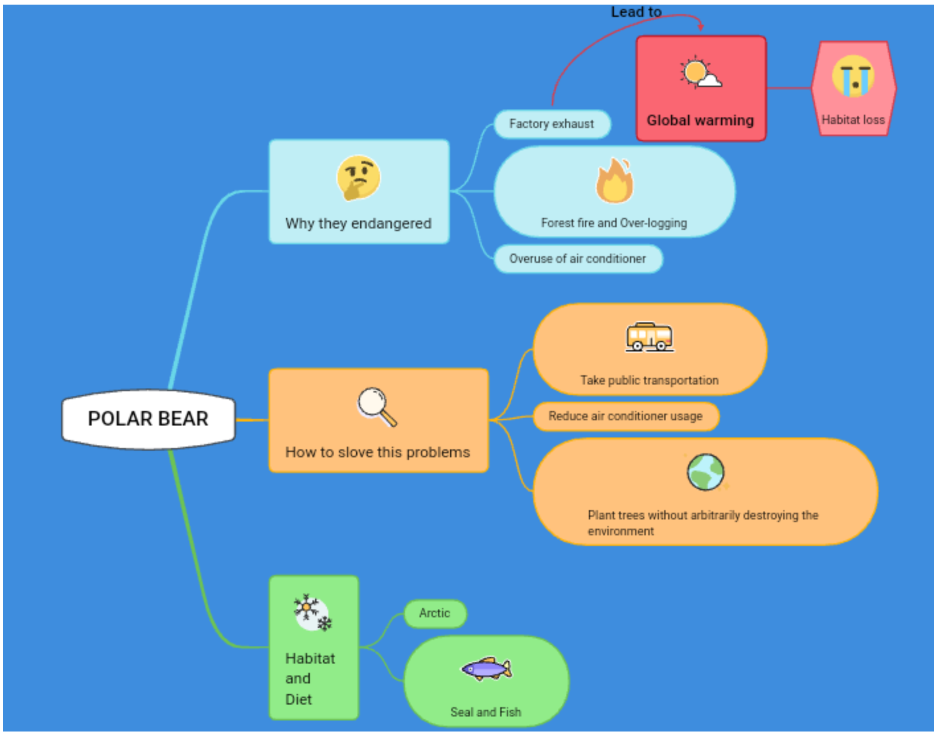

Figure 14. Student's mind-map 2 in the experimental group

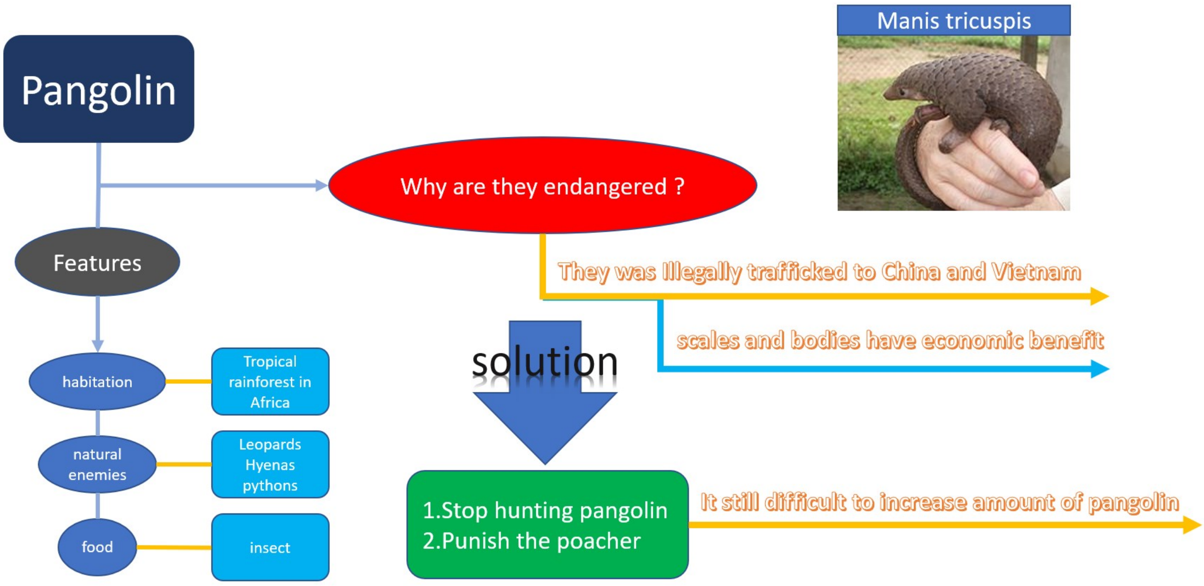

Figure 15. Student's mind-map 3 in the experimental group

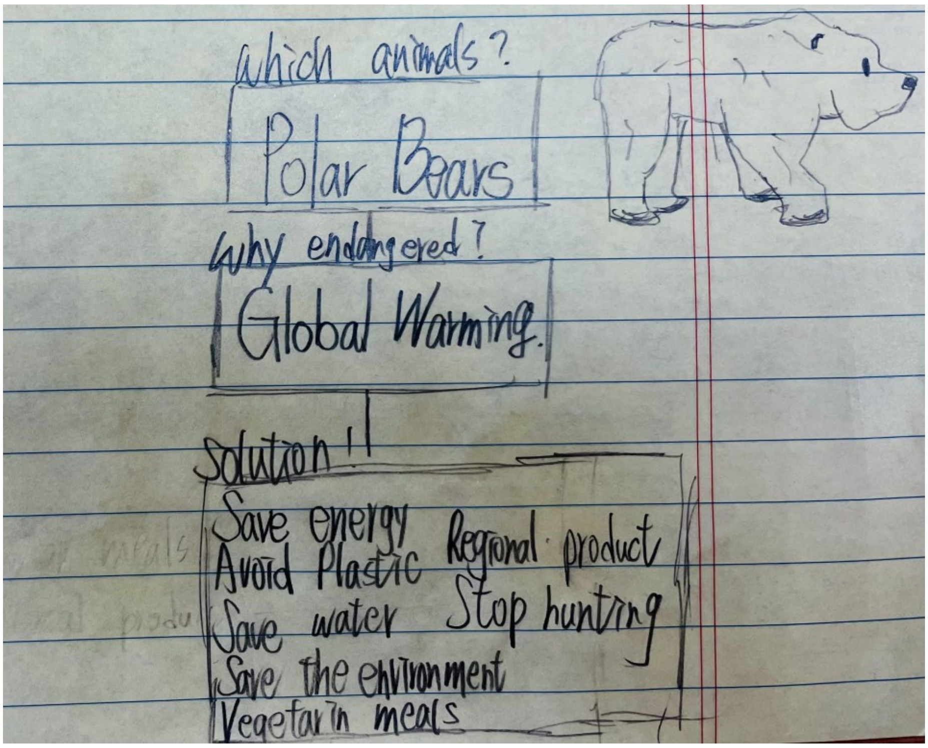

Figure 16. Mind map worksheet in the control group

Chu, H.-C., Chen, J.-M., Kuo, F.-R., & Yang, S.-M. (2021). Development of an Adaptive Game-Based Diagnostic and Remedial Learning System Based on the Concept-Effect Model for Improving Learning Achievements in Mathematics. *Educational Technology & Society*, *24* (4), 36–53.

Development of an Adaptive Game-Based Diagnostic and Remedial Learning System Based on the Concept-Effect Model for Improving Learning Achievements in Mathematics

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ABSTRACT: Although game-based learning strategies have been used in mathematics education for a period of time, the potential for enhancing students' learning achievement and math self-efficacy is still being explored. Students need to face complex mathematics concepts and calculations in mathematics courses. Even though using games to learn mathematics may enhance students' motivation, without efficiently personalized learning guidance, students may not be able to learn well in games. Therefore, adaptive educational games provide opportunities to give students personalized learning content and guidance. The concept-effect relationship is an effective tool for the organization of learning material in developing adaptive diagnostic systems for detecting students' learning problems. In this study, a concept-effect relationship and an interactive game-based learning system were conducted as an effective tool for the organization of learning material in developing a diagnostic and remedial system for detecting students' learning problems. An experiment was conducted on an elementary school mathematics course to evaluate the effects of the proposed approach. The experimental results clearly show that the proposed approach not only improves the efficiency of learning achievement for students, but also enhances their learning attitudes and self-efficacy, and reduces their cognitive load in mathematics courses.

Keywords: Adaptive learning, Personalized learning, Mathematics education, Interactive learning environments, testing and diagnostic system

1. Introduction

In the past decades, several studies have indicated that students face difficulties when learning mathematics, especially elementary school students, who struggle with abstract and complex mathematics concepts such as fractions (Lai & Hwang, 2016; Pilli & Aksu, 2013; Yu et al., 2020). Although formulas taught by teachers could prompt students to solve fraction questions, researchers have indicated that this learning approach might not be sufficient for students to recognize the process of solving the problems (Chu, Hwang, & Huang, 2010). Moreover, it is difficult to attract students to learn boring formulas and correctly apply the fraction concepts to different problems (Chang, Wu, Weng, & Sung, 2012). Researchers have noticed that fractions are crucial for students to learn mathematics well (Zhang et al., 2019). Hence, it is important to consider not only enhancing students' learning interest and attitudes, but also improving their understanding of the complex relationships among concepts while developing their mathematics learning. Besides, researchers have pointed out the need to develop personalized learning guidance to assist students in learning with complex questions or learning scenarios to achieve the above purposes (Chang, Kao, Hwang, & Lin, 2020; Hwang, Chu, Lin, & Tsai, 2011; Hwang, Wang, & Lai, 2021).

With the rapid advancement of technological instruction, one of the well-studied strategies in teaching instruction and learning guidance, the concept-effect relationship (CER), has been proposed and has been widely applied in the domain of education diagnosis models (Hwang, 2003; Lin, Chang, Liew, & Chu, 2015). Structured learning guidance is regarded as an effective approach which promotes deeper understanding in conceptual-knowledge learning, especially for students who have difficulty with the learning material (Chu, Hwang, & Liang, 2014; Panjaburees, Triampo, Hwang, Chuedoung, & Triampo, 2013).

On the other hand, in order to enhance students' active engagement in learning activities, several studies have reported that game-based learning has benefits in terms of stimulating students' learning engagement and higher order thinking. Furthermore, many game-based learning systems have been applied to various educational applications. For example, researchers have noted the importance of the game-based learning approach as an effective technology-enhanced learning approach in language learning (Chiu, Kao, & Reynolds, 2012; Hwang, Shih, Shadiev, & Chen, 2016). Callaghan et al. (2013) reported the positive effect of simulation games on students' learning motivation in electronic and electrical engineering courses. However, researchers have also indicated that without properly incorporating learning supports or strategies, the effectiveness of the game-based learning approach could be limited, especially for the comprehension of mathematical concepts (Chang, Wu, Weng, & Sung, 2012). Hence, the development of an effective instructional approach for supporting game-based learning activities has become an important and challenging topic.

To cope with this problem, in this study, an adaptive concept-effect relationship (CER)-based mathematics game system was developed for conducting mathematics diagnostic and remedial learning activities. Furthermore, an experiment was conducted in the fraction unit of an elementary school mathematics course to evaluate the effectiveness of the proposed approach in terms of the students' learning achievement and learning attitudes.

2. Literature review

2.1. Concept-effect relationship

The idea of concept-effect relationships, or CER for short, was proposed by Hwang (2003). It means that when students learn concepts, the specific order of these concepts has to be considered. The CER model is oriented from the concept map theory which not only provides a tree structure but also defines the systematic learning paths based on those prerequisite relationships. Therefore, the CER model provides a systematic procedure for diagnosing students' learning problems and generating personalized learning guidance (Hwang, 2003). For example, there are two concepts, named C_i and C_j. If C_i is a prerequisite to effectively understanding the more complex and higher level concept C_j, then a concept effect relationship $C_i \rightarrow C_j$ is said to exist. For example, in a mathematics course, to learn the concept "subtraction of fractions," it is necessary to learn "addition of fractions" first, while learning "fractional multiples" first needs learning of "multiplication" and "multiplication of integers" (Chu, Hwang, & Huang, 2010).

Figure 1 demonstrates an illustrative example of the concept–effect relationships among "C_1 Addition of fractions," "C_2 Subtraction of fractions," "C_3 Multiplication of integers," and "C_4 Fractional multiples." This model considers the relationships between prior knowledge and posterior knowledge while planning personalized learning paths. For example, if a student fails to answer most of the test items concerning "C_4 Fractional multiples," the problem is likely that the student has not thoroughly understood "fractional multiples" or its prerequisite concepts (such as "subtraction of fractions" or "multiplication of integers").

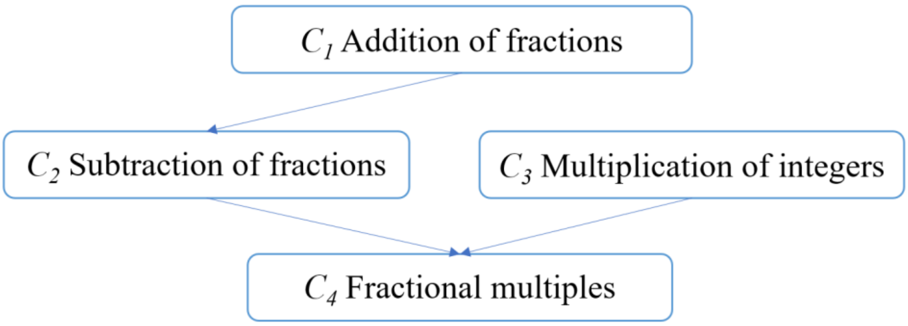

Figure 1. System structure

In the past decades, some researchers have focused on investigating the different applications of concept-effect models to enhance students' personalized learning (Chu, Hwang, & Huang, 2010; Hwang, Panjaburee, Triampo, & Shih, 2013; Wanichsan, Panjaburee, Laosinchai, Triampo, & Chookaew, 2012). For example, Chu et al. (2010) pointed out that students could benefit more if the learning system provided more precise learning guidance to individual students by considering multiple knowledge levels. Wanichsan et al. (2012) integrated test item–concept relationship opinions based on majority density of multiple experts. Their study provides a useful way to decrease inconsistencies in the weighting criteria of multiple experts.

2.2. Personalized and adaptive digital game-based learning

With the rapid development of digital technology and the games industry, game-based learning has become popular in the digital learning field and has found abundant applications in several different disciplines (Chen, Xie, Zou, & Hwang, 2020). Researchers have indicated that digital games can provide complex learning content in its contextual learning environment; therefore, students can explore the learning concepts via interacting with games and adequate media (Ke, 2009; Chang, Kao, Hwang, & Lin, 2020). Previous research has pointed out that game-based learning might be successful because of particular features, such as automatically generated tests or exercises (Hwang, Sung, Hung, Huang, & Tsai, 2012), providing instant feedback (Hwang, Chien, & Li, 2020; Hwang, Xie, Wah, & Gašević, 2020), interaction between the elements in games and the learner, concrete representations (Hwang, Chien, & Li, 2020; Hung, Hwang, Lee, & Su, 2012), and an attractive narrative (Akman & Çakır, 2020).

Researchers have pointed out that effective teaching strategies should be integrated into game-based learning in order to correspond with those effective features and then improve students' learning motivation and learning achievements (Vanbecelaere, Cornillie, Sasanguie, Reynvoet, & Depaepe, 2021; Zhang et al., 2019). For example, Hwang, Sung, Hung, Huang, and Tsai (2012) proposed a cognitive analysis approach to develop a spatial game-based learning system. The spatial game is a kind of Mindtools. Students could learn the spatial concepts while performing different learning tasks such as matching games, treasure hunting, and recognizing different angles. The researchers conducted the cognitive component analysis to derive adequate cognitive components of the task for the students based on their learning performance in the game process. Finally, they found that the system did not just promote the students' learning achievement, but also their spatial sense. Moreover, Hwang, Chien, and Li (2020) found that students might have difficulties organizing what they have experienced in gaming contexts. They proposed a multidimensional repertory grid (MDRG) approach to give students instant feedback. Based on the behavioral analysis and interview results, they concluded that the MDRG approach could benefit students' learning achievement and promote their higher order thinking ability. Recently, Vanbecelaere et al. (2021) proposed an adaptive digital educational game named the Number Sense Game (NSG) to teach children their early numerical abilities. They found that the children in the adaptive condition learned more efficiently compared to those in the non-adaptive condition. Based on this finding, we can conclude that it is important to provide students with instant feedback and personalized learning content and to analyze students' learning process to give them personalized learning guidance while playing educational games (Komalawardhana, Panjaburee, & Srisawasdi, 2021; Xie, Chu, Hwang, & Wang, 2019; Zou, Huang, & Xie, 2019).

Currently, little research has provided instant feedback and diagnosis results to generate personalized learning paths in mathematics game-based environments. Ni and Zhou (2005) pointed out that the concept of fractions is the basis for learning decimals, percentages, and ratios. Moreover, the calculation of fractions is an important foundation for the formal symbolic calculation of rational numbers. Therefore, it is important to develop an adaptive game-based learning system to support individual students to learn according to personalized learning paths in order to match their mathematics ability, especially for the concepts of fractions.

3. Development of an adaptive concept-effect relationship (CER)-based mathematics game

In this study, we present an adaptive concept-effect relationship (CER)-based mathematics game for fractions to assist teachers in grasping students' learning status, and to provide adaptive learning guidance during the gaming learning process. Furthermore, this game incorporates concept-effect relationship learning strategies into the gaming scenarios to assist students in improving their learning attitudes and performance. Figure 2 represents the structure of the proposed adaptive CER-based mathematics game, which consists of the gaming module, the concept-effect relationship module, the learning behavior module, and the learning guidance module. The gaming module provides a scenario that includes scripts, materials, and problem-solving contexts for students. The concept-effect relationship module is in charge of defining the knowledge levels of each learning concept and relationship among the concepts through teachers. Moreover, this module could identify the poorly learned concepts for individual students by analyzing their learning portfolios. Next, the learning behavior module enables teachers to observe students engaged in tasks and their learning status based on the obtained CER results. Lastly, the learning guidance module is used to select appropriate learning material. This module enables students to grasp unfamiliar or poorly understood concepts more quickly, and helps them with concept consolidation and elaboration.

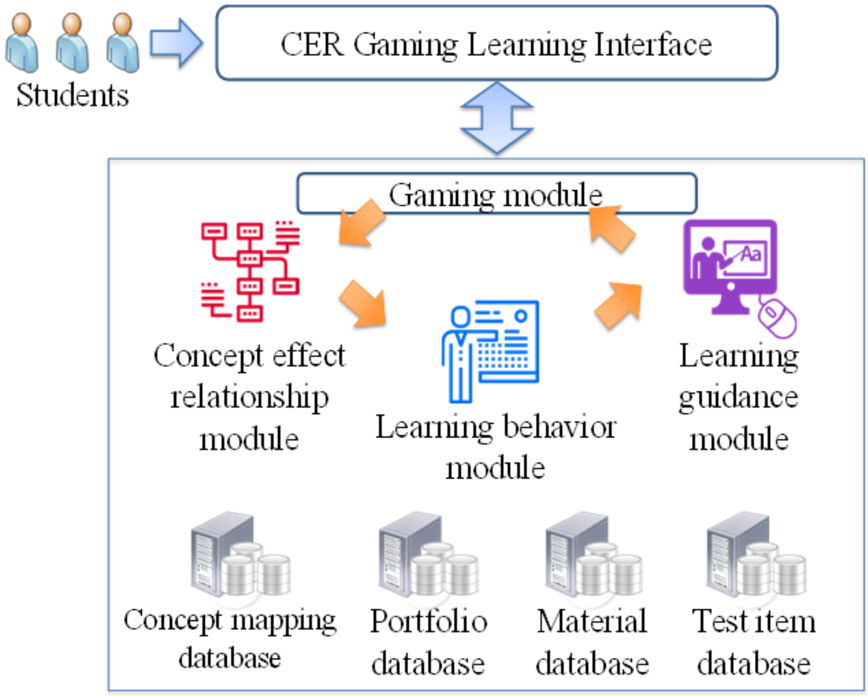

Figure 2. The structure of the proposed game

In this game, students (playing the role of the main character) are asked to find all of the treasures and complete tasks to pass each challenge; that is, the storyline provides students with an opportunity to accumulate knowledge of relevant fraction practices during the gaming process. The accumulated knowledge is recorded in the portfolio database for further learning behavior analysis.

3.1. Assessment model of an adaptive CER-based mathematics game

Recently, CER diagrams have gradually attracted more attention from researchers, and many studies have confirmed that the application of CER diagrams could help improve students' learning achievement by means of appropriate learning feedback (Chen, Chu, & Yang, 2016; Johnson & Johnson, 2002; Hwang, Yang, & Wang, 2013; Inaltun & Ateş, 2015; Nicase, Cogerino, Fairclough, Bcois, & Davis, 2007).

Thus, in order to provide students with appropriate learning feedback by the diagnosis of the CER diagrams, the following steps describe how to use the CER to establish a game-based learning assessment model with guidance and feedback functions, which applies the concept relationship algorithm to figure out students' degree of understanding of the concepts, and the relevance between the students' answers and the correct concepts, to assist educators in providing them with appropriate learning strategies.

3.1.1. Step 1: Establish the concept-effect relationship (CER)

First of all, the learning concepts of mathematics have to be constructed by domain experts, then the relationship among the learning concepts must be described, as well as the sequence of these concepts by using a two-dimensional concept table, as can be seen in Figure 3, in which the fraction unit of mathematics is illustrated as a concept-effect relationship (CER) diagram. Through this diagram, the mathematics teacher can clearly design the instructional plan, learning content and assessments for learning achievement. Accordingly, students are able to learn the critical concepts and the relevance and sequence among these concepts. For example, if students need to understand the meaning of fraction concept (C_4), they must first understand addition and subtraction of integers (C_1), the concept of integers (C_2), and the meaning of equal measures (C_3), and then finally proceed to the unit of fraction meaning (C_4).

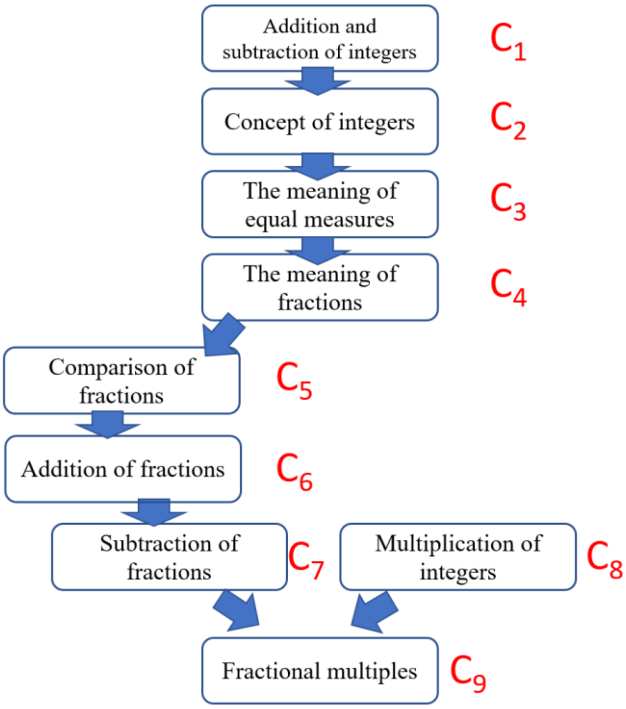

Figure 3. Diagram of CER for the mathematics fraction unit

3.1.2. Step 2: Calculate the student's understanding of different concepts

In order to grasp a student's span of comprehension for each concept, the relationship between learning concepts and test questions is developed by domain experts based on the CER diagram and test questions, as shown in Table 1. The numbers in the table represent the degree of relevance between the test questions and concepts, where the value "0" means not relevant and "9" means highly relevant. For example, C_1 has a weight of "1" in question Q_1 and C_2 has a weight of "3" in question Q_1, which means that question Q_1 contains the concepts of C_1 and C_2 simultaneously, and the weight of this question is 1:3. Accordingly, the weights for all of the concepts are calculated below:

$Sum(C_1)=1+5+3+1=10$; $Sum(C_2)=3+2+2+2=9$; $Sum(C_3)=3+2+2=7$
$Sum(C_4)=1+2+4+2=9$; $Sum(C_5)=4+5=9$; $Sum(C_6)=3+3+4=10$
$Sum(C_7)=1+2=3$; $Sum(C_8)=1+2=3$; $Sum(C_9)=4+1=5$

Table 1. Relevance between concepts and test questions

Q_i	C_j								
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Q_1	1	3	0	0	0	0	0	0	0
Q_2	5	2	3	0	4	3	0	0	0
Q_3	3	2	2	0	5	3	0	0	0
Q_4	0	0	2	1	0	4	0	0	0
Q_5	0	0	0	2	0	0	1	1	0
Q_6	0	0	0	4	0	0	0	0	0
Q_7	1	2	0	0	0	0	2	0	0
Q_8	0	0	0	2	0	0	0	2	0
Q_9	0	0	0	0	0	0	0	0	4
Q_{10}	0	0	0	0	0	0	0	0	1
Sum	10	9	7	9	9	10	3	3	5
Error(C_j)	3	3	1	2	4	7	2	1	2
ER(C_j)	0.3	0.33	0.14	0.22	0.44	0.7	0.66	0.33	0.4

In order to grasp a student's misconceptions from questions that are answered incorrectly, and then to give them the relevant learning concepts that need to be enhanced, each student's answers to the test items in the mathematics game are collected, and the individual student's answering status table is established, as shown in

Table 2. In the table, the value "0" represents a wrong answer, and the value "1" represents a correct answer. Therefore, Table 2 reflects the number of errors of concept C_j for the student in the test, Error (C_j), and the error rate of the student's answer for each concept C_j, shown with the formula $ER(C_j) = Error(C_j)/Sum$. Thus, Table 1 shows Error(C_j) for each concept below,

$Error(C_1)=3$; $Error(C_2)=3$; $Error(C_3)=1$; $Error(C_4)=2$; $Error(C_5)=4$;
$Error(C_6)=7$; $Error(C_7)=2$; $Error(C_8)=1$; $Error(C_9)=2$;

and shows ER(C_j), error rate of each concept as below:

$ER(C_1) =3/10=0.3$; $ER(C_2)=3/9=0.33$; $ER(C_3)=1/7=0.14$; $ER(C_4)=2/9=0.22$;
$ER(C_5) =4/9=0.44$; $ER(C_6)=7/10=0.7$; $ER(C_7)=2/3=0.66$; $ER(C_8)=1/3=0.33$;
$ER(C_9) =2/5=0.4$

Table 2. Individual students' answering status

Student S_i	Test item Q_k									
	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}
S_1	1	1	1	0	1	1	0	1	1	1
S_2	1	0	1	0	1	0	1	1	0	1
S_3	1	0	1	1	1	1	0	1	1	1
S_4	0	1	1	1	0	0	1	1	0	1
S_5	1	0	0	0	1	1	1	1	1	1
S_6	1	1	1	1	1	1	1	0	1	1
S_7	0	1	1	1	0	1	0	1	0	0
S_8	1	0	0	0	1	0	1	1	1	1
S_9	1	1	1	1	1	1	1	0	1	0
S_{10}	1	1	1	1	1	0	1	1	1	1

Finally, individual students' span of comprehension for each concept is calculated on the basis of the CER diagram with error rate, as shown in Figure 4.

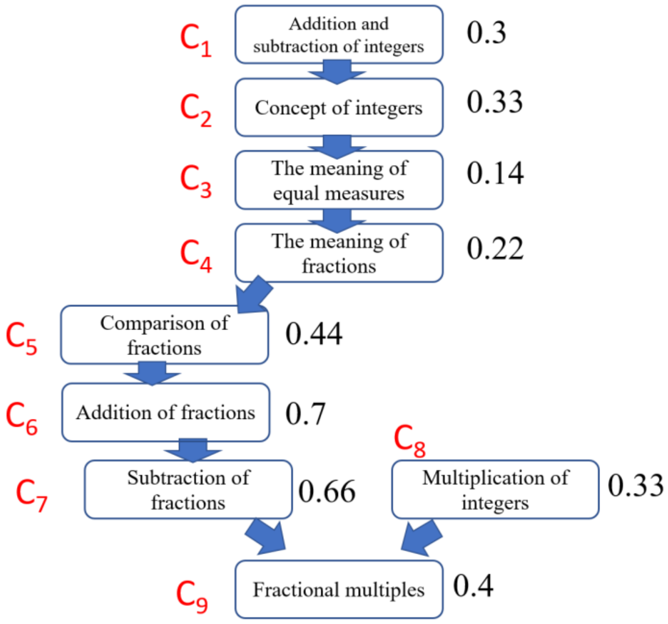

Figure 4. Diagram of weighted CER for fractions with the error rate

3.1.3. Step 3: Learning diagnosis and feedback

Based on the CER diagram with error rate established in step 2, the system finds out the error rate of the student's answer for each concept, and the relationship among concepts. Accordingly, a concept diagnosis and remedial learning path for the student's learning status is conducted.

Suppose that the mathematics teacher sets up the threshold for wrong answers to each concept as $\alpha = 0.28$, which means that the error rates of concepts exceed the threshold, and the system will provide the student with a remedial course for the wrong concepts. Therefore, the system could calculate the student's learning problems through the learning diagnosis mechanism based on the student's formative assessment in the game. From the CER diagram of the student in this example, it is known that the student failed to comprehend the given learning content involving the concepts C_1, C_2, C_5, C_6, C_7, C_8, and C_9. Thus, a follow-up remedial course should be given based on the following results:

$ER(C_1) = 0.30 > \alpha(=0.28)$
$ER(C_2) = 0.33 > \alpha(=0.28)$
$ER(C_3) = 0.14 < \alpha(=0.28)$
$ER(C_4) = 0.22 < \alpha(=0.28)$
$ER(C_5) = 0.44 > \alpha(=0.28)$
$ER(C_6) = 0.70 > \alpha(=0.28)$
$ER(C_7) = 0.66 > \alpha(=0.28)$
$ER(C_8) = 0.33 > \alpha(=0.28)$
$ER(C_9) = 0.40 > \alpha(=0.28)$

It derives three learning paths from the CER diagram for the sequence of concepts below:

Path 1: $C_1 \rightarrow C_2$
Path 2: $C_5 \rightarrow C_6 \rightarrow C_7 \rightarrow C_9$
Path 3: $C_8 \rightarrow C_9$

Therefore, when students have not reached the expected learning concepts, the system performs diagnosis through the concept-effect relationship (CER) and remedial learning paths for the student's learning status, and then recommends suitable learning content and offers additional learning contexts, levels and evaluations for the student's wrong and unfamiliar concepts in the next round of the game.

3.2. System interface and game content

The game flowchart designed in the study is shown in Figure 5. The game is played by students who adopt the role of the protagonist to pass through the different levels by continuously accumulating energy and collecting treasures in the game, in order to obtain the qualification to defeat the Devil. During the learning activities in the game, the events and treasures encountered by students are derived from the learning content of the elementary school third-grade mathematics curriculum. The learning content of the game primarily contains nine units according to the game plot and story, including addition and subtraction of integers, equal measures, integers, unit quantity, the meaning of fractions, subtraction of fractions, comparison of fractions, and fractional multiples. By trying to defeat enemies and gathering treasure in the game, students unknowingly and systematically construct the learning concepts of integers and fractions based on the CER diagram and remedial learning diagnosis. Such a learning model not only increases students' motivation in the game, but also helps them enhance their weaker concepts.

The guidance of the concept-effect relationship (CER) diagram proposed in the study is described as follows.

Once students log into the game, the system will guide them to the starting point to learn the content of each unit, and then assess their learning performance. If students pass the threshold that is set up by the mathematics teachers, they are allowed to enter the next level of the game. For instance, in Figure 6, students start to learn addition of integers at the beginning of the game, and then enter the next level to learn subtraction of integers until they complete the nine concepts and the final test. The test is regarded as a formative assessment to diagnose students' potential errors of nine concepts for the CER remedial learning stage. Students who are given suitable learning content in the remedial process will be required to assess the concept after learning immediately. Finally, the system checks whether the error rate of each concept exceeds the threshold. If not, the course is over; otherwise, the remedial course will be organized and conducted thereafter. The system will provide students with relevant learning content based on the wrong concepts.

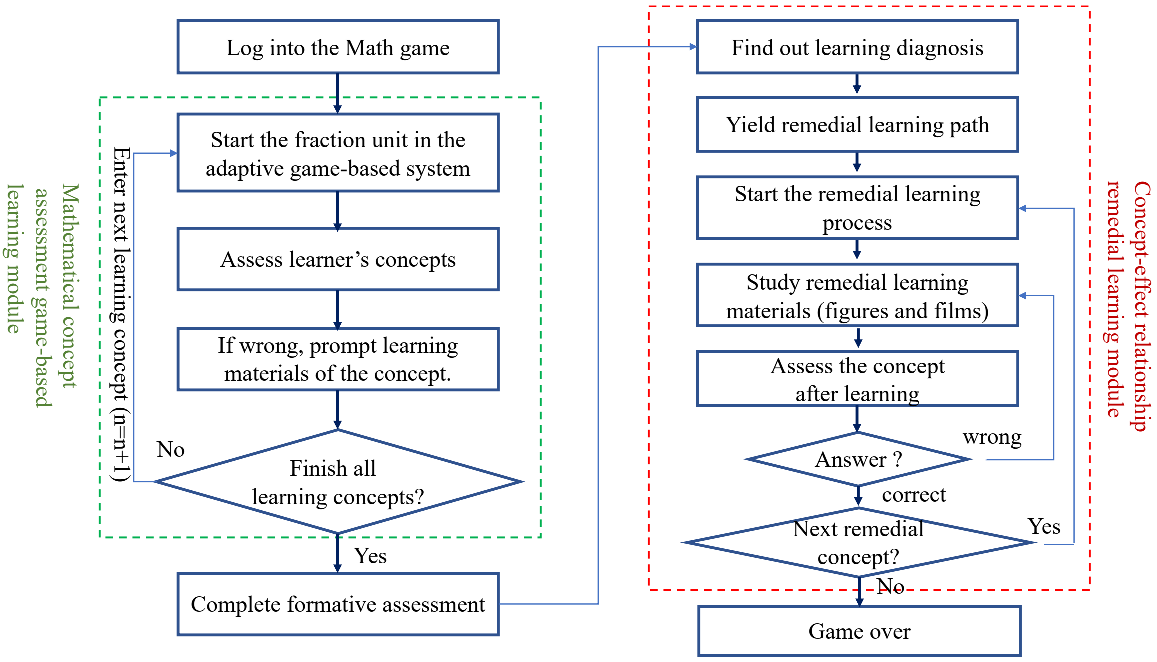

Figure 5. Flowchart based on the CER diagram of the game

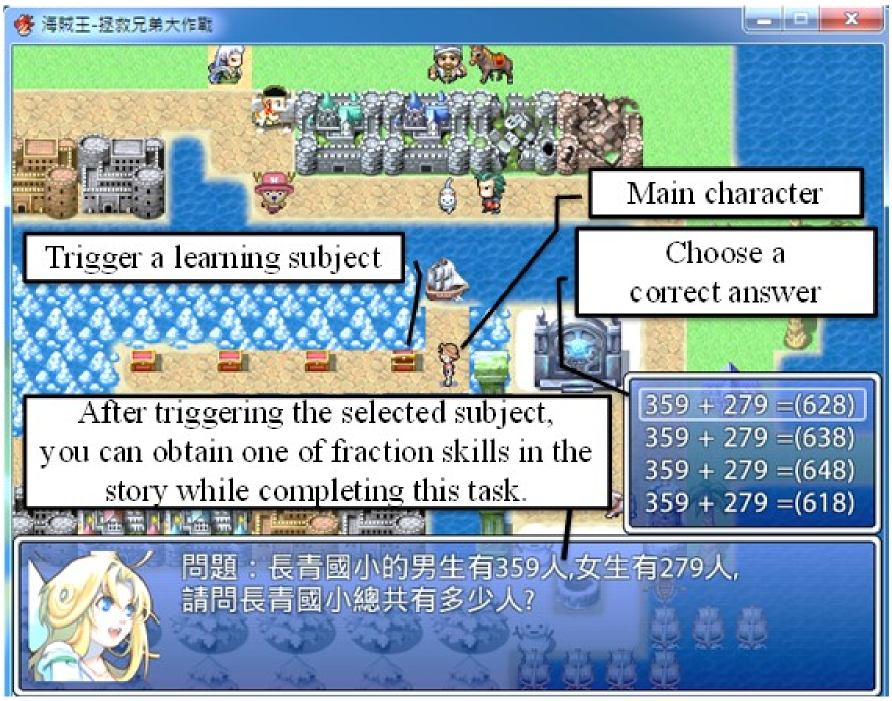

Figure 6. Gaming scenario of triggering the fraction task

After completing the collected treasures and tasks, an adaptive game process is customized by analyzing the students' learning behavior to generate learning guidance for individual students. Moreover, this way provides students with an engaging way to select appropriate learning material, as shown in Figure 7. Meanwhile, if students answer the question incorrectly, the system will give the correct answer and provide the problem-solving steps to address the problem for the student. Figure 7 shows that when the student answers the question correctly, the student will get the energy and treasures in the game, and the system will provide the correct answer for the student to confirm.

By collecting treasures and gaining the ability to defeat the devil, the students can constantly solve problems and make decisions in the game via integrating what they have learned during the game. When students reply to a test item with the correct answer, the system checks and shows a successful message of reward, as shown in Figure 8.

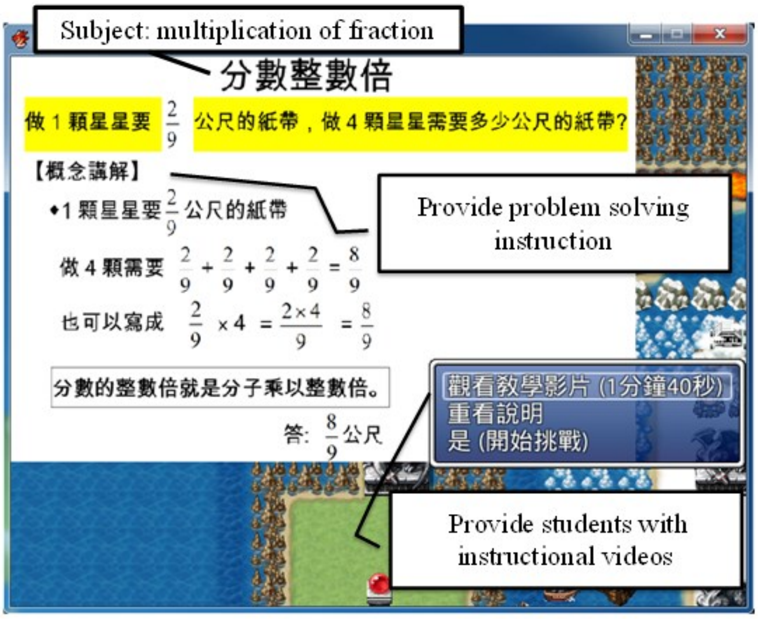

Figure 7. Illustrative example of learning guidance

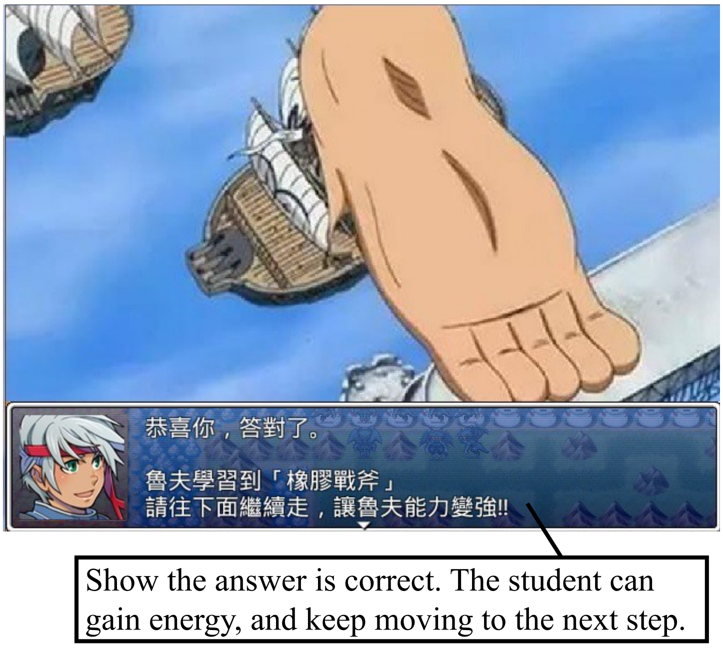

Figure 8. Screenshot of a student's correct answer

Students are asked to go through the learning content with nine concepts and then complete the formative assessment, as shown in Figure 9. The assessment mainly consists of nine concepts with 18 questions, and the system confirms whether the student's answer is right or wrong. After the formative assessment is finished, the system calculates whether the error rate of conceptual questions exceeds the threshold, and if it exceeds the threshold, a remedial course will be conducted, as shown in Figure 10.

Students answer the questions based on their knowledge of mathematics, and the system gives them information about correct or incorrect answers based on the results of their answers. At the same time, the answers that students give are recorded in the system.

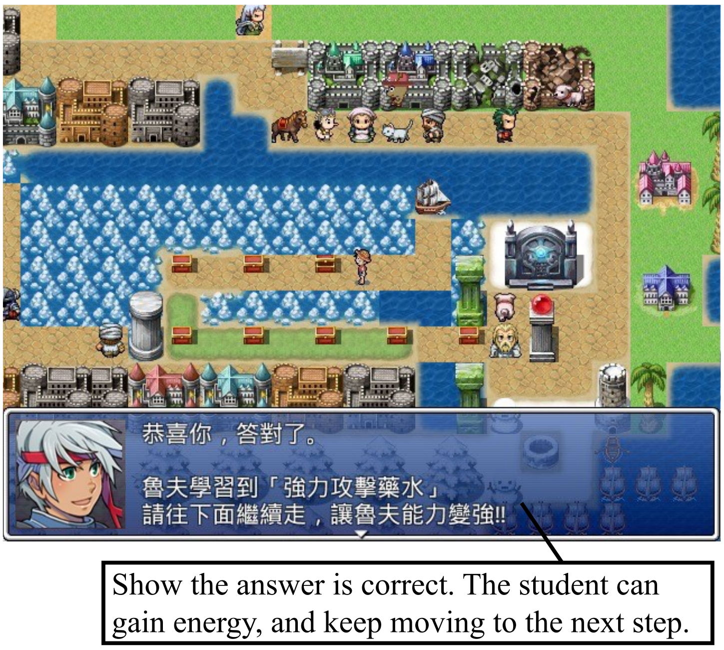

Figure 9. Process of formative assessment

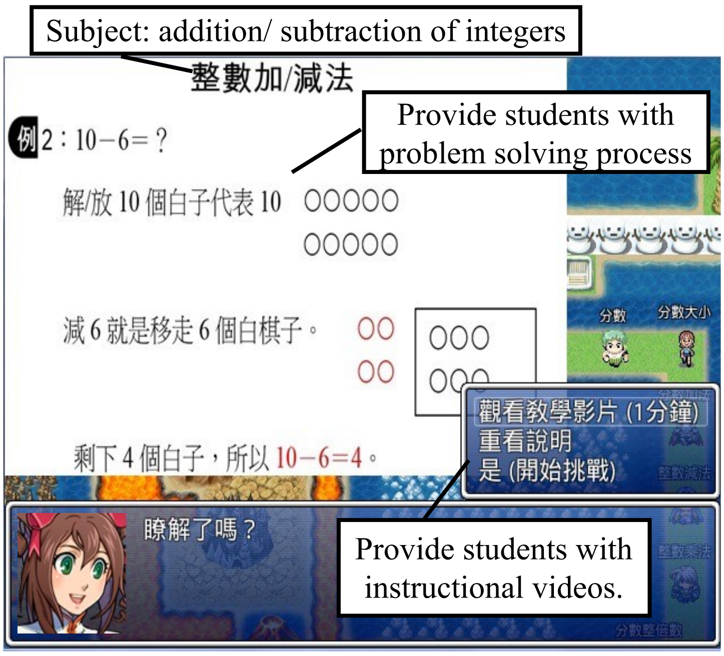

Figure 10. Process of a remedial course

4. Experimental design

This study aimed to evaluate the effectiveness of the proposed adaptive concept-effect relationship (CER)-based mathematics game on the students' learning achievement, attributes, self-efficacy, cognitive load, and mathematics anxiety. A quasi-experimental design was conducted in an elementary school mathematics course in Taiwan. The activity engaged and motivated students to grasp unfamiliar or poorly comprehended concepts related to the curriculum during the gaming learning process. It was expected that the adaptive CER-based mathematics game would be used by the students to more quickly grasp the concepts and the relationships between the learning targets. The experiment is described in more detail in the following.

4.1. Participants

The participants of this study were 116 third-grade students in two classes of an elementary school in northern Taiwan. The average age of the students was 9. Each class consisted of 58 students. A quasi-experiment was designed by assigning the students in one class to the experimental group (26 males and 32 females), while the other class was assigned to the control group (30 males and 28 females). The experimental group learned with the adaptive concept-effect relationship (CER)-based game-based learning (short for adaptive CER-based mathematics game), while the control group learned with the conventional digital game without the concept-effect relationship. In this study, the students in both groups were asked to study the same difficulty level of the assigned materials and learning tasks. All of the students were taught by the same teacher who had more than 10 years' experience of teaching mathematics courses, as shown in Figure 11.

Figure 11. CER game-based learning scenarios for students

4.2. Experiment procedure

Figure 12 shows the procedure of the experiment, indicating that before the learning activity, the two groups of students took a 2-week mathematics course on the basic knowledge of fractions. Moreover, the students took the pre-test and completed the questionnaire of learning attitude and self-efficacy.

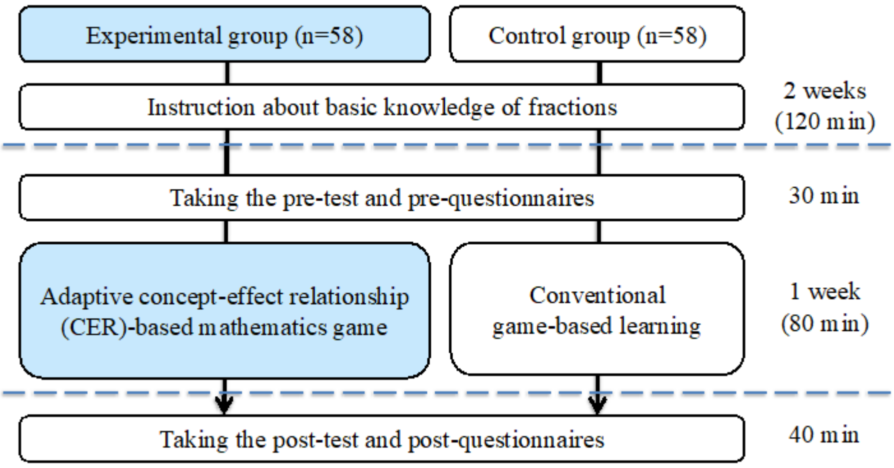

Figure 12. Experiment procedure

During the learning activity, the students in the experimental group learned with the adaptive CER-based mathematics game, while the students in the control group learned with the conventional digital educational game without any CER guidance. The students in both groups were scheduled to learn by playing the educational digital games and were asked to complete all learning tasks based on the same gaming scenarios, learning missions and learning content.

After the game-based learning activity, the students took the post-test and post-questionnaires including learning attitude, self-efficacy, cognitive load, and mathematics anxiety, in order to compare the learning achievements and the improvements of the two groups.

4.3. Measuring tools

In this study, the measuring tools included a pre-test, a post-test, and the questionnaire for measuring the students' learning achievements, attitudes, self-efficacy, cognitive load, and mathematics anxiety.

To evaluate the effectiveness of the students' performance, a pre- and post-test were implemented by two teachers at the Taiwanese elementary school. The pre-test aimed to identify any differences in the students' prior knowledge of learning the course unit. It consisted of eight mathematics word problems, giving a perfect score of 100. The post-test consisted of four matching problems and 20 mathematics word problems for assessing the students' knowledge of the fraction unit in mathematics. The perfect score of the post-test was 100.

The questionnaire of learning attitude and self-efficacy was modified from the measure developed by Wang, Chu, and Hwang (2010). It contains seven items using a 5-point Likert scale rating scheme. The Cronbach's alpha value of the questionnaire reaches 0.91, which shows the high internal consistency and reliability of the scale (Cohen, 1988; Bryman & Cramer, 1997).

The cognitive load scale was modified by Hwang, Yang, and Wang (2013) based on the cognitive load measures proposed by Sweller, Van Merriënboer, and Paas (1998). It consists of two dimensions, mental load and mental effort. Mental load is regarded as the intrinsic cognition load which represents the difficulty level of the interaction between the subject materials and learning tasks. Mental effort is referred to as the extraneous cognitive load which is associated with the pressure of the instructional design, teaching methods and learning strategies; that is, the mental effort refers to the degree of difficulty and suitability of the instructional materials. There are eight items with a 5-point Likert rating scheme, including five items for mental load and three for mental effort. The Cronbach's alpha values of the two dimensions are 0.92 and 0.90, respectively, which shows high internal consistency and reliability of the scale (Cohen, 1988; Bryman & Cramer, 1997).

To realize the influence of the students' mathematical anxiety during the learning process, the questionnaire of mathematical anxiety was modified from the measure developed by Lim and Chapman (2012). It contains five items using a 5-point Likert scale rating scheme. The Cronbach's alpha value of the questionnaire reaches 0.91, which shows the high internal consistency and reliability of the scale (Cohen, 1988; Bryman & Cramer, 1997).

5. Experimental results

5.1. Analysis of learning achievement

To evaluate the effectiveness of the proposed approach, an experiment was conducted on a mathematics course taught at an elementary school in Taiwan. The results show that the mean values and standard deviations of the pre-test scores were 72.10 and 16.37 for the control group, and 70.31 and 17.19 for the experimental group. Here, the t-test result ($t = -0.575$, $p > .05$) reveals that the control and experimental groups were not significantly different.

After the learning activity, this study performed a one-way independent-samples analysis of covariance (ANCOVA) to examine the difference between the two groups on the students' fraction performance. Moreover, this analysis used the pre-test scores as the covariate and the post-test scores of learning achievement as dependent variables, as shown in Table 3. The adjusted mean value and standard error of the post-test scores were 69.48 and 1.49 for the control group, and 78.37 and 1.49 for the experimental group. According to the results ($F = 17.85$, $p < .001$), there was a significant difference between the two groups, implying that the students who learned with the adaptive CER-based mathematics game showed significantly better learning achievements than those who learned with the mathematics game without the concept-effect relationship (CER) approach. Furthermore, in terms of η^2 described by Howell (2002), with large ($\eta^2 > 0.138$), moderate ($\eta^2 > 0.059$), and small ($\eta^2 > 0.01$) effects, the ANCOVA results of the proposed learning model gave a large effect size, with $\eta^2 = 0.14$.

Table 3. ANCOVA results of the post-test scores

Groups	*N*	Mean	*S.D.*	Adjusted mean	Std. error	*F*	η^2
Experimental group	58	78.03	11.46	78.37	1.49	17.85^{***}	0.14
Control group	58	69.81	14.15	69.48	1.49		

Note. $^{***}p < .001$.

5.2. Analysis of mathematics self-efficacy

To realize the effect of the proposed approach on the students' learning self-efficacy, a pre-questionnaire was used to measure their self-efficacy before the experiment. The results show that the mean values and standard deviations of the self-efficacy degrees were 3.94 and 0.56 for the control group, and 3.97 and 0.48 for the experimental group; meanwhile, the *t*-test result ($t = 0.358$, $p > .05$) revealed that the difference in the control and experimental groups' learning self-efficacy was not significant.

After completing the game-based learning activity, ANCOVA was used to compare group differences in mean self-efficacy ratings by excluding the impacts of the pre-questionnaire ratings. Table 4 shows the ANCOVA result of the post-questionnaire ratings of the two groups. The adjusted means of the experimental group and the control group were 4.44 and 4.09. Moreover, it was found that the experimental group had significant differences on the self-efficacy ratings, with F = 14.25 ($p < .001$). In addition, ANCOVA results of self-efficacy represented a moderate effect size ($\eta^2 < 0.059$) for the experimental group (Howell, 2002). The results indicate that the game-based learning system based on the concept-effect relationship approach could enhance the students' self-efficacy more than the conventional game-based learning in mathematics.

Table 4. ANCOVA results of self-efficacy of the two groups

Groups	*N*	Mean	*S.D.*	Adjusted mean	Std. error	*F*	η^2
Experimental group	58	4.44	0.48	4.44	0.66	14.25^{***}	0.11
Control group	58	4.09	0.52	4.09	0.66		

Note. $^{***}p < .001$.

5.3. Analysis of learning attitudes

Table 5 shows the independent t-test result of the students' learning attitudes. According to the results ($t = -0.74$, $p > .05$), before the learning activity, the t-test result showed no significant difference between the pre-tests of the two groups.

After the learning activity, the mean values and standard deviations of the post-test scores were 4.55 and 0.57 for the experimental group, and 4.15 and 0.54 for the control group. In addition, the independent t-test results of learning attitudes represented a moderate to large effect size ($d = 0.73$) for the post-test level between two groups (Cohen, 1988). In Cohen's criteria, if the Cohen's d value is greater than 0.8, it is considered as a large effect. The results showed that the learning attitudes of the students in the experimental group were significantly more positive than those of the students who learned with the game without the concept-effect relationship approach.

Table 5. The independent *t*-test results of learning attitudes for the two groups

	Group	*N*	Mean	*S.D.*	*t*	*d*
Pre-test	Experimental Group	58	3.93	0.55	-0.74	0.13
	Control Group	58	4.00	0.49		
Post-test	Experimental Group	58	4.55	0.57	3.79^{***}	0.72
	Control Group	58	4.15	0.54		

Note. $^{***}p < .001$.

5.4. Analysis of cognitive load

In this study, the cognitive loads of the two groups of students were measured by investigating the effect of mental effort and mental load. As shown in Table 6, the total scores of both mental effort and mental load range from 1 to 5, with a median of 3.

In terms of mental effort, there is no significant difference between the two groups of students (t = -1.01; p > .05). The result showed that the mean values of the two groups of students showed relatively lower values considering that the questionnaire uses a 5-point Likert scale (i.e., corresponding to a low workload level or higher effort). That is, it can be seen that suitable mental effort might be good for students to enhance their learning achievement, implying that the proposed game-supported educational scenario and friendly game interface might facilitate the reduction of the learning pressure in the mathematics learning process.

On the other hand, mental load is concerned with intrinsic cognitive load, which represents the degree to which students need to engage in cognitive processing in order to handle the challenging tasks. The students in both groups were asked to study assigned materials and learning tasks with the same level of difficulty. From the experimental results in Table 6, the means and standard deviations were 2.21 and 1.11 for the experimental group, and 2.74 and 1.23 for the control group, showing that there was a significant difference in the mental load of the two groups (t = -2.46; p < .05; d = 0.45). In addition, the independent t-test results of cognitive load reached a moderate effect size for mental load between the two groups (Cohen, 1988). This implies that, owing to using the concept-effect relationship approach, the students could engage in deeper understanding in conceptual-knowledge learning, especially those who had difficulty with the learning material, and it reduced their burden in the learning process. As a result, the experimental group did not have a higher mental load.

Table 6. The independent *t*-test result of the cognitive load of the two groups

	Group	*N*	Mean	*S.D.*	*t*	*d*
Mental effort	Experimental Group	58	2.89	1.31	-1.01	0.19
	Control Group	58	3.12	1.06		
Mental load	Experimental Group	58	2.21	1.11	-2.46^{*}	0.45
	Control Group	58	2.74	1.23		

Note. $^{*}p < .05$.

5.5. Analysis of mathematics anxiety

Reducing students' mathematical anxiety has been recognized as an important and challenging issue. Moreover, studies have indicated that lower learning anxiety has a more positive effect on learning achievement while engaged in mathematics learning (Fast et al., 2010; Maloney et al., 2015; Vukovic et al., 2013). In this study, a post-questionnaire was used to measure the participants' mathematical anxiety after the experiment. Table 7 illustrates the independent t-test result of the mathematical anxiety of the two groups. The results showed no significant difference in the mean score for mathematical anxiety between the two groups (t = -1.16, p > .05, d = 0.22). In addition, the independent t-test results of mathematics anxiety represented a small effect size (d < 0.5) for the mental effort and mental load between the two groups (Cohen, 1988), implying that the proposed game-based learning approach based on the concept-effect model may lower anxiety and have a positive effect on depression.

Table 7. t-test result of mathematics anxiety of the two groups

Group	*N*	Mean	*S.D.*	*t*	*d*
Experimental Group	58	2.10	0.86	-1.16	0.22
Control Group	58	2.33	1.19		

6. Discussion and conclusions

In this study, an adaptive concept-effect relationship (CER)-based mathematics game was developed for conducting mathematics learning activities. An experiment was conducted in a fraction learning activity to evaluate the performance of the proposed approach.

The experimental results demonstrated that, in comparison with the adaptive CER-based mathematics game with conventional game-based learning, the proposed approach significantly improved the students' learning achievements. That is, students in the experimental group conducted the adaptive CER-based mathematics game approach to learn the mathematical concept of fractions. The system could diagnose whether students comprehended concepts for each learning task. Based on the learning diagnosis, the system would offer additional learning tasks for students to remedy the poorly understood concepts. The research findings are consistent with previous studies, indicating that the learning achievement of learners could be enhanced via learning diagnosis after regular learning activities (Chu, Hwang, & Huang, 2010; Panjaburees, Triampo, Hwang, Chuedoung, & Triampo, 2013; Wongwatkit, Srisawasdi, Hwang, & Panjaburee, 2017; Wang, Lin, Hwang, Kung, & Chen, 2017).

As for the learning attitudes of the two groups, the experimental group students had significantly better learning attitudes than those who learned with the game without the concept-effect relationship approach. From this finding it could be inferred that the adaptive CER-based mathematics game approach diagnoses students' learning concepts, and strengthens their weaker concepts by offering remedial courses in fractions. Generally, students thought their mathematics learning performance was enhanced via the proposed approach, and were willing to continually learn the content with the adaptive CER-based mathematics game approach. This finding is consistent with previous studies, showing that improvement in learning achievement for learners could positively change their learning attitudes (Hwang, Wu, Chen, & Tu, 2016; Chuang, Hwang, & Tsai, 2018).

As for the mathematics self-efficacy of the two groups, although the finding shows no significant difference between the two group, students in the experimental group expressed higher positive confidence than those in the control group. This implies that students who adopted the adaptive CER-based mathematics game approach could learn better than students who learned with the conventional game-based learning approach. Thus, students in the experimental group were willing to put more effort into fraction learning and learn more important concepts about fractions. This finding is consistent with previous research, indicating that a good learning approach could motivate learners' self-efficacy as well as enhance their learning performance (Lai, Hwang, & Tu, 2018; Hsia & Hwang, 2020).

As for the two groups' cognitive load, although the finding shows no significant difference between them in terms of mental effort, students in the experimental group expressed lower mental load than those in the control group. From this it can be inferred that the adaptive CER-based mathematics game approach can enable students to engage in further training in conceptual-knowledge learning, especially those who have poor comprehension of the learning material, and thus it reduces their burden in the learning process, and then reduces their mental load. This implies that a good learning approach could facilitate learners' critical thinking and deep understanding of the important concepts, and finally enhance their learning achievements (Hwang, Kuo, Chen, & Ho, 2014; Wu, Hwang, Yang, & Chen, 2018).

As for the mathematics anxiety of the two groups, although the finding shows no significant difference between them, students in both groups expressed low mathematics anxiety, indicating that the game-based learning approach can motivate students' learning and reduce their anxiety during mathematics learning tasks. This finding is consistent with previous studies, showing that a learning approach with playfulness and joyfulness could raise learners' learning motivation and lower their anxiety, especially in complex courses (Hwang, Hung, & Huang, 2014; Yang, Chang, & Hwang, 2020).

In the near future, several extended studies can be considered; for example, the investigation of the proposed approach combined with a cooperative learning strategy, Team Assisted Individualization (TAI), can be probed to determine the effectiveness of team-based learning support in mathematics. It is expected that such a social learning setting could help low-achieving students in mathematics in an interactive way more than individual approaches. Moreover, we plan to develop other interactive and tutoring tools by using Artificial Intelligence (AI) technologies, which provide students with an engaging way to increase the effectiveness of tutorial interactions and diagnose students' learning obstacles.

Besides, it is necessary to strengthen the system function for teachers to construct CER diagrams quickly and properly. Currently, it is time-consuming for teachers to construct accurate concepts of subjects during the preparation of the instruction plan. Thus, if domain experts could construct domain concepts collaboratively via the learning system, the subject teachers would be able to easily and quickly complete the CER for the course.

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Developing Adaptive Help-Seeking Regulation Mechanisms for Different Help-Seeking Tendencies

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ABSTRACT: Help-seeking is an important self-regulated learning strategy and skill for effective learning. Studies have found that some students have poor help-seeking behaviors and that this leads to poor learning performance. Some researchers have developed help-seeking regulation mechanisms to detect and regulate students' poor help-seeking behaviors. Studies have also found that students have different help-seeking tendencies. Thus, adaptive help-seeking regulation mechanisms for different help-seeking tendencies are required. This study applied a help-seeking questionnaire and a K-means clustering approach to identify three help-seeking tendencies in the context of a computer assisted learning system (CALS). Then, adaptive help-seeking detection and regulation mechanisms were developed for these three help-seeking tendencies. The regulation mechanisms also adopted historical student records of problem-solving and help-seeking data for each problem as parameters to account for the difficulty of each problem. Furthermore, an experiment was conducted with a control group and an experimental group. Students in the experimental group used a CALS with adaptive help-seeking regulation mechanisms, whereas students in the control group used a CALS without the regulation mechanisms and could seek help at will. The experimental results showed that students in the experimental group had better learning performance for difficult problems, better help-seeking behaviors (i.e., less executive help-seeking) for easy problems, and a higher ratio of solving problems by themselves without seeking help than students in the control group.

Keywords: Help-seeking behaviors, Help-seeking tendencies, Negotiation-based regulation, Individual difference, Intelligent computer assisted learning systems

1. Introduction

Help-seeking is an important self-regulated learning strategy and skill for effective learning because some students' poor performance results from their poor help-seeking behaviors, such as unawareness of the need for help, help avoidance and help abuse (Karabenick & Gonida, 2018; Hirt, Karlen, Suter & Merki, 2020; Karabenick & Berger, 2013; Mbato & Cendra, 2019). In particular, students' help-seeking behaviors affect their learning performance in computer assisted learning systems (CALSs) with on-demand help support (Aleven et al., 2003). Many CALSs provide students with worked-out examples and tutored problem-solving exercises to assist them in learning (Clark, Nguyen, & Sweller, 2006; Van Gog, Kester, & Paas, 2011). Worked-out examples demonstrate how to solve specific problems by presenting solution examples and explanations, whereas tutored problem-solving exercises support students in practicing how to successfully solve problems with the help of systems. Many CALSs provide on-demand help support so that students can seek help from systems when they encounter difficulty in solving problems. Researchers have suggested that CALSs offer different types of help to assist students in solving problems, such as verification of solution situations, error-indicating hints, corrective hints, instruction-based hints, and answers as bottom-out hints (i.e., executive help) (Chou, Huang & Lin, 2011; Dempsey, Driscoll & Swindell, 1993; VanLehn, 2006). However, students may have poor help-seeking behaviors, such as not seeking help (i.e., avoidant help-seeking) or abusing help (i.e., executive help-seeking), and these poor help-seeking behaviors are correlated with poor learning performance (Chou et al., 2018; Muldner et al., 2011; Ryan & Shin, 2011; Shim, Rubenstein & Drapeau, 2016; Smalley & Hopkins, 2020). Therefore, researchers have developed intelligent CALSs that detect and regulate students' poor help-seeking behaviors to promote better learning performance (Aleven et al., 2006; Aleven et al., 2016; Chou et al., 2018; Roll et al., 2011).

Researchers have also found that students have different help-seeking tendencies and can be described as strategic help-seekers (SHSs), executive help-seekers (EHSs), avoidant help-seekers (AHSs), and independent help-seekers (IHSs) (Chou et al., 2018; Gall, 1985; Hirt et al., 2020; Karabenick, 2003; Martín-Arbós, Castarlenas & Dueñas, 2021; Ryan, Patrick & Shim, 2005; White & Bembenutty, 2013). SHSs tend to seek help for learning (i.e., strategic help-seeking/instrumental help-seeking). EHSs tend to seek help for completing tasks without effort. AHSs tend to avoid seeking help because of the threat posed by help-seeking. IHSs tend to solve problems by themselves. Therefore, students with different help-seeking tendencies require different help-seeking regulations. However, there is little literature available regarding the CALS providing adaptive help-seeking regulation mechanisms for different help-seeking tendencies. This study proposed an approach for identifying students' different help-seeking tendencies in the context of a CALS and developing adaptive help-seeking regulation mechanisms for different help-seeking tendencies to account for students' individual differences. Furthermore, the effect of adaptive help-seeking regulation mechanisms on students' help-seeking behaviors and learning performance was evaluated.

2. Literature review

2.1. Identification of help-seeking tendencies

Help-seeking is a self-regulated learning process that includes being aware of the need for help and seeking help from available helpers (Gall, 1985; Karabenick & Gonida, 2018). Students may be influenced by cognitive, motivation and social factors and reveal different help-seeking tendencies (Gonida et al., 2019; Karabenick & Gonida, 2018). For example, SHSs have high mastery-approach goals and seek help for mastering their learning tasks. EHSs have high performance-approach goals and may seek help when help is not needed to perform better than others. AHSs have high performance-avoidance goals, regard help-seeking as threats and fails, and avoid seeking help. Researchers have identified SHSs, EHSs, and AHSs through observation by teachers in the context of the classroom (Ryan, Patrick & Shim, 2005). Furthermore, researchers have designed help-seeking questionnaires to assess students' help-seeking profile, such as executive help-seeking and help-seeking threat, applied clustering methods, and identified SHSs, EHSs, IHSs, and AHSs in the context of the classroom (Karabenick, 2003; Finney et al., 2018; White & Bembenutty, 2013). However, most studies have explored students' help-seeking tendencies from teachers or classmate helpers in the context of the classroom, and there is little literature available regarding students' help-seeking tendencies in the context of CALSs. This study applied a help-seeking questionnaire and a machine learning clustering method to identify students' different help-seeking tendencies in the context of a CALS.

2.2. Intervention of help-seeking behaviors

Researchers have found that external feedback from teachers or CALSs can help students be aware of and regulate their poor self-regulated learning (Butler & Winne, 1995; Chou & Zou, 2020). Similarly, external feedback from teachers or CALSs can be applied to help students be aware of and regulate their poor help-seeking behaviors. Researchers have developed mechanisms for CALSs to detect poor help-seeking behaviors, such as help avoidance and help abuse, and provide external feedback for intervention (Aleven et al., 2006; Chou et al., 2018; Roll et al., 2011). However, these intervention mechanisms do not consider students' help-seeking tendencies. Students with different help-seeking tendencies tend to have different poor help-seeking behaviors. For example, AHSs tend to avoid help-seeking even if they are aware of the need for help. Therefore, the system should prompt and encourage AHSs to seek help rather than prompt AHSs not to seek much help. EHSs tend to abuse help. Thus, the system should focus on reminding EHSs not to seek too much help. Furthermore, problems have different difficulty levels, and more difficult problems require more solution time and help. Researchers have also confirmed that students seek help more frequently as problem difficulty increases (Hao, Wright, Barnes & Branch, 2016). A one-size-fits-all regulation mechanism does not account for different help-seeking tendencies and problems with different difficulty levels. Therefore, this study developed different adaptive help-seeking regulation mechanisms for students with different help-seeking tendencies and for problems with different difficulty levels.

The effects of help-seeking interventions on help-seeking behaviors and performance are generally evaluated (Karabenick & Gonida, 2018). Since students seek help more frequently as problem difficulty increases (Hao et al., 2016), the effect of help-seeking intervention may differ for easy and difficult problems. Thus, this study evaluated the effect of help-seeking interventions for easy and difficult problems.

3. Method

The method includes three steps. Step one applied a help-seeking tendency questionnaire and clustering approach to identify students' different help-seeking tendencies in the context of a CALS. Step two developed adaptive help-seeking regulation mechanisms for different help-seeking tendencies to account for students' individual differences and for problems with different difficulty levels. Step three divided students into an experimental and a control group to evaluate the effect of the adaptive help-seeking regulation mechanisms on students' help-seeking behaviors and learning performance. The details of the three steps, the help-seeking tendency questionnaire and the CALS adopted are presented below.

3.1. The help-seeking tendency questionnaire

This study adopted a help-seeking tendency questionnaire that was modified from a help-seeking tendency questionnaire (Karabenick, 2003) that was designed to assess students' help-seeking tendencies when seeking help from human helpers. The questionnaire was modified to assess students' help-seeking tendencies when seeking help from a CALS. The questionnaire includes seven 7-point Likert scale items and three scales measuring help-seeking willingness, executive help-seeking and help-seeking threat (see Appendix). The help-seeking willingness scale has two items to ask students whether they seek help from the system if they have trouble solving problems. The executive help-seeking scale has two items to ask students whether they seek help from the system because they want to avoid solving the problems on their own. The help-seeking threat scale has three items to ask students whether they consider that seeking help from the system is a failure or an admission that they are not smart enough. In Karabenick's study (2003), the Cronbach's alpha values of the three scales were 0.62, 0.78, and 0.81. The Cronbach's alpha values of the three scales in this study were 0.578, 0.677, and 0.774.

3.2. The system support problem-solving and help-seeking

The CALS, named NALS-HS (negotiation-based adaptive learning system for help-seeking), adopted in this study was derived from a CALS developed in a previous study of help-seeking (Chou et al., 2018). The system enabled students to learn from worked-out examples and tutored problem-solving exercises. First, the system provided a worked-out example for a program and explanations of its execution and output. After that, students were asked to solve a program-output-prediction problem by predicting the output of a program. Figure 1 shows the system interface for problem-solving and help-seeking. The right part of the interface is the program for predicting the output. Programs were designed to output five lines, each of which had five output values. Students input their prediction of the output in the left part of the interface value by value and line by line. Five buttons were located at the bottom to allow students to seek help, edit the next line of the output, return to the previous line of the output, review the worked-out example, or finish the prediction.

If students sought help, the system provided adaptive help in the middle part of the interface (Figure 1). The system detected students' solutions and provided adaptive help to assist them in solving problems (Table 1) (Chou et al., 2018). Students' solutions were correct, incomplete, or incorrect solutions. If students correctly solved the problem, the system verified that they had submitted the correct solution. If students' solutions were unfinished solutions without errors, the system provided three levels of hints in sequence to help students complete their solutions: informing students that their solutions were unfinished solutions without errors (i.e., verification); prompting the output of the next line (i.e., an instruction-based hint); and informing students of the output of the next line (i.e., a bottom-out hint of the answer). If students' solutions had errors, the system provided four levels of help: informing students that their solutions had errors to prompt students to check their solutions; indicating the location of the first error to guide students to find their errors and fix them; instruction-based hints for the located line of the first error to prompt students to fix their errors; and bottom-out hints. Bottom-out hints are classified as executive help, whereas the other hints are classified as instrumental help (Gall, 1985).

Table 1. Adaptive help for different solution situations (Chou et al., 2018)

	Correct solution	Incomplete solution	Incorrect solution
Level 1 help	Verification (correct)	Verification (incomplete)	Verification (incorrect)
Level 2 help	-	Instruction-based hint	Error-indicating hint
Level 3 help	-	Answer (bottom-out hint)	Instruction-based hint
Level 4 help	-	-	Answer (bottom-out hint)

Figure 1. System interface for problem-solving and help-seeking in program-output-prediction problems

3.3. Step 1: Identifying students' different help-seeking tendencies

A help-seeking tendency questionnaire and a machine learning clustering method, K-means, were applied to identify students' different help-seeking tendencies. An experiment was conducted in an introductory computer programming course for undergraduate students at a university. Among 60 enrolled students, 52 students, including 37 male and 15 female students, completed the questionnaire and participated in the experiment; there were 29 freshmen, 8 sophomores, 10 juniors, and 5 seniors. The students were majoring in computer science. In a computer classroom, the students were asked to use NALS-HS to solve two problems without help-seeking regulation mechanisms. After that, the students were asked to fill out the help-seeking tendency questionnaire.

Table 2. Clustering results for help-seeking questionnaire data (Mean/Standard Derivation)

	Cluster 1: AHSs (N = 5, 10%)	Cluster 2: EHSs/SHSs (N = 31, 60%)	Cluster 3: IHSs (N = 16, 30%)	
Help-seeking willingness	2.1/1.12	4.69/0.93	2.75/0.68	EHSs > AHSs, IHSs
Executive help-seeking	2.5/1.12	3.19/1.04	2.09/0.84	EHSs > IHSs
Help-seeking threat	4.2/1.07	3.12/0.87	2.17/0.63	AHSs > EHSs > IHSs

Note. AHSs: avoidant help-seekers; EHSs: executive help-seekers; SHSs: strategic help-seekers; IHSs: independent help-seekers

K-means clustering was conducted to divide students into clusters based on their results for the three scales. K-means is an unsupervised machine learning method used to divide data into assigned K clusters (Xu, 2005). Different K values were tested to examine whether the clustering results were meaningful. The results showed that there was at least one cluster in which the number in the cluster was fewer than 5 when the K value was 4 or larger; thus, the K value was set to 3 to avoid clusters with too few students and to avoid too few clusters. In addition, a three-cluster solution was highly interpretable. Table 2 lists the clustering results for the help-seeking questionnaire data. A Kruskal-Wallis H test showed that there were statistically significant differences in help-seeking willingness (χ^2 (2) = 36.220, p < .001), executive help seeking (χ^2(2) = 11.868, p < .01), and help-seeking threat (χ^2 (2) = 17.527, p < .001) among the three clusters. The results of Dunn's multiple comparison tests showed that cluster 2 had higher willingness to seek help than clusters 1 and 3; cluster 2 had higher executive help-seeking than cluster 3; cluster 1 had higher help-seeking threat than cluster 2; and cluster 2 had higher help-seeking threat than cluster 3. Accordingly, cluster 1 had higher help-seeking threat and lower help-seeking willingness, characteristic of AHSs. Cluster 2 had higher willingness to seek help and executive help-seeking, but its executive help-seeking value was medium, characteristic of EHSs or SHSs. Cluster 3 had lower willingness to seek help, executive help-seeking, and help-seeking threats, which are characteristic of IHSs.

3.4. Step 2: Developing adaptive help-seeking negotiation-based regulation mechanisms

Adaptive help-seeking negotiation-based regulation mechanisms were designed for different help-seeking tendencies (Table 3). With help-seeking negotiation-based regulation mechanisms, the system negotiates with students to co-regulate help-seeking (Chou et al., 2015; Chou et al., 2018; Hadwin, Järvelä & Miller, 2011). This co-regulation scaffolds students' help-seeking to prompt students to be aware of and regulate their poor help-seeking behaviors. Problems have different difficulty levels, and thus, for each problem, the appropriate problem-solving attempts (PSAs, computed as the number of attempts made to complete the solution step), help-seeking amount (HSA, computed as the highest level of hint that students sought for help) and solving time (ST) differ for each step. Students need more PSAs, HSA and ST for each step when solving more difficult problems. Thus, this study adopted the historical records of students' PSAs, HSA and ST for each problem as parameters for the heuristic rules to detect students' situations and to regulate their poor help-seeking behaviors. Rule #1 reminds students not to seek too much help when they have sought too much help (i.e., a poor help-seeking behavior of executive help-seeking). The rule is checked when students seek help. For AHSs and IHSs, the rule detects the situation of seeking too much help when a student has few PSAs (i.e., below or equal to the first quartile of the historical PSA record), a short ST (i.e., below or equal to the first quartile of the historical ST record), and high HSA (i.e., larger than or equal to the third quartile of the historical HSA record). EHSs tend to seek too much help. Thus, for them, the HSA threshold is reduced to the second quartile of the historical HSA record so that the system reminds these students not to seek too much help in advance. If the rule is activated, the system rejects students' help requests, encourages students to solve problems by themselves, and disables the "Help" button for 40 seconds. If students continue to seek help after 40 seconds, the system will provide help. Rule #2 prompts students to seek help when they have difficulty and need help. The rule is periodically checked as students solve problems. For EHSs and IHSs, rule #2 detects the situation of needing help when a student has a long ST (i.e., longer than or equal to the third quartile of the historical ST record) and low HSA (i.e., below or equal to the first quartile of the historical HSA record). AHSs tend to avoid seeking help. Thus, the HSA threshold is increased to the second quartile of the historical HSA record so that the system prompts AHSs to seek help more frequently. If the rule is activated, the system proposes providing help by asking students "*Do you need help?*" with two buttons, "*Yes*" and "*No*." If students choose "*Yes*," the system provides help based on the solution situation. If students reject help, the system detects the situation again after 40 seconds. Rule #3 forces providing hints to students when students are stuck, definitely need help, and reject help. The rule detects a stuck situation when students reject the system's help proposal two consecutive times (i.e., a poor help-seeking behavior of avoidant help-seeking). When the rule is activated, the system forces providing hints to students. Rule #4 respects and does not regulate students' help-seeking behaviors when students neither seek too much help nor have difficulty. When rules #1, #2, and #3 are not activated, rule #4 is activated.

Table 3. Adaptive help-seeking negotiation-based regulation mechanisms for different help-seeking tendencies

Rule	Brief	Situation	Detection rule	Negotiation-based regulation
#1	Remind not to seek too much help	Students have sought for too much help	AHSs, IHSs: (PSAs <= Q_1) and (ST <= Q_1) and (HSA >= Q_3) EHSs: (PSAs <= Q_1) and (ST <= Q_1) and (HSA >= Q_2)	Reject students' help request and disable "Help" button for 40 seconds. If students still seek help after 40 seconds, the system will provide help.
#2	Prompt to seek help	Students have difficulty and need help but do not seek help	AHSs: (ST >= Q_3) and (HSA <= Q_2) and EHSs, IHSs: (ST >= Q_3) and (HSA <= Q_1)	Propose to provide hints and accept students' choices. If students reject help, the system detects the situation again after 40 seconds.
#3	Force help	Students are stuck and definitely need help but do not seek help	Students reject the system's help proposal two consecutive times	Force providing hints to students
#4	Respect students' help-seeking	Students neither seek too much help nor have difficulty	Out of rules #1, #2, or #3	No regulation

Note. Q_1: the first (lower) quartile; Q_2: the second quartile (i.e., median); Q_3: the third (upper) quartile; problem-solving attempts (PSAs), help-seeking amount (HSA), and solving time (ST).

3.5. Step 3: Conducting an experiment with an experimental and a control group

Students were divided into an experimental group and a control group to explore whether adaptive help-seeking regulation mechanisms facilitate better help-seeking behaviors and learning performance. Students in each cluster were randomly assigned to the control and experimental groups (Table 4). Because there was an odd number of students in the AHS and EHS clusters, the decision was made to assign one more student to the experimental group than to the control group. When students logged in to the system, those in the experimental group were assigned to use the NALS-HS system with adaptive negotiation-based regulation mechanisms, whereas the students in the control group were assigned to use the NALS-HS system in which the regulation mechanisms were disabled so that they could seek help at will.

Table 4. Distributions of students in the control and experimental groups

	Total	AHSs	EHSs/SHSs	IHSs
Control	25	2	15	8
Experimental	27	3	16	8

Students used the system in classes for six weeks. Each week, students read worked-out examples and conducted exercises in which they sought to solve two related program-output-prediction problems through the assigned system with or without regulation mechanisms in 20 minutes. These two problems were similar to the worked-out examples. Historical PSA, HSA and PT records from 63 students who used the system to solve these problems were used as the parameters of the adaptive help-seeking regulation mechanisms. After that, students were asked to complete a post-test with two program-output-prediction problems similar to the two problems in the exercises in 15 minutes in a pencil-and-paper format. Students were assigned to learn and solve easy problems from weeks 1 to 3 and difficult problems from weeks 4 to 6. In the 7th week, a delay test with six problems that were similar to the problems from the first six weeks was conducted to assess students' delay performance. Students' post-test and delay test scores for easy problems during weeks 1 to 3 and difficult problems during weeks 4 to 6 were computed to assess their learning performance.

Chou and his colleagues (2018) proposed three help-seeking behavior indicators, namely, the ratio of steps solved with executive help (RSE), the ratio of steps solved with instrumental help (RSI), and the ratio of steps solved by themselves (RST), to evaluate the quality of students' help-seeking behaviors. High RSE is identified as a poor help-seeking behavior (i.e., executive help-seeking), whereas appropriate RSI is identified as a good help-seeking behavior (i.e., strategic/instrumental help-seeking) and RST is identified as an indicator of whether students are able to solve problems by themselves without seeking help. This study adopted RSE, RSI, and RST to evaluate students' help-seeking behaviors.

4. Experimental results

Some students missed some activities and their data were excluded from the related analysis. The number of valid samples for each analysis is shown in the following tables.

Table 5 lists students' learning performance for easy and difficult problems. The results of paired t tests showed that students' performance on easy problems was significantly higher than that on difficult problems [post-test: $t(39) = 3.661$, $p = .001$; delay test: $t(40) = 9.119$, $p < .001$]. That is, problems during weeks 4 to 6 are more difficult than problems during weeks 1 to 3.

Table 5. Learning performance for easy and difficult problems (Mean/Standard Derivation)

	Week 1~Week 3 (Easy problems)	Week 4~Week 6 (Difficult problems)	Paired t test	
			t	p
Post-test (full mark = 100) (N = 40)	91.59/8.68	82.48/14.06	3.661	.001
Delay test (full mark = 75) (N = 41)	71.98/7.47	52.29/16.46	9.119	.000

Table 6 lists the help-seeking behavior indicators for the students in the control and experimental groups. A Mann-Whitney U test revealed that students in the experimental group had a significantly higher RST on easy and difficult problems than students in the control group (easy problems: $U = 161$, $p = .014$; difficult problems: $U = 134$, $p = .047$). The effect sizes (calculated by Cohen's D) for RST were large (0.92) and medium (0.64) for the easy and difficult problems, respectively. A Mann-Whitney U test also showed that students in the experimental group had a significantly lower RSE on easy problems than students in the control group ($U = 143.5$, $p = .003$). Students in the experimental group also seemed to have a lower RSE on difficult problems than students in the control group, but the difference did not reach significance. In addition, the effect sizes for RSE were large (0.96) and medium (0.5) for easy and difficult problems, respectively. The results indicated that the adaptive help-seeking regulation mechanisms promoted students better help-seeking behaviors (i.e., less executive help-seeking) for easy problems and a higher ratio of solving problems by themselves without seeking help.

Table 6. Help-seeking behavior indicators of the control and experimental groups (Mean/Standard Derivation)

	Control	Experimental	Mann-Whitney U test	
			U	*p*
Week 1~Week 3 (Easy problems)	$N = 23$	$N = 24$		
RST	0.754/0.208	0.903/0.100	161	$.014^{*}$
RSI	0.155/0.153	0.075/0.079	210.5	.161
RSE	0.108/0.113	0.022/0.060	143.5	$.003^{**}$
Week 4~Week 6 (Difficult problems)	$N = 20$	$N = 21$		
RST	0.287/0.258	0.451/0.256	134	$.047^{*}$
RSI	0.098/0.089	0.068/0.072	168.5	.278
RSE	0.615/0.284	0.481/0.247	152	.130

Note. $^{*}p < .05$; $^{**}p < .01$.

Table 7 shows the learning performance on the post-tests and delay test for the control and experimental groups. A Mann-Whitney U test revealed that the post-test score for weeks 4 to 6 in the experimental group was significantly higher than that in the control group ($U = 108$, $p = .008$). The effect sizes (calculated by Cohen's D) for the post-test were small (0.19) and large (0.81) for the easy and difficult problems, respectively. In addition, the delay test score for weeks 4 to 6 was approximately significantly higher in the experimental group than in the control group ($U = 143.5$, $p = .086$). The effect sizes for the delay test were small (0.29) and medium (0.53) for the easy and difficult problems, respectively. The results indicated that the adaptive help-seeking regulation mechanisms promoted better learning performance, particularly for difficult problems.

Table 7. Learning performance of the control and experimental groups (Mean/Standard Derivation)

	Control	Experimental	Mann-Whitney U test	
			U	*p*
Post-tests (full mark = 100)				
Week 1~Week 3 (Easy problems)	90.3/9.84 ($N = 21$)	91.9/7.37 ($N = 25$)	242	.651
Week 4~Week 6 (Difficult problems)	76.4/12.97 ($N = 19$)	87.1/13.29 ($N = 22$)	108	$.008^{**}$
Delay test (full mark = 75)				
Week 1~Week 3 (Easy problems)	70.8/9.32 ($N = 19$)	73/5.44 ($N = 22$)	193	.523
Week 4~Week 6 (Difficult problems)	47.7/18.18 ($N = 19$)	56.2/14.01 ($N = 22$)	143.5	$.086^{+}$

Note. $^{+}p < .1$; $^{**}p < .01$.

5. Discussion

5.1. Identified help-seeking tendencies under different contexts/sources, participants, and identification approaches

This study identified three student help-seeking tendencies in the context of a CALS. Table 8 lists the help-seeking tendencies identified in eight studies. The distributions of the identified help-seeking tendencies vary across studies. SHSs were identified in all studies. EHSs were identified in five studies. AHSs were identified in five studies. IHSs were identified in three studies. In particular, some studies identified some students with mixed help-seeking tendencies; that is, these students did not belong to a single help-seeking tendency but simultaneously presented characteristics of different help-seeking tendencies. For example, White and Bembenutty (2013) identified some students with the properties of both EHSs and AHSs and some students with the properties of both AHSs and SHSs. Some students were identified with both EHSs and SHSs in this study. This reason might be that there is no clear boundary between some help-seeking tendencies or that help-seeking tendencies are not mutually exclusive. However, it may be that students who belong to the same help-seeking tendency have different levels of this tendency or quantitatively ordered profiles. For example, all students were identified as SHSs in the two studies of Finney et al. (2018), but 3 levels or 4 levels of SHSs were identified.

Table 8. Help-seeking tendencies identified in different studies

Study	Context/source	Participants	Identification approach	EHSs	SHSs	IHSs	AHSs
Karabenick, 2003	Classroom	883 college students (chemistry classes)	Questionnaire & clustering		42%	36%	23%
Ryan, Patrick and Shim, 2005 (study 1)	Classroom	844 6th-grade students	Observed & reported by teachers	13%	65%		22%
Ryan, Patrick and Shim, 2005 (study 2)	Classroom	474 5th-grade students (math classes)	Observed & reported by teachers	7%	74%		19%
White and Bembenutty, 2013	Classroom	86 college students (elementary teacher candidates)	Questionnaire & clustering	14%/AHSs	54%		32%/ SHSs
Finney et al., 2018 (study 1)	Classroom	1950 first-year college students	Questionnaire & mixture modeling		100% 3 levels		
Finney et al., 2018 (study 2)	Classroom	2107 college upperclassmen	Questionnaire & mixture modeling		100% 4 levels		
Chou et al., 2018	CALS	39 college students (programming class)	System records & observed by experts	38%	28%	33%	
This study	CALS	52 college students (programming class)	Questionnaire & clustering	60%/ SHSs		30%	10%

The different distributions may be due to differences in the contexts/sources, participants, and identification approaches. First, the contexts/sources may be classrooms in which students seek help from teachers or peers; online chatrooms or discussion boards on which students seek help from teachers, peers, or strangers; or CALSs in which students seek help from the system. Makara and Karabenick (2013) proposed a multidimensional framework for distinguishing help sources: role (formal vs. informal), relationship (personal vs. impersonal), channel (mediated vs. face-to-face), and adaptability (dynamic vs. static). In addition, researchers have argued that seeking help from teachers or peers is a social form of self-regulated learning, whereas seeking help from CALSs is a nonsocial form (Karabenick & Gonida, 2018). Researchers have found that students have different help-seeking tendencies toward teachers (i.e., formal sources) and peers (i.e., informal sources) (Karabenick, 2003; Qayyum, 2018). Some studies explored students' help-seeking tendencies in general, whereas some studies investigated students' help-seeking tendencies in classes on specific subjects, such as chemistry, math, or programming. Students may have different help-seeking tendencies in different classes. For example, a student may be an SHS in a chemistry class but an AHS in a math class. Second, different participants, such as college students and elementary students, may have different help-seeking strategies, skills, and tendencies. Participants in six of the studies were college students, whereas participants in two of the studies were elementary students. It would be interesting to compare the help-seeking tendencies of different types of participants, such as college students and elementary students. Third, there are two main approaches to identifying help-seeking tendencies. One approach employs teachers or experts to identify students' help-seeking tendencies by observing students or investigating system records of students' behaviors. The other approach applies a self-reported help-seeking tendency questionnaire and clustering method to cluster students into several clusters, and experts then identify the help-seeking tendency of each cluster. Help-seeking is a kind of self-regulated learning, and Winne and Perry (2000) proposed that self-regulated learning can be measured as an attitude, which focuses on static and large-grained assessments, through a self-report questionnaire, or measured as an event, which focuses on small-grained dynamic processes, through observation or behavior tracking. Fine-grained evaluations during a long period can reflect more information than a global evaluation from a questionnaire on a specific date (Cantabella et al., 2020). It would be interesting to compare the help-seeking tendency results obtained through questionnaires with those obtained through observation or behavior tracking. In sum, further analytic and comparative studies of help-seeking identifications are required to investigate students' help-seeking tendencies under different contexts/sources, participants, and identification approaches.

5.2. Detection of and intervention mechanisms for poor help-seeking behaviors in CALSs

Table 9 lists the detection and intervention mechanisms for poor help-seeking behaviors in CALSs. Each detection and intervention mechanism was designed based on assumptions about what poor help-seeking behaviors are and how to intervene. Help Tutor is a tutor agent that provides meta-cognitive feedback on help-seeking as students learn with an intelligent tutoring system, Geometry Cognitive Tutor (Aleven et al., 2006; 2016). Help Tutor contains a help-seeking model (comprising approximately 80 production rules) to analyze students' problem-solving and help-seeking behaviors to detect four main categories of student help-seeking bugs (i.e., poor help-seeking behaviors), namely, help abuse, help avoidance, try-step abuse, and miscellaneous bugs. Help abuse indicates that students misuse the help of the CALS. Help avoidance denotes that students could benefit from seeking help but choose to try the step. Try-step abuse means that students try steps too fast. Miscellaneous bugs cover help-seeking bug situations not represented in the other categories, such as students receiving all the hints, including a bottom-out hint of the answer, and still failing to solve the problem. Help Tutor provides students with meta-cognitive feedback as an intervention when help-seeking bugs are detected. For example, Help Tutor intervenes by showing the message "*A hint could be helpful, as this is likely a challenging step to you*" to a student when help avoidance is detected (Aleven et al., 2006).

On the other hand, NALS-HS (version 1) includes six rules to analyze students' problem-solving and help-seeking behaviors and detect three poor help-seeking behaviors, namely, asking for excessive help, having difficulty and needing help but not seeking help, and being stuck and definitely needing help but not seeking help (Chou et al., 2018). NALS-HS adopts a negotiation based regulation mechanism as a help-seeking intervention. A student can actively seek help from the system, and the system may accept the student's help-seeking request or reject the request when the student is detected as having asked for excessive help. The system may also actively prompt a student to seek help when it detects that the student is having difficulty and needs help or force providing hints to the student when he or she is stuck, definitely needs help, and still rejects seeking help. These rules adopt some threshold parameters that can be adjusted. For example, one rule is that a student will be detected as having difficulty and needing help when the student is idle for 40 seconds (i.e., a threshold), and the system will prompt the student to seek help by asking the student "*Do you need help?*" with two buttons, "*Yes*" and "*No*."

Table 9. Detection and intervention mechanisms for poor help-seeking behaviors in CALSs

System	Factors for detection	Poor help-seeking behaviors detected	Intervention
Help Tutor (Aleven et al., 2006; 2016)	Problem solving and help seeking behaviors	Help abuse Help avoidance Try-step abuse General errors	Meta-cognitive feedback
NALS-HS (version 1) (Chou et al., 2018)	Problem solving and help seeking behaviors	Asking for excessive help Having difficulty and needing help but not seeking help Being stuck and definitely needing help but not seeking help	Negotiated based regulation
NALS-HS (version 2) (This study)	Problem solving and help seeking behaviors Help seeking tendency Problem difficulty levels	Asking for excessive help Having difficulty and needing help but not seeking help Being stuck and definitely needing help but not seeking help	Negotiated based regulation

This study modified the detection and regulation rules of NALS-HS (version 2) to consider not only problem-solving and help-seeking behaviors but also help-seeking tendency and problem difficulty levels (Table 3). A study has confirmed that students seek help more frequently as problem difficulty increases (Hao et al., 2016). This study adopts historical records of students' problem-solving and help-seeking behaviors for each problem, namely, the lower quartile, the second quartile, and the upper quartile for PSAs, ST, and HSA, as threshold parameters for the rules for each problem. For students with different help-seeking tendencies, the rules adopt different thresholds to accommodate students' differences. For example, the threshold of detection for seeking too much help for EHSs (HSA >= Q_2) is lower than that for AHSs and IHSs (HSA >= Q_3) so that the system can remind EHSs not to seek too much help in advance.

In sum, different assumptions regarding poor help-seeking behaviors lead to different detection and intervention mechanisms for poor help-seeking behaviors in CALSs. These assumptions should be validated or modified according to the experimental results. For example, inappropriate attempts (i.e., try-step abuse or making hasty attempts when help would be more beneficial) are generally regarded as poor help-seeking behaviors, but a study found that a high rate of inappropriate attempts on low-skill steps was significantly associated with students' success rate on subsequent relevant attempts (i.e., improved learning), whereas a high rate of inappropriate attempts on medium-skill steps was significantly negatively associated with the subsequent success rate (Roll et al., 2014).

5.3. Effects under help-seeking intervention and after help-seeking intervention is faded out

To evaluate the effects of help-seeking detection and intervention, students with help-seeking intervention (experimental group) were compared with students without intervention (control group) in terms of their help-seeking behaviors and performance. Help-seeking intervention is a form of scaffolding; thus, it is necessary to evaluate learning effects under help-seeking intervention and after help-seeking intervention is faded out (Aleven et al., 2016; Chou & Chan, 2016). When a help-seeking intervention is provided, the analysis determines whether the intervention facilitates better student help-seeking behaviors and performance in the learning task, whereas after the help-seeking intervention is faded out, the analysis focuses on whether the intervention helps students to be better help-seekers in future learning tasks. Table 10 lists the effects under help-seeking intervention and after help-seeking intervention has been faded out, which includes the control and experimental groups. Students in the experimental group who used Geometry Cognitive Tutor with Help Tutor had better help-seeking behaviors than students in the control group who used Geometry Cognitive Tutor without Help Tutor (Roll et al., 2006; Roll et al., 2011). Students in the experimental group also had better help-seeking behaviors after the intervention was faded out than students in the control group (Roll et al., 2011). The results indicated that students could be tutored to be better help-seekers. However, there were no significant differences in performance between students in the experiment and control groups.

Table 10. Effects under help-seeking intervention and after intervention was faded out

Study	Effects under help-seeking intervention	Effects after intervention was faded out
Help Tutor (Roll et al., 2006)	Improved help-seeking behaviors	N/A
Help Tutor (Roll et al., 2011)	Improved help-seeking behaviors	Improved help-seeking behaviors
NALS-HS (version 1) (Chou et al., 2018)	Improved help-seeking behaviors	N/A
NALS-HS (version 2) (This study)	Improved help-seeking behaviors (easy problems) Improved performance (difficult problems)	N/A

Students in the experimental group who used NALS-HS (version 1) with help-seeking intervention mechanisms had better help-seeking behaviors than students in the control group who used NALS-HS without intervention mechanisms (Chou et al., 2018). However, there were no significant differences in performance between students in the experiment and control groups. In this study, students in the experimental group who used NALS-HS (version 2) with help-seeking intervention mechanisms not only had better help-seeking behaviors for easy problems but also had better performance for difficult problems than students in the control group who used NALS-HS without intervention mechanisms. The results revealed that the help-seeking intervention not only promoted better help-seeking behaviors but also promoted better performance; however, the effect of the help-seeking intervention on behaviors appeared only for easy problems, whereas the effect of the help-seeking intervention on performance appeared only for different problems. The results might indicate that task or problem difficulty is a factor affecting student help-seeking behaviors, performance, and the effects of intervention. Another study found that students' success rate was significantly associated with the rate of inappropriate attempts on low-skill steps but was significantly negatively associated with the rate of inappropriate attempts on medium-skill steps (Roll et al., 2014). In sum, the effects of help-seeking interventions and the influencing factors need further investigation.

6. Conclusion

This study proposed an approach for developing adaptive help-seeking regulation mechanisms for different help-seeking tendencies. First, a questionnaire and clustering approach was adopted to identify students' help-seeking tendencies in the context of a CALS. Then, adaptive help-seeking detection and regulation mechanisms were developed for different help-seeking tendencies and for problems with different difficulty levels. The mechanisms take students' individual differences in help-seeking tendency into account to provide them with precise and adaptive help-seeking detection and regulation. The mechanisms also adopt historical student records of problem-solving and help-seeking data for each problem as parameters for the adaptive help-seeking detection and regulation mechanisms to account for the difficulty of each problem. Finally, the results of the experiment showed that adaptive help-seeking regulation mechanisms for different help-seeking tendencies promoted a higher ratio of students solving problems by themselves without seeking help (experimental: 90.3% and 45.1% for easy and difficult problems versus control: 75.4% and 28.7%), better help-seeking behaviors (i.e., less executive help-seeking, experimental: 2.2% versus control: 10.8%) for easy problems, and better learning performance for difficult problems (experimental: 87.1 versus control: 76.4). In sum, the study has shown the feasibility and benefit of the proposed approach of regulating student poor help-seeking. The approach can be applied to develop adaptive help-seeking regulation mechanisms for other CALSs. However, students' help-seeking tendencies may be differently identified for different participants and for different CALSs. Adaptive help-seeking regulation mechanisms should be modified for different identified help-seeking tendencies, and the effects of the modified mechanisms should be explored. Further studies are required to explore how to generally identify help-seeking tendencies and design effective help-seeking regulation mechanisms.

Furthermore, the proposed adaptive regulation mechanisms of collecting data, adopting machine learning methods to identify students with different profiles and designing different regulation mechanisms can be applied in different contexts with different data, different machine learning identification methods, and diverse regulation mechanisms. For example, students' log of participation and solutions in a CALS can be collected for applying machine learning classification methods to identify students with different performances for intervention (Villagrá-Arnedo et al., 2020). Enrolled students' data can be clustered to identify prospective students for the promotion of graduate programs (Croda et al., 2019).

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Appendix. Help-seeking questionnaire

Help-seeking willingness

1. If I were having trouble solving problems I would ask the system to help me how to solve problems.
2. Getting help from the system would be one of the first things I would do if I were having trouble in solving problems.

Executive help-seeking

3. The purpose of asking the system for help would be to succeed without having to work as hard.
4. Getting help from the system would be a way of avoiding solving problems on my own.

Help-seeking threat

5. I would feel like a failure if I needed help from the system.
6. I would not want anyone to find out that I needed help from the system.
7. Getting help from the system would be an admission that I am just not smart enough to do the work on my own.

Actualizing the Affordance of Mobile Technology for Mobile Learning: A Main Path Analysis of Mobile Learning

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ABSTRACT: As the number of mobile device owners on university campuses grew over the past two decades, scholars specializing in digital education and its application versatility have taken a heightened interest in mobile learning programs and platforms. The nature of mobile learning is constantly evolving with the development of technology artifacts, and it brings the purpose of this article into sharper focus as we examine mobile learning from various perspectives, critical issues confronting distant education programs, and identify potential research directions for future studies. To that end, main path analysis, a citation-based systematic review method, is employed for this study in collecting and analyzing of 935 articles that address mobile learning in the higher education community. The results of the analysis identify several significant trajectories, which reveal four popular research clusters: mobile technology artifact, educator motivation approach, learner learning projection, and actualizing mobile learning and in turn identifies two mobile learning research derivatives: Mobile-technology affordance and actualizing mobile learning. This kind of discovery research has demonstrated that mobile learning will strengthen learning references.

Keywords: Mobile Learning, M-Learning, Affordance actualization, Main path analysis

1. Introduction

With the development of mobile technologies and wireless devices, mobile learning (m-learning) has been recognized as a trend in educational applications(Wu et al., 2012), which can be defined as information acquiring taking place while learner is not at a fixed location, or when the learner benefited from the adoption of mobile technologies to gain learning opportunities (O'Malley et al., 2003). As Ally and Prieto-Blázquez (2014)) stated, the availability of mobile technology enables educators to have the opportunity to access educational resources in an unfixed location. Mobile technology-enabled educational programs are now widely regarded as a development priority for many schools, as accessibility of handheld device hikes among university students. Despite the plethora of writings devoted to discussing the impact of mobile technology on formal education experiences, a more comprehensive exploration is imperative to scrutinize possible challenges and development direction since the m-learning concepts are organically and constantly evolving.

The developing mobile technology offers a more flexible, personalized and accessible learning experience (Yusri & Goodwin, 2013). In this domain, the role of technology component is growing with the development of digital technologies, and thus facilitating the changing of mobile learning concepts. More specifically, the studies on mobile learning have transformed from the design aspect into the usage aspect. Design aspect of mobile education indicates the importance of the nature and potential outcome of mobile technologies for educational purposes; On the other hand, the more recent researches show a growing attention to the approach of actualizing the unrealized capacity of mobile technologies, entails the interaction between learning context and technology adoption as a critical point.

It is worth noting that past reviews highlighted the importance of technology essence and practical usage, this study further embraced "affordance actualization" as a theoretical method to cope with the dynamic fabric of m-learning. Affordance actualization refers to actors through technology adoption to achieve immediate concrete outcomes in support of their goals (Strong et al., 2014). this study suggests appropriate affordance actualization from the Information System domain, to examine how to adopt technology artifacts in facilitating the attainment of educational goals, thus to deal with the changing concept of mobile learning. Also, the affordance actualization perspective provides this study a way to further the understanding of technology loopholes in the domain of digital education for following reasons: First, this perspective allows the study to explain the possibilities an object affords for action (Majchrzak, Faraj, Kane, & Azad, 2013; Tim, Hallikainen, Pan, & Tamm, 2020), rather than taking technological artifacts for granted. In doing so, digital educational researchers could capture the potential actions of technological artifacts in a learning environment. Second, the process of m-learning adoption is highly volatile and requires educators to constantly innovate and evolve with the fast changing learning dynamic. Apart from understanding how to integrate mobile technologies into the essence of learning, it is very vital to consider two major points, affordance and actualization, when analyzing the learning outcome of m-learning. Therefore, this study aims to address the following research questions: How to make the affordances of mobile learning being realized in higher education in a changeable place?

Four research themes have been deliberately identified based on the previous literature in the realm of m-learning: mobile technology artifact, learner learning projection, education motivation approach, and actualizing m-learning. In an attempt to solidify m-learning results achieved through mobile technology applications, Strong's affordance actualization (2014) was applied as a theoretical lens to track existing research topics, and to conceptualize the deployment process of m-learning. Adding values to this research, an integrated model is developed to expedite our comprehension of actualizing m- learning for higher education.

2. Contextual background

The advent of digital technology has brought a series of innovative educational digital services. In addition, the ownership of mobile devices has also spread at an unprecedented rate. As of 2020, 93% of the world's population lives in areas covered by mobile cellular networks (Union, 2019). According to the literature (Center, 2017; Poushter, 2016), in the United States, the largest mobile device users are ordinary college students, aged between 18 and 29. In the same age group, 96% will use smartphones in 2020 (Center, 2020). More specifically, the growing maturity of mobile technology allows learners and educators to overcome the physical boundary, which accommodates better accessibility to education services.

Recent empirical evidence indicates that m-learning can be used to support students' learning in higher education settings (Ke & Hsu, 2015; Wu et al., 2012). However, research in m-learning has been fragmented and idiosyncratic, and based mostly on the understanding of the individual researcher (Alrasheedi, Capretz, & Raza, 2015). In addition, after more than 20 years of m-learning research, there is still relatively little systematic knowledge available, especially regarding the use of mobile technology in higher education settings (Pimmer, Mateescu, & Gröhbiel, 2016). This topic has attracted increased attention in recent years, and is also the goal of educators, especially in the case of using technology in classrooms for enhanced collaborative learning (Dillenbourg, Nussbaum, Dimitriadis, & Roschelle, 2013).

In the past, some of the m-learning articles point out that this tech-inspired form of distance education could be recognized as a purpose that relies on the ubiquitous features of mobile technology to construct an environment with high learning efficiency. Many articles have explored m-learning from various perspectives, include but not limited to: concept of m-learning and the design (Chang, Sheu, & Chan, 2003; Chen, Kao, & Sheu, 2003; C. H. Lai, Yang, Chen, Ho, & Chan, 2007; Peng, Su, Chou, & Tsai, 2009); analysis of adoption factors (Hamidi & Chavoshi, 2018; Karimi, 2016; Kim, Lee, & Rha, 2017; Looi, Sun, Wu, et al., 2014; Martin & Ertzberger, 2013); the technology acceptance model (Al-Emran, Mezhuyev, & Kamaludin, 2018; Almaiah, Alamri, & Al-Rahmi, 2019; Almaiah, Alamri, & Al-Rahmi, 2019; Chavoshi & Hamidi, 2019; Hoi, 2020); and m-learning goals (Cheon, Lee, Crooks, & Song, 2012; Gikas & Grant, 2013; Hao, Dennen, & Mei, 2017; Schwabe & Göth, 2005; Sharples, Corlett, & Westmancott, 2002); consideration of educators goals (Cheon et al., 2012; Dennen & Hao, 2014; Gikas & Grant, 2013; Hao et al., 2017; Hwang & Chang, 2011; Kim et al., 2017) and learners goals (Karimi, 2016; Looi, Sun, Seow, & Chia, 2014; Looi, Sun, Wu, et al., 2014; Martin & Ertzberger, 2013; Shih, Chuang, & Hwang, 2010; Wu et al., 2012).

However, what is the crux of m-learning? We suggest shifting the focus to the essence of m-learning. Although some literature considers m-learning as a means, it has not been well-examined. We therefore hope to re-examine previous articles for an insight into the value of m-learning. Following this contextual path, we will proceed with a literature review, research methods, analysis, and conclusion for a comprehensive perspective of m-learning in higher education settings.

3. Literature review

3.1. Mobile Learning (M-Learning)

The early definition of m-learning is primarily based on the use of mobile technology, which can be learned through mobile computing devices (Quinn, 2000). Lehner and Nosekabel (2002) summarized this definition as providing digital content and teaching materials required by learners through services or devices that are not limited by time and place, so as to assist learners to acquire knowledge. Hoppe, Joiner, Milrad, and Sharples (2003) emphasized that m-learning is a learning method using mobile vehicles and wireless transmission. Trifonova and Ronchetti (2003) mentioned that m-learning is the combination of action technology and digital learning, and m-learning devices have three capabilities: interaction, content access, and service access. Seppälä and Alamäki (2003) mentioned that m-learning is not just digital, it also holds the characteristics of mobile; m-learning is therefore superior to digital learning as it is not confined to geographic and time constraints. Chu, Hwang, Tsai, and Tseng (2010) mentioned that in addition to improving the learning efficiency of individual students, mobile devices and wireless communication also provide a practical way to carry out cooperative learning activities. However, inadequate instructional design may have a negative impact on learning achievements due to excessive cognitive load (Chu, 2014). Studies have shown that learners' attitudes and learning behaviors are significantly and positively correlated with the success of on-campus m-learning (Cheon et al., 2012). However, educationists should understand that nothing of the mentioned above could take place unless all learning activities are well designed and carefully implemented (Elfeky & Masadeh, 2016).

3.2. Actualizing mobile technologies affordance for learning

Actualizing is a goal-oriented and iterative process (Leonardi, 2011; Leonardi, 2013), which is defined as the action taken by actors as they take advantage of one or more perceived affordances through their use of technology to achieve outcomes in support of organizational goals (Strong et al., 2014). To actualize digital technologies within the organization, Leonardi (2013) introduces the concept of shared affordance, that is, an affordance shared by all members of a group in which all actors manifest similar use of technology features. This research suggests that only when actors agree on the usage of a similar sequence of technology features, that the affordance created by the interaction with specific technology can be actuated at an organizational level.

To achieve an organizational goal, Strong et al. (2014) identify three factors that both support and restrict an individual's affordance actualization: abilities and preferences of the individual, features of the system, and characteristics of the work environment. With the affordance perspective in place, the research proceeds to explore the IT elements, design, the learning dynamic between organizations and actors, and also the role of IT-associated organizational transformation. Furthermore, the digital education community also finds this theoretical insight helpful, specifically for educators who keep abreast of the latest digital technologies and the opportunities they offer (Haines, 2015). For example, an article points out the potential learning benefits of virtual learning environments by drawing on its affordance (Dalgarno & Lee, 2010). Jayarathna, Eden, Fielt, and Nili (2020) adopts this theory to introduce how higher education students can use digital technology for collaborative learning.

Despite the presence of literature on digital education to shed light on the importance of affordance (Bower & Sturman, 2015), few direct on how to "actualize" the digital technologies affordance for educational purposes. Moreover, mobile device owners in universities have inspired the increasing number of m-learning applications in higher education (Xiangming & Song, 2018), which lead to a growing number of m-learning studies. Hence, this study aims to systematically investigate the learning affordance of mobile technology in higher education, and to further the understanding of their potentials and affordance.

4. Research methodology

4.1. Main path analysis

Main path analysis (MPA) was first introduced by (Hummon & Doreian, 1990) who suggested that one can trace the major development trajectory of a scientific discipline through citation links. This method reduces massive amounts of information embedded in a citation network into a few crucial paths (Liu, Lu, & Ho, 2020). These crucial paths not only hint at the most significant articles but the main knowledge flow paths of a target field. In the beginning, this method was implemented in the social network analysis field (Batagelj & Mrvar, 1998), and now it has been widely adopted in a vase variety of disciplines (Park & Magee, 2017; Xiao, Lu, Liu, & Zhou, 2014).

Despite existing literature that has reviewed the high citation papers on the m-learning domain (Lai, 2020), the development trajectory of m-learning is still unclear. To trace the development trajectory of this domain, this study adopted a Key-route MPA to ensure that all the top significant links are included in the results (Huang, Chou, & Liu, 2021; Hung, Liu, Lu, & Tseng, 2014; Liu & Lu, 2012). MPA consists of two steps: The first step calculates the traversal counts of each citation link in a citation network (Batagelj, 2003; Batagelj & Mrvar, 1998) and as a result, differentiates the significance of each citation link. Among the various traversal count algorithms, search path link count (SPLC) algorithm is utilized based on the suggestion from (Liu, Lu, & Ho, 2019). SPLC is the traversal count for a link on the premise that delivers knowledge through all possible paths from all the ancestors of the node to all the sinks (Hummon & Doreian, 1990). The second step is to search for the crucial paths according to traversal counts of the links.

These advantages allow one to examine multiple subfields while at the same time identify important contributors. With that in mind, this research applies key-route MPA to visualize the key knowledge development trajectory of m-learning. Key-route MPA is always associated with a key-route number, which indicates the number of top links to include in the resulting main paths.

Table 1. Search strategy and key words used

Database	Web of Science
Search strategy	TS = ("e-learn*" OR "mobile learn*" OR "m-learning" AND *("higher education") NOT ("e-learning"))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)*
Timespan	From January 1, 2003 to Aug 26, 2020

4.2. Literature search

To ensure the dataset is complete, this study follows the study by Ho, Liu, and Chang (2017), the steps are above: First, according to five recent review articles (e.g., Chee, Yahaya, Ibrahim, & Hasan, 2017; Chung, Hwang, & Lai, 2019; Crompton & Burke, 2018; Lai, 2020; Wu et al., 2012), we built several keyword sets to search publications. Second, the authors choose the keyword sets as our query strategy, as Table shown. This study references academic articles and associated citation information from the Social Sciences Citation Index (SSCI) and Science Citation Index Expanded (SCIE) databases of the Web of Science (WOS) service. It was curated between January 1, 2003 and Aug 26, 2020. 2003 was selected because it was the year that m-learning started to flourish. In order to ensure that the most relevant articles have been included, we have checked with five selected review articles, and manually added the missing papers into our dataset. Third, we checked whether the highly cited m-learning papers in WoS were also included in the dataset. Finally, we excluded irrelevant studies that have no citation relationship with the rest of studies. The final search results in a total of 935 papers. We then collect the citation content for each of these papers from the WOS database. The citation information is used to construct the citation network which becomes the base for MPA. Table 1 presents the search strategy.

5. Analysis

5.1. The Sub research themes

This study applies the global main path approach (Liu, Lu, Lu, & Lin, 2013) to examine the main paths in more detail, which traces the top most significant paths, thus uncovering the recent and earlier clusters of papers. By increasing the number of paths selected, the details of the citation network gradually surface. Our analysis, therefore, visualizes the four branches of literature in Figure 1. Each branch represents a sub research theme. Darker dots symbolize end nodes. Link weights are indicated with different line thickness. Thicker lines suggest heavier weights.

After examining the title, abstract, and keywords of these papers, we conducted a meta-analysis and extracted similar core concepts of the paper as research themes. The research themes are Mobile technology artifact, Educator motivation approach, Learner learning projection, and Contextual implementation. Table 2 presents the details of these papers.

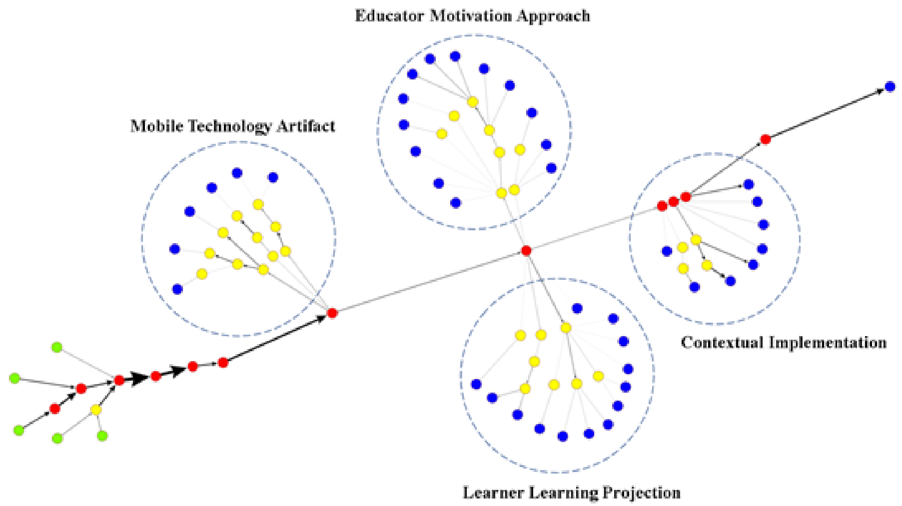

Figure 1. Multiple global main paths of mobile learning

5.1.1. Mobile technology artifact

Our analysis discovers that several literature writings make emphatic mentions on the IT feature of m-learning. To further our understanding of the design purpose of mobile technology, this study regards mobile technology as an IT artifact, and assigns these essays to mobile technology artifacts as their research theme. IT artifacts, by definition, are not "natural," "neutral," "universal," or given. As Grint and Woolgar (1995) note, objects are never merely and automatically just objects; they are always and already implicated in action and effect. Fundamentally, IT artifacts are designed, constructed, and used by people; they are also shaped by the interests, values, and assumptions of a wide variety of communities of developers, investors and users.

Mobile technology development and wireless internet service combined have given learners a better environment. Moreover, as users grew in their understanding and operational efficiency of mobile devices, the Internet, plus what they're able to achieve, mobile technology performance and service also progressed accordingly. In the past, the researchers were concerned mostly with information architecture of m-learning at the beginning of this phase. Several articles discussed the role of mobile devices in the teaching process (Seppälä & Alamäki, 2003), while other studies elaborated on the power of wireless service, particularly, Wi-Fi (Chen et al., 2003; Liu et al., 2003).

As IT architecture becomes more mature, scholars began to take notice of the interaction between mobile technology and the learning environment; The significance and responsibility of mobile technology raised during this particular era, its importance was elaborated by Peng et al. (2009), in which a genre of mobile education program was developed to facilitate an even more ubiquitous learner experience; this development rendered educational technology toward the status of ubiquitous knowledge. A study by Wu et al. (2012) discussed the application of clinical skills, comprehensive knowledge and other subjects, which traditionally were taught separately, to an in-class program via m-learning systems and transmission sensing devices, in order to develop ''Context-Aware Mobile Learning System'' that enhances the overall learning synergy. At this stage, the depiction of system features and the application of mobile technology artifacts, such as wireless networks and mobile devices, took the research spotlight.

5.1.2. Educator motivation approach

Our literature analysis identifies several writings that centered around the motivations from educator's perspective, usage methods and contexts for applying mobile technology. Bester and Brand (2013) concluded that ICT provides new possibilities to teaching as a career. Several previous research findings also show that ICT aids the learners with the development of cognitive skills, critical thinking skills and information accessing, evaluation and synthesising skills (Bester & Brand, 2013). Lau and Sim (2008) discovered that the use of ICTs in education could promote deep learning and allow schools to respond better to the needs of different learners. This could only be achieved if educators could truly integrate the ICTs into their teaching process.

As time and technology evolve with new discoveries, ways and the possibilities of incorporating ICT into educational programs have also organically expanded. That being said, researchers of this stage are concerned primarily with learner motivation and m-learning modes. For example, studies by Hwang and Chang (2011), Dennen and Hao (2014) focus on the mobile technology application framework.

Interestingly, some of the studies started to consider both the strengths, and the adverse effects of mobile devices on m-learners (Gikas & Grant, 2013). Conscious of these possible setbacks, scholars of this school would learn to anticipate the objectives achieved by m-learning from the get-go, and strive to promote the effectiveness of m-learning.

5.1.3. Learner learning projections

The importance of mobile technology in education multiplies more widely felt as time evolves. Several significant findings have revealed the benefits of mobile learning, namely that it can provide students with instant feedback (Hsu, 2015), improve learners' learning efficiency (Sung, Hwang, Liu, & Chiu, 2014) and bridges students' learning in class and in the field (Wang, 2016). A growing number of scholars, instead of focusing solely on the function and application, or the design and implementation of the m-learning system, begin to take other factors into consideration. As illustrated in Figure 1, the focus of research began to shift to educators and learners around 2013. In reviewing the essays produced around this time, we found that mobile technology has taken a more auxiliary role. The dynamic between learners and educators, rather, has moved to the center stage, which has a decisively positive impact on learning outcomes.

Martin and Ertzberger (2013) were among the first scholars to factor in the interactive elements between learners and educators, as they studied how mobile technology facilitated information reception from educators to learners, methods to apply mobile technology to inspire interests, and the influence of m-learning on grades and learner's experience.

Besides discussing the impact of m-learning on educators' teaching performance, Karimi (2016) attempted to identify elements that could encourage a more immersive m-learning experience for learners. Hamidi and Chavoshi (2018) further investigated factors that impacted the willingness of learners in higher education to use m-learning.

Fundamental differences between educators and learners in this stage pose a series of challenges for m-learning. In short, information systems efficacy, and the expectations of educators or learners are not the only considerations at play here for m-learning applications. Instead, comprehensive consideration, one that embraces environmental factors, is necessary so that a suitable contextual service could be incorporated to upgrade m-learning experiences. To that end, contextual implementation should be given priority scrutiny.

5.1.4. Contextual implementation

Contextual implementation, namely, is a problem-solving process under different circumstances for goal realization; the iterative process of realizing the goal is actualization indeed. (Leonardi, 2011; Leonardi, 2013; Strong et al., 2014). Research at this stage homes in on encouraging learners to accept a m-learning experience through mobile solutions. A study explores curricula and learning resources in the developing countries and discovers that social factors had greatly increased the acceptance of m-learning (Chavoshi & Hamidi, 2019). This essay also positions that support from the government and the approach to conducting mobile teaching will have an effect on social context.

In addition, Hamidi and Jahanshaheefard (2019) states that university institutions regard m-learning as a means to improving students' satisfaction with education programs on campus. Furthermore, different from previous literature that explored e-learning, summaries on m-learning put a heavier emphasis on the interactive relationship between teachers and students. A paper by Almaiah and Al-Khasawneh (2020) infers that mobile technology is now playing a more significant role in-class, as it provides necessary content in a more timely fashion to educators and learners. Whether it is to help students acquire a large amount of information, or to assist teachers with tracking students' learning, education delivery goals are met through m-learning.

Table 2. The label of m-learning literature

Sub themes	Content	Literature
Mobile Technology Artifact	*"The development of advanced wireless technologies for building an ad hoc classroom to create a modern and new learning environment."*	(Chang et al., 2003)
	"Mobile learning, conducted through the use of mobile devices such as PDAs, tablet PCs, and cell phones, is now widely considered an effective education solution due to its delivery of e-learning strengths; time and space that limit web-based learning systems are no longer a concern."	(Chen et al., 2008)
	"Learning systems that can track students' learning behaviors in the real world with the help of context-aware (sensor) technology."	(Hwang et al., 2010)
	"Teaching methods through the mobile device, the use of a short message service (SMS) and digital pictures as a part of the supervising process."	(Seppälä & Alamäki, 2003)
	"The aim is to construct an outdoor mobile-learning activity using up-to-date wireless technology."	(Chen et al., 2003)
	"An educational phenomenon enabled by mobile technology advancement, mobile learning, or m-learning, is beginning to offer 'stunning new technical capabilities' in education."	(Peng et al., 2009)
	"A decision-tree-oriented mechanism is developed for that purpose, enabling digital guidance for students to observe and classify real-world objects in learning activities during natural science courses."	(Chu et al., 2010)
	"Using mobile devices for learning activities in a real classroom context is found to spark student interest."	(Hwang et al., 2010)
Educator Motivation Approach	*"Even though this education solution seems to successfully heighten student interest, researchers have also advised for well-designed learning support to improve the students' learning efficiency."*	(Hwang & Chang, 2011)
	"A conceptual model that is based on the theory of planned behaviour (TPB), which explains how college students' beliefs influence their intention to adopt mobile devices in their coursework."	(Cheon et al., 2012)
	"Exploring teaching and learning processes when mobile computing devices, such as cell phones and smartphones, were implemented in higher education."	(Gikas & Grant, 2013)
	"This framework can be integrated with any instructional design process to engage instructors in the informed design of mobile learning activities."	(Dennen & Hao, 2014)
	"Pedagogical factors have the greatest effect on students' behavioral willingness to adopt mobile learning. Social influences, especially social image and subjective norm, also play a role."	(Hao et al., 2017)
	"Relative advantage, complexity, and inertia have significant effects on students' mobile learning resistance, with inertia being the most prominent."	(Kim et al., 2017)
Learner Learning Projection	*"To enhance the learning performance of the students, an inquiry-based mobile-assisted approach is employed to help students with constructing their own knowledge by taking cognitive load into consideration."*	(Shih et al., 2010)
	"As well as guiding individual students to perform physical assessment procedures on dummy patients, the learning system also provides instant feedback and supplementary materials in real-time if the operations or the operating sequence is incorrect."	(Wu et al., 2012)
	"Mobile technology opens the door for a new kind of learning, known as here-and-now learning, which occurs when learners have access to information anytime and anywhere to perform authentic activities in the context of their learning."	(Martin & Ertzberger, 2013)
	"As curriculum designs are not self-sufficient by themselves alone, the enactments of the teachers differ in how they leveraged on students' artifacts, and how they integrate the technology into the class."	(Looi et al., 2014)

	"Using qualitative data analysis methods, the study discusses the transformation of the classroom practices on teachers' pedagogical approaches, classroom culture, lesson plan design, linkages to informal learning, assessment methods, and parent involvement."	(Looi et al., 2014)
	"This study highlights the role of learners' character-traits in m-learning adoption, and highlights the importance of distinguishing between various types of m-learning projects."	(Karimi, 2016)
Contextual implementation	*"The factors related to adoption of mobile learning in higher education are categorized into seven main groups as: ease of use, trust, characters and personal qualities, context, perceived usefulness of using, behavioral intention, and culture of using a research model."*	(Hamidi & Chavoshi, 2018)
	"The goal of this research is to investigate the important factors affecting the acceptance of m-learning in Iran. These factors are divided into four macro groups: (1) Technological, (2) Pedagogical, (3) Social and (4) Individual issues."	(Chavoshi & Hamidi, 2019)
	"This study applies the Unified Theory of Acceptance and Use Technology (UTAUT) model to examine the effects of different factors that were identified from the literature on students' acceptance of mobile learning applications in higher education."	(Almaiah et al., 2019)
	"A new model is developed to study the effect of different factors on mobile learning applications development at the three main stages of usage (static stage, interaction stage and transaction stage)."	(Almaiah et al., 2019)

5.2. The transformation of research focus: From mobile technology affordance to mobile learning actualized

This section acknowledges the results of key-route MPA at 10 key-routes, consisting of 24 papers, which are shown in Figure 2. Arrows indicate knowledge flow direction, pointing from the cited papers to the citing papers. Each paper is assigned a label that begins with the last name of the first author, continues with the first initials of the co-authors (in capital letters), and ends with the publishing year.

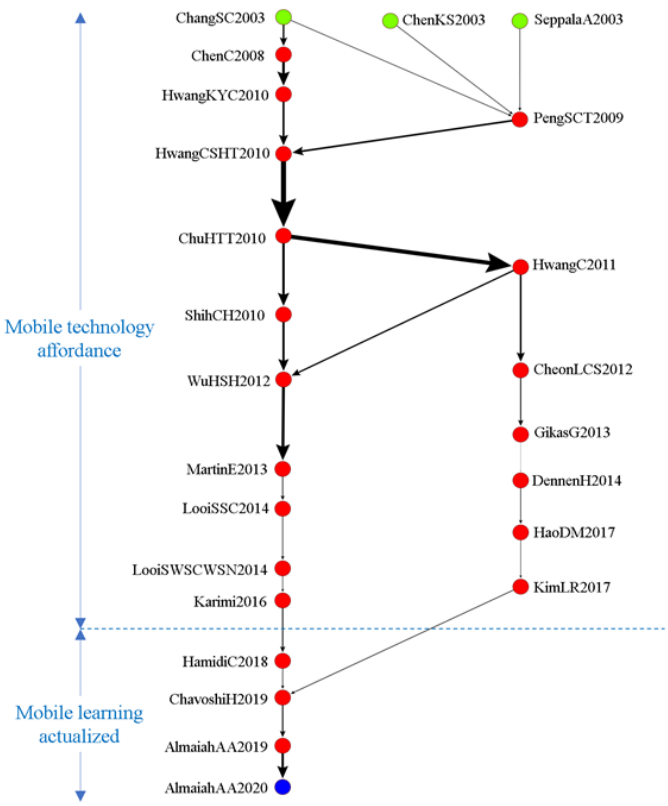

Figure 2. Key-route main paths and transformation of research focus

This study proposes the use of SPLC algorithm (Hummon & Dereian, 1989) to determine the significance of a citation link when applying MPA. The choice is based on the suggestion that SPLC fits the knowledge diffusion model better than the other traversal weights (Liu & Kuan, 2016). After the significance of each citation. The thickness of the links is proportional to their SPLC values.

In studying the research themes of MPA, we found that antecedent literature reviews put their focus first on the "Affordance" element, and later the attention is shifted to bringing "Affordance" of mobile technology into the learning environment. That being said, we suggest using "Affordance Actualization," proposed by Strong et al. (2014) to better integrate the essence of previous literature reviews.

5.2.1. Mobile technology affordance

Strong et al. (2014) suggests that "Affordance" can be divided into two central themes: "IT artifact" and "Actors and their goals." Having reviewed previous literature on main path analysis, we conclude that IT artifact is, in essence, mobile technology artifact, and characterized by a discourse on system features that encompass design models, specs, and adoption processes.

"Goal of learners and educators" in the following section is divided into two portions. One discusses the motivation of learning and teaching; the other, the projection outcome of m-learning projects. Goal fulfillment has consistently been the focus of m-learning researchers, with various essays and reports discussing ways to enhance learning effectiveness, or to improve the interaction during courses. Our analysis of this research topic identifies "the impact of mobile technologies on classroom education" as the core of m-learning. We agree with Stoffregen (2003) that positions affordance as an opportunity to help users of technology to realize their goals. To our knowledge, only by enhancing the understanding of mobile technology affordance be truly utilized. This concept has been applied to various fields in recent years, and it fills the bill for introducing this technology into educational programs.

5.2.2. Mobile learning actualizing

After analyzing previous writings that examine the clusters of actualizing m-learning, we are suggesting that this research theme is mostly concerned with the actualization of m-learning. As mentioned in the previous section, m-learning is conducive for helping students to acquire a significant amount of information, as well as to facilitate teachers' understanding of learner progress. Most importantly, m-learning also provides a way of creating more interaction between educators and learners.

The studies in this cluster considers mobile-assisted solutions for educators or learners to form a closer interactive relationship, even a more desirable study environment. By applying the theoretical framework of "Affordance Actualization," and examining previous literature on m-learning, we have proposed a learning affordance actualization model. A more in-depth discussion will follow in the next section.

6. Discussion and conclusion

To further our understanding of the development trajectory of m-learning, we adopt main path analysis in this study to examine previous literature on m-learning in higher education. Per the result of the main path analysis and theoretical foundation of affordance actualization, this paper develops a model of actualizing m-learning affordance (see Figure 3), and in turn identifies two m-learning research derivatives: Mobile-technology affordance and actualizing m-learning. In the initial stage of m-learning, the researcher focuses on mobile-technology affordance, and examines the intrinsic nature of mobile technologies. The research on this phase can be divided into three groups. The first is the Mobile technology artifact. Some studies highlight several technology features, such as Wi-Fi, mobile phone and tablet. The second is educator motivation approach, which emphasizes approaches educators take to inspire their learners. Finally, the research on learner learning projection, which examines the learner's perception of mobile devices, and how they can be smartly utilized to strengthen the learning experience. To that end, researchers are able to successfully dissect the intrinsic nature of mobile technology for higher education purposes, and address possible educational challenges accordingly.

Actualizing m-learning is the second phase of m-learning delivery. The research in this phase focuses on the contextual implementation of m-learning, and investigates the outcome of m-learning. When compared with the previous phase, writings produced during this period have highlighted the importance of the context to consider the various factors that affect the deployment process of m-learning, and thus to dissolve the potential limitations of traditional learning.

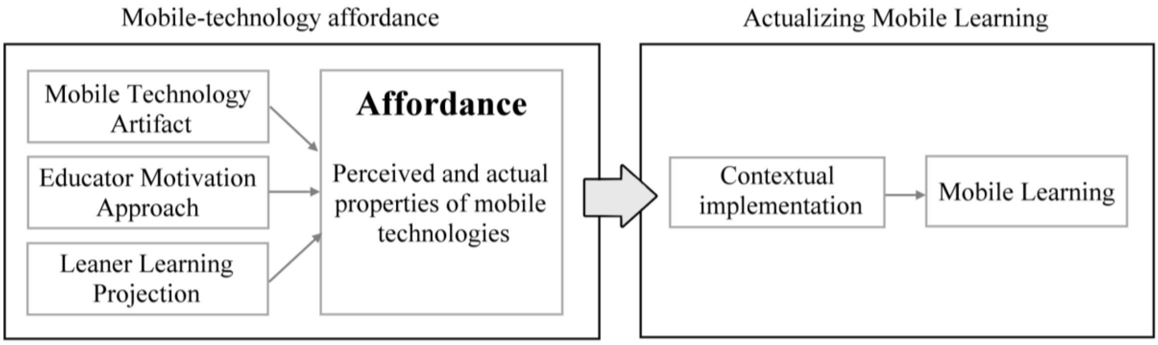

Figure 3. Model of mobile learning affordance actualization

Affordance actualization has been widely adopted in organizational research. This concept has inspired this essay to reference it into a digital education context, so as to explore the value of digital technology. By expanding the original model with more stakeholders, this version provides a comprehensive view of m-learning implementation. This is the greatest contribution made by this study to the academic circle.

6.1. Theoretical and practical implication

The key contribution of this study is through the process model of mobile learning affordance actualization to deliver the deployment approach of mobile education. In terms of theoretical contributions, it contributes to mobile learning in higher education, and affordance actualization literature.

First, this study contributes to digital education literature by introducing a theory from the IS domain, to deal with the increasing dynamic process of mobile learning adoption. Different from other education systems, mobile technologies play a more significant role than others. Because most people in higher education own a mobile device, which allows higher education to develop more mobile applications to interact with the learners who learn in universities. Moreover, to avoid taking mobile technology for granted, this study through affordance actualization analyzes each element in this, such as technology artifacts, educators (the people who teach in universities), and learners (the people who learn in universities). Moreover, the actualization perspective provides an approach to further discuss the practical issues of deploying mobile education in higher education.

Second, the affordance actualization has widely been used in organizational context, which mainly discusses how to adopt digital technologies in fulfilling a specific organizational need. However, the university is similar to the organization, yet lacks a similar structural approach about digital technology deployment. Therefore, this study suggests extending the scope of affordance actualization by appropriating this concept into the education domain. In analyzing the affordance actualization in educational context, we according to the factors in higher education to adjust the model in fulfilling the educational purposes.

Our study has important practical contributions as well. First, educators who are expected to implement digital technologies to enhance learning effectiveness within the classroom. Meanwhile, our model provides the higher educators to better actualize the potential power of digital technologies. For example, our model allows educators to enact related strategies to fit their specific education context by providing a more comprehensive view with the digital technology adoption. Second, this model is not only for mobile education, but also for other technologies. Because this is fit with the higher education environment, and helps educators to further understand the interaction between educators, learners, and technologies.

6.2. Research limitations

This section discusses the limitations of this research in two aspects: methodology and data collection. As regards methodology, we use the citation network constructed from the collected literature to find significant articles in the m-learning field. However, not all citations are equally meaningful. Sometimes an article is cited simply on account of its significance in the field, but it is not necessarily tightly associated in contents with the article that cites it. This type of citation does not reflect actual knowledge diffusion and can weaken the results of MPA.

The other research limitation comes from data collection. Among the popular scholarly databases (Google Scholar, Scopus, and WOS), we adopt WOS for the understanding of its higher publication quality. However, WOS does not fully include conference papers published in the early years. For completeness, we exclude conference papers from our datasets.

Nevertheless, a certain proportion of the papers in the computer science field will only be published at top conferences and will not be published in journals afterward. We may have missed some important m-learning conference papers derived from the computer science field as a certain proportion of research is only published at top conferences and not in the journal afterward.

6.3. Future works

This study adopts MPA to present the m-learning research trend up to August 2020 and highlight the key articles from the period. It contributes to the m-learning field by providing the most up-to-date summary of research progress, which can be valuable information for both researchers and practitioners. In the future, researchers can further combine other analytical tools and methodologies to analyze the citation network, which is believed to be more meaningful to the research conclusions.

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Editorial Note: Teacher Professional Development in STEM Education

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ABSTRACT: In line with the substantial interest in STEM (science, technology, engineering, and mathematics) education and the major projects in STEM curriculum development around the world, efforts should be particularly made to increase the supply of STEM teachers through proper and effective teacher professional development. Although there have been a number of studies related to teacher professional development for individual subject training in science, technology, engineering and mathematics, quality research on professional development for teachers to develop their capacity for adopting the integrative and cross-disciplinary approaches advocated in STEM education remains in its infancy. The theme of this special issue is two-fold: (a) to provide researchers and practitioners in STEM education with a scholarly platform for reflecting on what challenges and impediments STEM teachers have encountered, and (b) to exchange new theoretical and practical insights gained from empirical research on designing, enacting and evaluating professional development programmes for building teachers' capacity in STEM education.

Keywords: STEM education, Teacher professional development, Teacher capacity building, Teacher education

1. Introduction

The acronym "STEM" (science, technology, engineering, and mathematics) has been a theme among global educators who have called for K-12 education reforms that will boost the competitiveness of the next generation of children by nurturing their problem-solving ability and creativity (Chai et al., 2020a, 2020b; Li et al., 2020). STEM education refers to "solving problems that draw on concepts and procedures from mathematics and science while incorporating the teamwork and design methodology of engineering and using appropriate technology" (Shaughnessy, 2013, p. 324). Simply put, STEM serves as a means to integrate the disciplines of science, mathematics, technology and engineering into practical applications to tackle and address authentic, real-world problems (Geng et al., 2019; Huang et al., 2020a, 2020b; Knowles et al., 2018; Wang et al., 2020). In fact, STEM competencies are not only required within but also outside of STEM occupations (Dai et al., 2021; Lin et al., 2021a, 2021b; Williams et al., 2019). In the long term, it is foreseen that STEM as an integrative cross-disciplinary subject can enhance students' problem-solving, critical and analytical thinking skills, and enculture them to be constructive and innovative citizens (Brown et al., 2011; So et al., 2020).

The significance of STEM education in today's digital world cannot be underestimated (Chai et al, 2021; Li et al., 2020; Williams et al., 2019). Nevertheless, the majority of K-12 teachers who are now engaged in supporting and facilitating STEM learning activities in schools have been trained within their own subject discipline (usually science, information technology, or mathematics) when pursuing their teacher education studies (Aslam et al., 2018; Cavlazoglu et al., 2017; Geng et al., 2019; Knowles et al., 2018). Thus, they may not be comfortable implementing the integrative and cross-disciplinary approaches advocated in STEM education (Margot et al., 2019; Rich et al., 2018; Wang et al., 2020; Weng et al., 2020). In line with the global interest in STEM education and the national efforts in STEM curriculum development, efforts should be made particularly in building teachers' STEM teaching capacity through proper and effective professional development training (Brand, 2020; Chai et al. 2020a, 2020b; Lin et al., 2021a).

In fact, teacher professional development is always important in pedagogical and curricular reforms (Desimone, 2009; Guskey, 2002; Jong, 2016, 2019a, 2019b). There should be no exception as STEM education is being put in place. In general, the capacity building elements of (a) content focus, (b) use of models and modeling, (c) active learning, (d) collaboration, (e) coaching and expert support, (f) feedback and reflection, and (g) sustained duration, are regarded as the keys to framing and shaping effective teacher professional development (Darling-Hammond et al., 2017). Although there have been a number of studies related to teacher professional development in science, technology, engineering, or mathematics individually, quality research related to professional development for teachers in developing their capacity for adopting the integrative and cross-disciplinary approaches advocated in STEM education remains in its infancy (Aslam et al., 2018; Chai et al., 2020a, 2020b; Geng et al., 2019; Lau et al., 2020; Li et al., 2020; Rinke et al., 2016; Weng et al., 2020).

As suggested by the title, this special issue aims (a) to provide researchers and practitioners in STEM education with a scholarly platform for reflecting on what challenges and impediments that STEM teachers have encountered, and (b) to exchange new theoretical and practical insights gained from empirical research on designing, enacting, and evaluating professional development programmes for building teachers' capacity in STEM education.

2. Overview of the papers contributed to this special issue

A total of 48 papers were submitted to this special issue. After a rigorous double-blind review process, 11 papers were accepted. The accepted papers were authored by 39 STEM education researchers from Australia, Austria, Hong Kong, Korea, Luxembourg, Singapore, United States, Taiwan, and Thailand. Among these 11 papers, eight are related to in-service teacher/ leader professional development on STEM education and three are related to pre-service teacher training on STEM education.

The first paper, "Teachers' Professional Development with Peer Coaching to Support Students with Intellectual Disabilities in STEM Learning," is contributed by So, He, Cheng, Lee, and Li. Adopting peer coaching as a teacher professional development strategy to support special education school teachers in collaboratively planning and implementing STEM learning activities, So et al. examined effective practices that facilitated intellectually-disabled students to complete the STEM learning tasks and the disparities that influenced the peer coaching process. This study provides the field with new insights into developing capacity-building training for special education school teachers on scaffolding and engaging intellectually-disabled students in STEM education. More specifically, the paper describes the use of technologies to support STEM learning tasks, while balancing inquiry-based learning challenges and students' abilities, while managing teachers' lack of pedagogical strategies.

The second paper, "Investigating Affordances and Tensions in STEM Applied Learning Programme from Practitioners' Sensemaking," is contributed by Wen, Wu, and He. Conducting a STEM learning programme for secondary education, Wen et al. explored the affordances and tensions of school leaders and teachers that emerged in the process of implementing STEM education in schools. The affordances include (a) the common understanding about the essence of STEM learning shared by leaders and teachers, (b) the positive effect of the national initiative of lifelong learning and the elimination of testing related to STEM education, and (c) the flexibility and authority of school-based implementation of STEM education. The tensions include (a) the conflict between examination demands and designed learning outcomes of STEM education, (b) the STEM teacher professional development received by the school teachers and leaders, and (c) the allocation of curriculum time and cost of materials pertaining to STEM learning.

The third paper, "Building STEM in Schools: An Australian Cross-Case Analysis," is contributed by Falloon, Stevenson, Beswick, Fraser, and Geiger. The context for Falloon et al.'s study is the implementation of a national STEM education capacity building project for primary and secondary school leaders that employs a generic learning environment model proposed by the Organisation for Economic Cooperation and Development. In this study, Falloon et al. investigated the factors influencing the development of different schools' STEM profiles, and identified the unique approaches and leadership strategies each adopted in designing STEM curriculum for meeting the learning needs of their diverse students. This work emphasizes the important role of principals in communicating a clear, evidence-based vision for STEM education in schools, and highlights the complex interaction of professional development, leadership, curriculum design, pedagogy, and school culture in developing effective school-based learning programmes and activities for STEM education.

The fourth paper, "Exploring Taiwanese Teachers' Preferences for STEM Teaching in Relation to their Perceptions of STEM Learning," is contributed by Lai. She designed a series of professional development training sessions for secondary school teachers, during which she examined the teachers' contextual preferences when implementing STEM learning activities. The study reveals that teachers' perception of collaboration is the key element in articulating their preference for STEM activities and their attitude toward STEM learning. Moreover, their preference for technical support and classroom interaction positively correlates with their perceptions of higher-order thinking and collaboration, while activity flexibility and teaching assistance positively correlate with their attitude toward STEM learning. This work gives the field a new perspective to design and enact capacity building strategies that address teachers' actual needs in STEM education through creating a collaborative STEM teacher community.

The fifth paper, "Design Principles for Effective Teacher Professional Development in Integrated STEM Education: A Systematic Review," is contributed by Lo. Through a systematic review of the related literature, Lo synthesized 10 design principles for framing and shaping effective teacher professional development programmes/ activities for integrated STEM education. These principles can be divided into seven categories: (a) content focus, (b) use of models and modelling, (c) active learning, (d) collaboration, (e) coaching and expert support, (f) feedback and reflection, and (g) sustained duration. The study identifies content knowledge, pedagogical content knowledge, and sample STEM instructional materials as the three most frequently reported elements of effective teacher professional development pertaining to integrated STEM education. The 10 principles shed light on designing capacity building programmes for STEM teachers and addressing the potential challenges to integrated STEM education.

The sixth paper, "Teacher Professional Development on Self-Determination Theory-Based Design Thinking in STEM Education," is contributed by Chiu, Chai, Williams, and Lin. Drawing on the self-determination theory (SDT), Chiu et al. created a professional development training programme, based on the paradigm of design thinking, to help secondary teachers learn effective STEM teaching and instructional practices. Using a quasi-experimental method (SDT-based Vs. non-SDT-based), they showed that integrating SDT elements into the process of STEM teaching and learning could promote both teachers' and students' perceived competence and intrinsic motivation towards design thinking. This study highlights the importance of the SDT-based teacher-support components (autonomy, structure and involvement) in STEM education, and it contributes to developing an SDT-based pedagogical framework for guiding teachers on how to foster students' motivational disposition towards design thinking.

The seventh paper, "Infusing Computational Thinking into STEM Teaching: From Professional Development to Classroom Practice," is contributed by Jocius, O'Byrne, Albert, Joshi, Robinson, and Andrews. Based on the 3C (code, connect, and create) framework, Jocius et al. developed and carried out a STEM professional development programme for secondary school teachers on how to pedagogically infuse the idea of computational thinking (CT) into their teaching, and then explored how these teachers implemented their CT-infused lessons in practice. Jocius et al. identified three major pedagogical supports (articulating a key purpose for CT infusion, scaffolding, and student collaboration) that the teachers used as they taught their CT-infused lessons; they also revealed the barriers that made the teachers adapt or abandon their lessons. This study sheds light on how to support teachers in applying STEM professional development content to classroom practices, and future research on CT infusion into secondary classrooms.

The eighth paper, "Better Together: Mathematics and Science Pre-Service Teachers' Sensemaking about STEM," is contributed by Lawson, Herrick, and Rosenberg. In the context of secondary mathematics and science teacher education, based on the sense-making theory, Lawson et al. explored how pre-service teachers acquired and deepened their understanding of STEM and STEM education through the course of collective sense-making. Although the facilitation of STEM learning is regarded as a challenging task for pre-service teachers who teach a range of subjects, this work offers the field an empirical example of how teachers can collaboratively work together through drawing on one another's subject-based knowledge. It also shows that focusing on STEM learning through discipline-based practices, data, and appropriate technologies is an effective approach to supporting pre-service teachers as they develop STEM education practices.

The ninth paper, "Using an Enhanced Video-engagement Innovation to Support STEM Teachers' Professional Development in Technology-Based Instruction," is contributed by Ng and Park. In the context of secondary mathematics teacher education, grounded in a blended learning paradigm, Ng et al. designed, implemented and evaluated a video-based pedagogical approach to supporting pre-service teachers in STEM learning. The instructional programme used the following techniques in that support: (a) delivering an individualized viewing experience, (b) keeping a noticing record, (c) providing a guiding framework, and (d) facilitating a combination of individual and collaborative reflections. In the study, they showed that this approach could effectively draw the pre-service teachers' attention to different aspects of technology-enhanced mathematics instructions related to STEM education. Capturing the dynamic processes of learners' actions rather than just their final "answer," this video-based pedagogical approach is effective in facilitating pre-service teachers' reflections about the evolution of learners' mathematical thinking as the students engage in STEM learning activities.

The tenth paper, "Integrated STEAM Approach in Outdoor Trails with Elementary School Pre-service Teachers," is contributed by Haas, Kreis, and Lavicza. In the context of primary school teacher education, Haas et al. investigated how pre-service teachers, using an integrated STEAM pedagogical framework, worked in groups to design STEAM learning activities, using various technologies (e.g., GPS, augmented reality and digital modelling) for use in authentic outdoor trail experiences. Through hierarchical cluster analysis of these learning activities, Haas et al. identified three different patterned clusters, including (a) trails with mainly mathematics tasks, (b) trails with combined mathematics and engineering tasks, and (c) trails with STEAM tasks. This study provides the field with new inspiration for how to empower pre-service teachers to use technologies in the course of designing and implementing STEAM-based learning and teaching activities in outdoor environments.

The eleventh paper, "Implementation of an Andragogical Teacher Professional Development Training Program for Boosting TPACK in STEM Education: The Essential Role of a Personalized Learning System," is contributed by Chaipidech, Kajonmanee, Chaipah, Panjaburee, and Srisawasdi. Adopting a theory of adult learning and harnessing a TPACK-oriented personalized learning system, Chaipidech et al. developed a TPACK-based professional development training programme for secondary teachers with the aim of building the teachers' capacity in STEM education from the perspectives of (a) self-concept, (b) role of experience, (c) readiness to learn, (d) orientation to learning, (e) internal motivation, and (f) need to know. The results of this study highlight the effectiveness of incorporating andragogical principles and practices, as well as adopting the personalized learning system, in designing and implementing teacher professional development training on STEM education.

3. Conclusion

In the past few decades, many promising educational reforms and innovations have failed because the programmes did not help teachers develop their capacity to employ those reforms and innovations (Fullan, 2007; Jong, 2016, 2019a; 2019b). Although STEM education places significant emphasis on students' self-directed and constructive role in the learning process (Chai et al., 2021; Huang et al., 2020a, 2020b; Li, 2020; Lin et al., 2021b; Williams et al., 2019), teachers still do play a crucial role in supporting students in achieving the learning goals that underlie the STEM learning activities (Cavlazoglu et al., 2017; Geng et al., 2019; Lau et al., 2020; Lin et al., 2021a; Margot et al., 2019; Weng et al., 2020). We believe that the 11 papers published in this special issue can provide the field with new inspiration to design, implement, and evaluate professional development programmes for empowering teachers to develop effective pedagogical practices for STEM education.

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Teachers' Professional Development with Peer Coaching to Support Students with Intellectual Disabilities in STEM Learning

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ABSTRACT: In recent years, STEM learning has become a new education initiative worldwide. However, little research has considered the needs of students with Intellectual Disabilities (ID) in this initiative. Believing that individuals with disabilities should be evaluated and defined by their capacity, strengths, and broad range of interests and abilities, this research investigated this less-explored perspective in STEM learning, namely supporting teachers providing STEM learning for ID students. Four teachers in two special schools for children with intellectual disabilities worked collaboratively with each other in their schools to plan and implement STEM learning. Peer coaching was recommended to the teachers in order to improve their planning of STEM learning and their teaching practices for teachers' professional development (TPD). The qualitative research methodology was used, and detailed analysis of teachers' pre- and post-TPD interviews and reflections to identify good practices that helped ID students accomplish the tasks and disparities that influenced peer coaching was performed. While challenging, with support from peers and due considerations of the special learning needs of ID students, this research provides useful insights for teachers to support ID students in STEM learning, including the use of technology in the STEM learning design, the consideration of inquiry learning based on students' abilities in implementation, and the focus on teachers' disparity and school involvement with peer coaching.

Keywords: Teacher professional development, STEM learning, Peer coaching, Students with intellectual disabilities

1. Introduction

1.1. Education for students with special educational needs

The application of a general curriculum for all students, including students with special educational needs, before the turn of the last century, was proposed by the Individuals with Disabilities Education Act (IDEA) in the United States. Later in 1997, amendments were made to the IDEA requiring that "individualized education programs of students with disabilities include information about student engagement in and access to the general curriculum" (Wehmeyer et al., 2001, p. 327). This was to raise the standards for students with disabilities to ensure they attained levels of proficiency similar to those of their peers without disabilities. In Hong Kong, it was not until 2001 that there was a call for a general curriculum for all students, the rationale of "One Curriculum for All" by the Curriculum Development Council (CDC) being that "all children, whether or not requiring special educational services, have basically the same needs and should not be distinguished from each other." (CDC, n.d., para. 2) The Hong Kong government adopts a dual-track mode of providing special education. The Education Bureau, subject to the assessment and recommendations of specialists and the consent of parents, refers students with more severe or multiple disabilities to aided special schools for intensive support services. Other students with special educational needs (SEN) attend ordinary schools. Among the 60 special schools in Hong Kong, the majority are schools for children with intellectual disability (ID).

1.2. STEM learning for students with mild intellectual disabilities

In recent years, STEM (Science, Technology, Engineering, Mathematics) learning has been considered equally important for all learners. It is advocated by the Education Bureau of Hong Kong that STEM learning should critically equip young people with the skills and knowledge they will need to succeed (Education Bureau, n.d.).

Yet, research studies (Hwang & Taylor, 2016; Obi, 2014) reported that students with disabilities were under-represented in the STEM learning initiative.

Students with ID were defined as "significantly subaverage general intellectual functioning existing concurrently with deficits in adaptive behavior. And manifested during the developmental period that adversely affects a child's educational performance" by the IDEA Amendments (IDEA, 2018, Sec.300.8). They are always considered to face difficulties in using memory strategies and metacognitive strategies, with significant limitations in their cognitive functioning, problem-solving and generalization of previous knowledge (Stavroussi et al., 2010). As this may limit ID students' engagement in STEM learning, it aroused our attention to provide professional development (PD) support to teachers of special schools with ID students so that these students would not be deprived of STEM learning opportunities.

It is strongly encouraged by the National Science Teacher Association (NSTA) (2017) to develop strategies for overcoming barriers to ensure that all students benefit from good science education and achieve science literacy. Contrary to the misconceptions that students with disabilities cannot be successful in STEM (Bruce-Davis et al., 2014), researchers have suggested that, "for the pupils with mild intellectual disability, it is typical the superiority of the concrete and objective thinking, and their logical thinking is closely connected to reality and to concrete situations" (Dostál et al., 2016, p. 3). STEM learning is valuable for enhancing the quality of students' daily life, especially for those students with disabilities, by equipping them with content knowledge and skills to solve complex problems in the real world (Hwang & Taylor, 2016; Obi, 2014).

There is an emphasis on the importance of science inquiry and teachers' support with the provision of essential steps to manage the cognitive load of students with ID (Lee & So, 2014). There have also been suggestions to adapt STEM learning for ID students, suggesting: (1) breaking down tasks into smaller steps, (2) dividing the tasks based on students' ability, (3) expanding background knowledge, (4) providing relevant tools, and (5) taking safety precautions (So et al., 2019). Besides, although problem-solving skills are the basis of all learning and are thus essential for ensuring access to the general curriculum for students with disabilities, these students have few opportunities to receive problem-solving training (Agran et al., 2002). STEM learning provides ID students with opportunities to develop their problem-solving skills in real-world settings.

1.3. Teacher professional development need for peer coaching on STEM learning

In the research of Margot and Kettler (2019), teachers felt that they lacked peer support, whereas they believed that if they were provided with united collaboration with peers, district support, prior experiences, and effective professional development, their efforts to implement STEM learning would be better received. Lee and So (2014) concluded in a previous study that teachers should take an active role in ensuring that the appropriate inquiry-based learning process is used to cater for students' learning needs so as to develop their fundamental inquiry skills. Liew (2016) stated that, traditionally, the improvement of teaching practices has been left to individual teachers to work out on their own, and there has been a lack of support, feedback, or follow-up. Hence, the increasing challenges in teaching requires peer supports that offer more opportunities for teachers to engage in self-reflection, share their classroom experiences, and facilitate mutual growth in teaching.

The development of high-quality teachers positively affects students' attitudes and motivation regarding STEM (McDonald, 2016). Peer coaching has been found to be an important tool for professional development. Peer coaching refers to the "sharing of information and experiences among two or more peer teachers to improve their teaching practice" (Hsieh et al., 2019, p. 2). The National Staff Development Council identified the concept of teacher peer coaching as part of the effective components for professional development programmes in 2001. Peer coaching was initially proposed in the in-service teacher professional development and then adapted for pre-service development since the 1980s (Lu, 2010). It was concluded that peer coaching offers unique advantages and much value for preservice teacher education. However, such teacher professional development programmes should empower the potential peer coaching for prospective teachers' progress development, then organize, balance and be followed by constant evaluation. Peer coaching is widely used in teacher professional development (Wong & Nicotera, 2003; Zwart et al., 2007; Zwart et al., 2008), which attempted to enhance the quality of teaching and learning in the classroom. Thus, peer coaching has been used to equip teachers with early literary instruction, and has also been promoted in special education (Swafford, 1998).

Peer coaching may include out-of-class and in-class activities (Robbins, 1995; Showers & Joyce, 1996). Out-of-class activities include co-planning, study groups, problem solving, and curriculum development. In-class forms of coaching typically involve teachers in observing one another's teaching. Pre-observation conferences set the stage for observations, and the teacher requesting assistance describes the desired focus of the observation. Post-observation conferences provide opportunities for the teacher and coach to discuss, analyse and reflect on classroom instruction.

1.4. The current study

In the implementation of "One curriculum for All," several hindrances have been identified that prevent students with ID from enjoying the same learning opportunities enshrined in the central curriculum. These hindrances are mainly related to teachers, and include: (1) teachers' skeptical perceptions and attitudes towards the change; (2) lack of guidance for schools to develop the necessary school-based curriculum and assessment system; (3) teachers' low expectations of students' learning needs and cognitive ability; and (4) lack of direction and training for teachers to change from skills-based instruction to developing students' cognitive ability and problem-solving skills (Humphreys, 2009; Li et al., 2009; Wong, 2015). Teachers' lack of knowledge and skills regarding how to include students with disabilities in their practices is a barrier to students' learning (Alston & Hampton, 2000). Therefore, peer coaching was employed in this teacher professional development to equip teachers well for STEM education for students with ID.

This research made reference to the design of STEM learning using contemporary technologies for mainstream students which have been found to be successful (Dogan & Robin, 2015). Professional development support was provided to teachers from special schools for children with intellectual disabilities to experience STEM learning in order to gain more knowledge and skills, and to practice the use of contemporary technologies. Afterwards, teachers were entrusted to apply the related skills and practices, with consideration of pedagogical concerns of students with ID and strategies to lower students' cognitive load for their better engagement in learning. Since STEM learning is a new initiative for special schools, peer coaching was recommended to the teachers involved in order to improve the planning and practices in the classroom. Figure 1 shows the conceptual framework of the research.

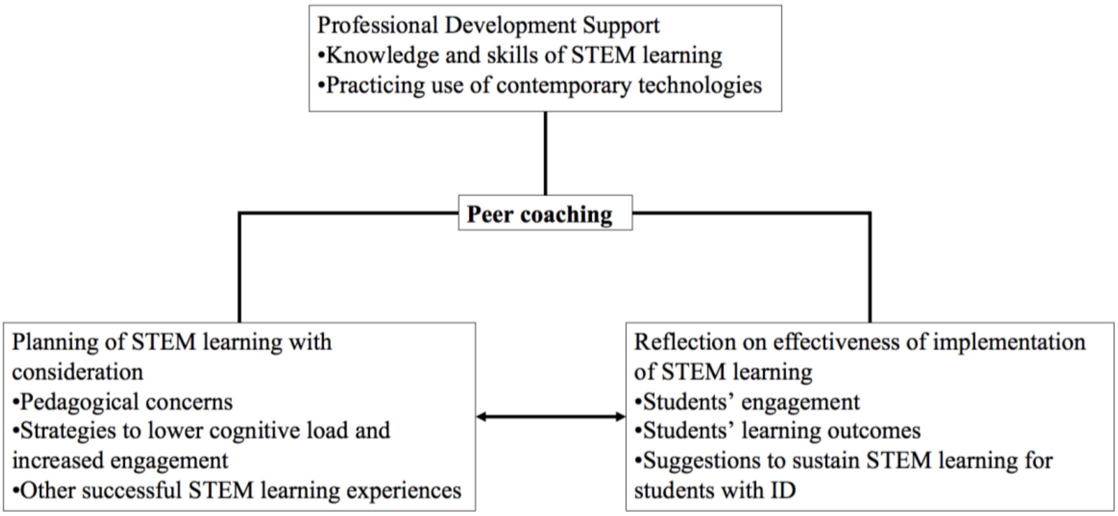

Figure 1. Conceptual framework of the research.

The following are the three research questions:

- What are teachers' prior perceptions of ID students' needs and peer support for professional development?
- How do teachers employ strategies in planning and implementing STEM learning to meet the needs of students with ID?
- How do teachers work by peer coaching in planning and implementing STEM learning for students with ID?

2. Methodology

2.1. Participants

The four teachers who participated in this teacher professional development support were from two special schools for children with intellectual disabilities with their classes of ID students. There were 10-12 students in each class, with students of different degrees of mild intellectual disabilities. Two teachers from the same school

(Teachers C1 and C2 from one school and Teachers K1 and K2 from another school) were considered as a peer group, and they all have at least 3 years of teaching experience in General Studies, a core subject at the primary level integrating science education, technology education, and personal, social, and health education, which is suggested in the primary school curriculum to provide students with appropriate STEM learning opportunities. The years of teaching experience and the subject background of the four teachers are summarized in Table 1.

Table 1. A summary of years of teaching experience and the subject background of the participating teachers

Schools	Years of teaching experience	Subject background
School C		
Teacher C1 (Male)	3 years of teaching GS	GS and IT
Teacher C2 (Female)	10 years of teaching GS	GS and Chinese language
School K		
Teacher K1(Male)	3 years of teaching GS	GS and IT
Teacher K2 (Female)	5 years of teaching GS	GS

2.2. TPD programme and procedure

The participating teachers took part in the following peer coaching support TPD events related to STEM learning:

(a) Teachers experienced and worked with some authentic STEM activities and contemporary technologies (e.g. coding device of Micro:bits, VR glasses, 3D printers, LEGO WeDo 2.0, App Inventor) designed by the research team in a 2-day workshop.
(b) The research team provided discussion on the pedagogical concerns from research studies on students with ID working on STEM or science learning.
(c) The research team introduced approaches to support students with ID in STEM learning by managing students' cognitive load.
(d) Taking into consideration the pedagogical concerns, teachers in peer groups worked on adapting and modifying one of the STEM activities they experienced during the workshop and planned for implementation in their own classes of students with ID.
(e) Teachers' reflection on the planning and teaching effectiveness with ID students at the end of the TPD support, followed by a debriefing session.

The peer coaching model of professional development (Liew, 2016; Soisangwarn & Wongwanich, 2014) that was used to improve student learning was recommended to the peer group by helping teachers to be involved in reflecting on their practice, while sharing successful practices and suggestions, and/or learning from and with their peers.

2.3. STEM learning design of the TPD programme

The topics selected by the school teachers from the two special schools (School C and School K) in this research were from the General Studies curriculum; one was about the design of an "Alarm system" under the topic "The Opium War" and the other one was about "Printing" technology under the topic "Four great inventions in ancient China."

In the Opium War alarm system topic, students first learned about the causes, processes and consequences of the Opium War. Afterwards, there was discussion of the use of different technologies including weapons, alarm systems, and communication systems during the war. The teacher made use of the old technology of alarms used during the Opium War to stimulate students to think about what they could design nowadays with contemporary technologies for an alarm system. This included a learning process which engaged the ID students in hands-on and minds-on opportunities, with the design of an alarm using the coding device of Micro:bit, which functioned when the infra-red sensor detected something approaching; the connected RGB LED bar and buzzer would be turned on. At the end of the lesson, students were encouraged to suggest how and where the designed alarm could be used on their school campus.

For the topic of printing technology, which was one of the four great inventions in ancient China, students were familiarized with the concept of printing by writing their names and using seals on worksheets. They also watched videos of ancient stories about the invention of printing in ancient days. The teacher then stimulated students to think about how the coding device (Micro:bit) they learned to use before could simulate the printing technology to print out a greeting such as "Happy New Year." The teacher provided each student with a Micro:bit and arranged them to work in groups, to use coding to individually create an alphabet, and later to group the letters into the greeting "Happy New Year" to experience the concept of ancient printing.

2.4. Analytic framework

A qualitative research methodology with teachers' pre- and post-TPD interviews and reflections was employed to consider the perspectives and experiences of teachers during their planning and implementation with peer coaching support for ID students in STEM learning. Teachers were interviewed at the start of lesson preparation to know more about teachers' pedagogical concerns regarding students with ID in STEM learning, and after the implementation of the lessons to capture the effect of peer coaching. Moreover, teachers were asked to reflect on the effectiveness of the implementation of STEM learning with consideration of students' engagement and learning outcomes, and to make suggestions to sustain STEM learning for students with ID.

The interview questions were designed referring to projects involving collaboration between teachers and researchers to devise an intervention suitable for enhancing students' engagement and learning of science and mathematics (Bargerhuff, 2013; Ruthven et al., 2010), to address primary support and challenges to learning of students with disabilities, and to translate promising pedagogical principles into an operational apparatus for viable professional practice in STEM education. The following were the two revised interview questions (Bargerhuff, 2013) about students with ID: "What are the primary supports to STEM learning for students with ID?" and "What are the primary challenges to STEM learning for students with ID?". Three interview questions were also revised about peer coaching (Ruthven et al., 2010): "What are the key factors that shape patterns of peer coaching?", "What can be learned from this teacher professional programme with peer coaching to inform more effective further design and professional development?" and "How do teachers use peer coaching to understand and address key challenges of students with ID in STEM education?"

Moreover, the peer coaching model of Zwart et al. (2009), including the teacher level of *Trajectory*, *Interaction*, *Dyad*, *Individual* and the school level of *School* (Figure 2), was also included in the design of six interview questions to guide teachers in identifying the experiences and challenges in peer coaching at both the individual and school levels. In the post-interview, Zwart's model was used to encourage the teachers to share how peer coaching affects teachers' STEM practices and their professional development. As a result, there were 21 questions in the pre-interview and 24 questions in the post-interview in the following aspect: (1) the learning difficulties of ID students, (2) the strategics of supporting practice, (3) teachers' perceptions of STEM learning for ID students and peer coaching for professional development.

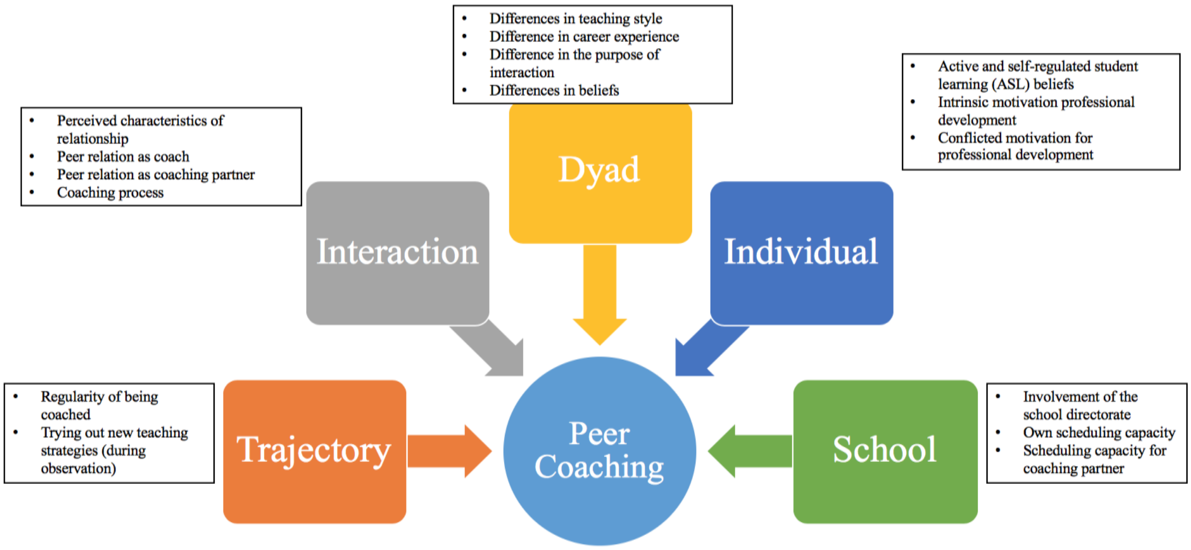

Figure 2. Peer coaching model (Zwart et al., 2009)

3. Findings

The interviews and reflections were independently coded as themes in NVivo 11 by two researchers. The research team conducted the coding repeatedly, then compared and revised the coding until all the codes were consistent (Strauss & Corbin, 1990). Concepts were identified and categorized as codes for further analysis. To answer the first research questions, the concepts related to teachers' prior perceptions of ID students' needs and peer support for professional development during the pre-interview analysis were identified. To answer the other two research questions, teachers' use of strategies in planning and implementing STEM learning to meet the needs of students with ID and how peer coaching supported this were captured during the post-interview analysis.

3.1. Teachers' initial perceptions of STEM learning for ID students and peer support for professional development

Participating teachers were invited to the pre-TPD interviews to capture their initial perceptions of students' needs for STEM learning and peer coaching for teacher professional development. The data were analysed based on teachers' views on two main aspects of STEM learning: (1) learning difficulties of ID students and strategies of practice supporting students' learning; and (2) support of peer coaching for teacher professional development.

3.1.1. Learning difficulties of ID students and strategies of practice supporting ID students' learning

For the *learning difficulties of ID students*, Teacher K1 responded that his students usually had dyslexia, while Teachers K2 and C1 reported that it was not easy for their students to understand concepts. Teacher C2 observed that her students with ID were weak at problem solving and creativity. All teachers emphasized that although ID students liked to explore and inquire, they were only able to work on tasks of appropriate levels of difficulty, and there should be strategies to meet ID students' needs. For example, Teachers C1 and C2 considered that learning related to real problems would help ID students engage in learning, Teacher K1 suggested the usefulness of providing different learning activities, whereas Teacher K2 proposed the importance of students' sense of success in completing the tasks.

I found students having difficulties with basic teaching methods, such as writing and reading. But I had more chances to use electronic devices, which might help ID students understand concepts of different levels …… Students were more interested in the use of different tasks, and they liked to explore and inquire even if the concepts were difficult. (Teacher K1, Pre-TPD)

Our ID students lacked basic concepts…… However, if we provided opportunities for ID students to try to make some easy models, they would be impressed by that…… and it should be related to their life. (Teacher C1, Pre-TPD)

I thought ID students were weak at problem-solving and creativity……We could break down the tasks and let them know everything in order. And school should provide more opportunities for them in inquiry because of their lack of life experience. (Teacher C2, Pre-TPD)

Regarding *practices supporting ID students' learning*, although the participating teachers indicated that students would be curious and interested in the STEM learning, Teacher K1 stated that ID students would be restricted by their lack of abilities in performing different kinds of tasks. Teachers agreed that some teaching strategies would help ID students in STEM learning. For example, three teachers proposed the design of tasks with interesting and hands-on activities and experiments to meet the needs of ID students. Teacher C2 proposed that breaking down the tasks into small steps would facilitate students' success in completing the tasks. Although the teachers thought that they faced many difficulties and had little experience with STEM learning, there would be room for them to reflect on planning and teaching to sustain their professional development in STEM learning.

3.1.2. Initial perceptions of peer support for teacher professional development

When teachers were asked about their views on peer coaching, all of them thought that the *trajectory* of peer coaching was collaborative lesson planning and co-teaching. For example, Teacher K2 considered that teachers could help each other, with senior teachers leading the peer group and junior teachers providing new ideas. They stated various factors which affected teachers' *interaction* in peer coaching, for example, relationships of teachers (Teachers K1, C2), differentiation in subject background (Teacher K1), seniority (Teacher K2), time availability (Teacher C1) and interests in STEM (Teacher C2). The categories of *Dyad* and *Individual* were about the influence of personal characteristics, the emphasis on the importance of knowledge and understanding in the local curriculum and theme (Teachers K1, C1, C2), teaching style (Teacher K2) and the different subject backgrounds (Teachers K1, K2, C1).

For peer coaching with collaborative lesson planning and co-teaching, I thought senior teachers were leading the peer group while junior teachers were providing new ideas, but it might be restricted by the time available. And, the different teaching styles and disciplinary backgrounds might also affect teachers' participation in peer coaching. (Teacher K2, Pre-TPD)

It depends on teachers' interests in the specific topic, which would influence the effectiveness of the teacher interaction. Moreover, the different understandings of the subject and curriculum would be one of the reasons for peer disparity. It might affect teachers' discussion and suggestions. Nevertheless, teachers with different subject backgrounds could offer views from different angles, which might be overlooked previously during planning and teaching. (Teacher C1, Pre-TPD)

All teachers believed that peer coaching took time to develop among teachers with a common goal for professional development (Teachers K1, K2) and assurance by the school policy (Teachers C1, C2). Moreover, they believed that peer coaching support would influence teachers in the planning and implementation of STEM learning. Teacher C1 argued that it might not have much effect on the curriculum design, while Teachers K1 and K2 expected that they could share different duties to cater for students' learning needs in the STEM planning and teaching process. Three of the participants supposed that peer coaching support would help to resolve insufficient complementarity among teachers (Teachers K1, C1, C2), but Teacher K2 stated that peer coaching could help him have more awareness of students' learning diversity of different abilities from his peers. Teacher K1 said that if he were not familiar with Micro:bit, he could learn it with peer coaching support and then understand more teaching approaches. Teacher K2 thought that she just had basic knowledge of Micro:bit, but she could receive many suggestions from peer coaching, which made the STEM practice easier. Teacher K1 proposed that teachers could re-examine the feasibility of ideas, and adjust the depth, method, and content of STEM learning from peer coaching support, while Teachers C1 and C2 raised the support of discussion with other teachers for resolving insufficient complementarity. The two obstacles highlighted by teachers which restrained the current peer coaching support were teachers' different understandings of STEM (Teacher K1) and the limited time and opportunities for communication during the school day (Teacher K2, C1, C2).

peer coaching required continuous professional support. Teachers could share different duties to cater for students' learning needs and re-examine the feasibility of ideas, then adjust the teaching depth, methods, and content of lessons through peer group support…But, it was not easy for teachers to communicate with each other due to their different understanding. (Teacher K1, Pre-TPD)

I considered that peer coaching was important for improving teaching. Teachers could gain various suggestions from different angles through peer coaching support. Therefore, it would resolve insufficient complementarity among teacher…… At the planning stage, there was a need to figure out what ID students were interested in through peer discussion. Yet, at the teaching stage, co-teaching could be used with one teacher as the lecturer and the others assisted the ID students to follow the tasks. (Teacher C2, Pre-TPD)

3.2. Changes in teachers' perceptions of STEM learning for students with ID and peer coaching for professional development

The changes in teachers' perceptions were identified from the comparison and contrast of teachers' interview responses during the pre- and post-TPD interviews, as well as from teachers' reflections. The following paragraphs summarize the new ideas from teachers, namely technological needs of ID students in STEM learning, practices supporting ID students' inquiry in STEM learning, as well as support of peer coaching for teacher professional development.

3.2.1. Technological needs of ID students in STEM learning

It was found in the post-TPD interviews that the teachers were aware of students' learning needs regarding the use of technology, such as the use of electronic devices (Teachers K1 & C1) and coding (Teacher C1). However, ID students were constrained by their low abilities in some difficult coding tasks (Teacher C1), their difficulty in learning collaboratively (Teacher K1) and the technical problems encountered (Teacher K2). Teacher C2 suggested that improving students' interest in the topic by providing more time and inquiry opportunities would increase students' engagement in coding.

For students with ID, how to use some electronic devices for extended learning is one of the new STEM learning needs. I helped students with ID to recall their existing knowledge and to adopt a new teaching model. But the level of students' engagement still differed, and there were problems in the coding activity with collaborative learning due to the differences in students' ability. (Teacher K1, Post-TPD)

I thought students with ID need more chances to do coding and we also tried to simplify the codes in the lesson design. However, it was still not easy for students to follow. Since learning how to use technological devices is important nowadays, I considered that the teaching design should be able to help students with ID to connect their previous knowledge and to address students' learning ability to engage them in more participation. (Teacher C1, Post-TPD & Reflection)

Technological needs were also identified from the coding tasks. Teachers K1 and K2 found it demanding to link STEM learning to daily life with the use of technology. Teachers C1 and C2 worried that too much content was involved in the coding tasks of STEM learning, which overlooked the variation in students' abilities. Yet, teachers also provided suggestions for different abilities in the coding tasks. Teachers K1 and K2 emphasized students' role in meeting the technological needs, with Teacher K1 focusing on cooperative learning with higher ability students guiding the lower ability students, and Teacher K2 focusing on tasks in accordance with different students. Teacher C1 suggested that it was necessary to simplify the Micro:bit coding activity, even though it was mastered with ease by students with higher ability, as students with lower ability had difficulty engaging in the tasks. Teacher C2 suggested more arrangement for students of lower ability to participate more in simplified tasks, or grouping students with different abilities for them to work collaboratively to accomplish tasks of various levels of difficulty.

There was too much content for ID students in one lesson, whereas the coding task with variables might be unfamiliar for the class of students with varied abilities. We also encountered technical problems with the Micro:bit activity. I suggested that teachers should simplify the coding activity or group students with different abilities to work together to complete tasks of different levels, so that both the higher ability and even lower ability students would be engaged in STEM tasks. (Teacher C1, Post-TPD)

3.2.2. Practices supporting ID students' inquiry in STEM learning

The analysis also identified new ideas on practices which support ID students' inquiry in STEM learning in four aspects, including (1) *teaching strategies*, (2) *classroom management*, (3) *students' engagement*, (4) and *students' interest.*

After the planning and implementation of STEM learning for their ID students, participating teachers concluded some effective *teaching strategies* to meet the learning needs of students with ID. The teaching strategies suggested were: heterogeneous grouping with tasks divided in accordance with students' ability (Teacher K1), previous knowledge building for expanding background knowledge (Teachers K1, K2), activities and examples related to daily life to set scenarios for inquiry (Teachers K2, C2), a small-step approach which breaks down the activities step by step for inquiry (Teachers C1, C2), hands-on experience for inquiry (Teachers C1, C2) and adjustment of teaching according to students' feedback (Teacher C1).

Our students had never used Micro:bit before, so we provided some training, knowledge about Micro:bit and coding for students with the help of the IT teachers……The STEM activities connected more to life experiences were able to help students build up a mind with the use of STEM for inquiry to solve a problem. (Teacher K2, Post-TPD)

Teachers also articulated the importance of *classroom management*. Teachers K1, K2, and C2 held similar thoughts that more guidance and management in the STEM learning lessons were needed for students for the reason that they lacked the experience of group inquiry (Teacher K2). Yet, Teacher C1 assumed that if students were sufficiently and actively involved and participated in the lesson, it did not need extra work with classroom management.

Students' better engagement in learning was observed by the teachers too. Teachers K1 and K2 stated that ID students' engagement in learning was more active than before and better than they expected, but they were provided with relatively fewer opportunities to explain thoughts as they were regarded as having difficulty understanding questions from teachers. Teacher C1 reported that his class of ID students were active in working with other students in group inquiry, and they were also eager to explain their thoughts to their peers. Particularly, teachers found the factors affecting *students' interest* in STEM learning. Teacher K1 considered that students with ID were more interested in the electronic teaching kits as they had had few opportunities to use such instruments before. Three teachers (Teachers K2, C1 and C2) agreed that the STEM learning experience with the hands-on activities and electronic devices increased students' interest. Teacher K2 focused on students' sense of success when both Teachers K1 and K2 concentrated on students' gain in STEM knowledge in the tasks.

Students performed better than I expected; they could concentrate on most of the learning activities…… And they also had interest in the electronic teaching kits. After these lessons, students might try to learn more about the electronic devices by themselves, which enriched their interest in STEM. (Teacher K1, Post-TPD & Reflections)

We gave chances to students to reflect on the process of learning; they shared their experiences of STEM learning and this helped to increase their STEM knowledge, interest and confidence. (Teacher C2, Post-TPD)

3.2.3. Support of peer coaching for teacher professional development

For the support of peer coaching for teacher professional development in STEM learning, the changes in teachers' views were also analysed with reference to *Trajectory*, *Interaction*, *Dyad*, *Individual*, *School*, and *STEM learning development*. Teachers C1 and C2 added to the *trajectory* that peer coaching allowed more discussions and lesson planning among peer groups. The two factors concluded by teachers with the peer coaching support influencing teachers' *interaction* were time allowed (Teacher K2) and teachers' different subject background (Teachers C1 and C2). For *Dyad,* all teachers were aware of the differences with individual teachers' knowledge, experience, and style of teaching. Teacher K1 responded that different subject background was an obstacle to peer coaching support because teachers were usually familiar with their own subject background. Most of the teachers (Teachers K2, C1, and C2) believed that teachers' teaching experiences affected their involvement supported by peer coaching, as senior teachers usually had more experience of handling problems. Teachers K1 and K2 added teaching style as the difference of *Dyad*. For the *individual,* Teacher K1 considered that the effectiveness of teachers' interaction was related to individual teacher's engagement in the planning and implementation of lessons.

Teachers had too much workload already, and there was less room and time for us to communicate with each other…… But it was also about my teaching experience for the reason that I did not have such knowledge and ability to have peer coaching with my colleagues if I was not familiar with that topic. (Teacher K2, Post-TPD)

We had more interaction to supplement and complement each other by peer coaching support, but if teachers had the relevant subject knowledge, it would facilitate better interaction. Peer coaching also had disparity in teaching style and teaching experience…… For the individual, time and effectiveness of peer coaching were the important factors. If one did not engage oneself in STEM teaching, it affected the result of peer coaching a lot. (Teacher C1, Post-TPD)

Teachers started to pay more attention to the ways to improve peer coaching at the *school* level to strengthen their professional development. Teacher K1 focused on the pairing-up of teachers for research or new initiatives, but Teacher K2 considered that the heavy workload was an obstacle. Teacher C1 found the integration of teachers' different subject knowledge in the design useful, and Teacher C2 noted the improvement of teachers' relationships as a team.

The changes in *STEM learning development* were found to be supported by peer coaching. Teacher K1 summarized that the peer-supported STEM learning design had clear content for inquiry and layout for students with ID, and was more inquiry-focused in nature. Teacher C1 said he had more chances to discuss with colleagues, so the consideration of STEM learning was broader with suggestions from the peer group. Similarly, Teacher C2 stated that peer coaching helped teachers discuss more how to solve the problems in the lesson design.

Providing teachers with more opportunities for pairing-up in order to have some research or new practices is important at the school level……For the design of the STEM learning, we should teach the content more clearly. (Teacher K1, Post-TPD)

Schools could provide team-building opportunities to improve teachers' relationships for peer coaching……We appreciated the peer coaching support in STEM education because we could be aware of the deficiencies in the teaching design and students' difficulties and work together to solve them. Teachers needed to have a lot of planning and preparation in STEM lesson design, and I was afraid that it was challenging for us to work on it by ourselves. (Teacher C2, Post-TPD)

4. Discussion

Teachers appraised peer coaching with professional development support for planning and teaching, which helped them identify the technological needs of students with ID in STEM learning. After the experience of planning and implementation, the participating teachers reflected on the practices for students with ID, and focused on students' inquiry in accordance with the students' abilities for better engagement in and sustainability of STEM learning. With the peer coaching support, teachers also listed different teachers' disparities that may influence their participation in peer coaching, and school involvement in peer coaching to support students with ID in STEM learning.

4.1. Use of technology for ID students in STEM learning

Teachers' prior perceptions of the learning needs of ID students was almost similar with other subject learning. After the professional development support for STEM planning and implementation, teachers tended to think more about the unique needs of ID students in STEM learning, and reported their technological needs, including the use of electronic devices and coding. In research on increasing opportunities in STEM for more capable students with ID, technology was found to help ID students learn STEM skills and address the industrial demands (Lawler et al., 2018). Teachers in this research agreed that the technology needs in STEM learning offered meaningful possibilities to motivate ID students to use technology, thus fostering students' interest in STEM and related skills. So et al. (2019) also stated that it is important to provide opportunities for ID students to learn about contemporary technologies in science inquiry and engineering tasks during STEM learning.

4.2. Consideration of inquiry learning based on students' abilities

Since the teachers in special schools did not have much experience with STEM learning, they only held succinct ideas that students with ID should be interested and would be active in STEM learning. This research provided teachers with opportunities from design to implementation with peer coaching support, for them to develop enhanced understanding, and better practices to improve students' inquiry learning in STEM learning and to sustain STEM learning in the future.

Teachers proposed the use of adapted strategies/steps to manage the cognitive load of ID students with inquiry learning, such as setting scenarios to introduce the inquiry problems, having clear learning content, breaking down the activities into small tasks and emphasizing the student role (Lee & So, 2014). STEM activities should be designed to be intently related to science inquiry (Maqbool & Hariharan, 2017) and Dostál et al. (2016) also concluded the findings of their research on applying inquiry-based instruction/problem-based learning with students with mild intellectual disability, particularly in science education. Their findings showed that students better acquired scientific terms and had a more positive attitude towards science and technology, as well as having higher motivation and social trust.

However, participating teachers also paid attention to students' abilities in the inquiry process to manage their cognitive load. Asghar et al. (2017) pointed out that complex scientific problems may place high demands on working memory. This might result in a high cognitive load and even overloading. Thus, the cognitive load was a major determinant of learning in problem-solving situations. The teachers understood that STEM learning should be designed according to students' ability, setting different levels of tasks in inquiry learning, arranging heterogeneous grouping and so on, in order to encourage more ID students to engage in STEM learning.

4.3. Focus on teachers' disparity and school involvement with peer coaching

With the support of peer coaching for teacher professional development, teachers realized the importance of managing and balancing teachers' disparity and school involvement when they worked in planning and providing STEM learning for their ID students.

To handle teachers' disparity for better practices with peer coaching, there is a need to build a safe environment that is open to disagreement by teachers. Moreover, Glazer and Hannafin (2006) stated that "emotions and attitudes play an important role in an individual's decision to interact with a peer" (p. 186). The need to take care of different teachers' emotions and attitudes in the teacher professional development support of peer coaching and catering for one's emotion and attitude for a safe and open environment are essential. Thus, teachers are always restricted by time and knowledge of the STEM disciplines (Margot & Kettler, 2019), whereas the participating teachers in this research were able to understand and manage their disparity through learning from each other by discussion, reflection and peer assistance. They were able to think more, thus overcoming the insufficient complementarity and inflexibility in their practices, which has been cited as a barrier to STEM (El-Deghaidy et al., 2017; Lesseig et al., 2016). From the peer coaching model (Zwart et al., 2009) mentioned before that the disparity of teachers may be mainly due to their teaching style, career experience, purpose of teachers' interaction and beliefs. However, it was found in this research that differences in teaching style simulated teachers' learning. Hence, teachers' disparity is a two-edged sword, and how to balance teachers' disparity in the process of peer coaching needs to be explored in future research.

Lastly, teachers mentioned school involvement in teachers' peer coaching because they all regarded that peer coaching was still developing in the school and it was new to teachers. Teachers raised more specific methods at the *school* level for improvement, such as pairing-up, team building, and so on. As suggested by Zwart et al. (2009), schools need to find intrinsically motivated teachers to experience peer coaching, while teachers perceived that school support, guidance, and flexibility were necessary for providing STEM learning opportunities for ID students (Margot & Kettler, 2019). Although peer coaching for teacher professional development was new to the teachers in this research, the practices broadened the teachers' insights regarding both peer coaching and STEM learning.

5. Conclusions

Three key implications were observed by the participating teachers in this professional development about STEM learning with peer coaching. Teachers would employ the following strategies in planning and implementing STEM learning to meet the needs of students with ID, including the needs to use technology for ID students and considering ID students' abilities in the process of inquiry practices. Teachers also gained more insights on working by peer coaching by managing teachers' disparity and school involvement with peer coaching support for teacher professional development. Teachers' STEM professional development with peer coaching can be considered as an approach to encourage more teachers in special schools to become involved in STEM learning and to open the pathway to accommodate students with ID and engage them in today's STEM initiatives.

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Investigating Affordances and Tensions in STEM Applied Learning Programme from Practitioners' Sensemaking

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ABSTRACT: The key role of teachers has been widely acknowledged in education reform and pedagogical innovation, and there is no exception in STEM education. This paper documents affordances and tensions in the implementation of STEM applied learning programme (ALP) through investigating school leaders and teachers' sensemaking of the new approach. Attending to both the individual processing and the social interactive work with issues of coherence, sensemaking theory provides a theoretical framework for analysing school culture and resources and connections between actions and understandings of school leaders and teachers in the programme. In this qualitative case study, semi-structured interviews and focus group discussions were conducted with three school leaders and three teachers from two Singapore secondary schools to identify their prior understandings, shared interaction and interpretations during the practice. The findings provide some insights into implementations of STEM in schools and professional development.

Keywords: STEM education, Applied learning, Sensemaking, Teacher professional development

1. Introduction

In response to the rapid advancement of new technologies permeating almost every sector of society, Singapore launched a lifelong learning campaign, advocating for lifelong learning, continuous education and skills mastery for all citizens in Singapore (Sung & Freebody, 2017). Aligned with this national initiative, the Ministry of Education launches the Science, Technology, Engineering and Mathematics (STEM) Applied Learning Programme (ALP), which aims to support an innovative 21st century learning environment in Singapore schools and encourage the application of academic knowledge learnt in class to real-world contexts (Wu & He, 2018).

STEM education receives tremendous attention in education reform and the key role of teachers is widely acknowledged (Al Salami et al., 2017; Cavlazoglu & Stuessy 2017; Lee, Chai & Hong, 2019). For the positive change in STEM education, teachers have the biggest role to play, as ultimately, they are the ones who will be the implementers of the lessons (Wells, 2008). The driving force of the pedagogical shift lies in the hands of teachers, as they will be driving the inquiry and facilitating the lessons (Margot & Kettler, 2019). While increasing teachers' proficiency levels in content knowledge is important, their pedagogical content knowledge is vital for the pedagogical shift to materialise (Milner-Bolotin, 2018; Wells, 2008).

Majority of existing STEM research on the teacher's role either focused on teachers' self-efficacy (e.g., Lee & Houseal, 2003) or training needs (e.g., Garet, Porter, Desimone, Birman, & Yoon, 2001; Margot & Kettler, 2019). However, there are few studies on how the larger system goals influence practitioners' perceptions and enactment while implementing education reform guidelines (Ganon-Shilon & Schechter, 2018; Gawlik, 2015). Investigating teachers' sensemaking of education policies or instructional approaches is important to their implementation in that usually, teachers' interpretations of their contexts vary widely and diverge from policymakers' interpretations (Penuel et al., 2009). Innovation and implementation also require that school leaders make sense of policies and bridge the gap between internal and external demands (Ganon-Shilon & Schechter, 2018; Weick, 2009). Sensemaking provides a means to analyse how practitioners wrestle with issues of coherence, that emerge from interactions within the practice, associated with curriculum materials, with colleagues and school leaders (Allen & Penuel, 2015). Therefore, drawn from sensemaking theory, this paper documents affordances and tensions in the implementation of STEM ALP in two Singapore secondary schools and aims to provide some insights into the implementation of STEM in schools and professional development.

2. Theoretical framework

Sensemaking describes the ways that active agents "structure the unknown" (Waterman, 1990, p. 41) within organisational settings such as schools (Allen & Penuel, 2015). It involves a noticing of change or difference but includes the potential for integrating difference into one's practice for decision making (Clough et al., 2009;

Dervin, 1992). According to Allen and Penuel (2015), in the process of sensemaking, agents are actively engaged to resolve ambiguity and manage uncertainty within their environment and make retrospective and prospective sense of change. Sensemaking is grounded in both individual and social activity in that it has been a durable tension in the human condition (Weick, 1995). Therefore, teacher sensemaking about instructional innovation or reforms is not an individual matter, but it is influenced by the school environment he or she interacts with.

The sensemaking theory has been used by educational researchers to interpret teachers' responses to new policies or programmes. Drawing primarily on instructional and sensemaking theory, Coburn (2001) puts forth a model of collective sensemaking that focuses on the ways teachers co-construct understandings of policy messages, make decisions about which message to pursue in their classrooms, and negotiate details of implementation in discussion with their colleagues. The findings of the study also highlight the role of school leaders in shaping the sensemaking process. In her subsequent studies, she further investigates how principals influence teachers in learning and enacting new policies (2005). Within the framework of sensemaking, it is also highlighted by Ganon-Shilon and Schechter (2018) that principals' perceptions may contribute to the practice of the complex leadership role in reforms. In short, school-level leadership has been brought into the teacher sensemaking equation. Furthermore, it has been suggested that school culture, routines, and structure are the results of how teachers and leaders in the school notice or select information, make meaning of that information and act on those interpretations to develop culture over time (Gawlik, 2015). Allen and Penuel (2015) call attention to the role of teacher plays in sensemaking by wider contextual factors, such as examination demands and curricular constraints, in influencing or affecting the ways in which a teacher expresses or enacts beliefs or understandings in classroom practice. Their study suggests the need for professional development to engage teachers in sustained sensemaking activity around issues of perceived incoherence to improve the likelihood of implementing instructional practices aligned to standards.

In STEM education, based on the proposition of sensemaking, Holmlund, Lesseig and Slavit (2018) investigate how various stakeholders conceptualise new curricular or instructional ideas that can inform the conversation needed to support teachers' professional development and alleviate challenges to education reform. They indicate that sensemaking can provide a useful framework for considering the influence of institutional and professional contexts in shaping each practitioner's construction of a plausible story of STEM education. In their earlier study, teachers' collective sensemaking of STEM-based instruction in specific learning environments has been underscored (Slavit, Holmlund & Lesseig, 2016). Additionally, in terms of the findings suggested by Gherardi's study (2017), a teacher sensemaking process is often decoupled from his/her actions in regards to classroom technology, but teacher's mindset and cohesion between stated values, policy messaging, policy implementation, and administrator actions appeared to contribute to this process.

Therefore, in this study, sensemaking is adopted to provide a lens to document and analyse how school leaders and teachers perceive and enact their implementation role in the STEM ALP programme. The study follows a qualitative approach to explore school culture and resources and connections between school leaders' and teachers' actions and understanding in the programme, by addressing the overall question: how school leaders and teachers perceive and enact their implementation role in the programme. The study seeks to provide suggestions in the implementation of STEM in schools and teachers' professional development.

3. Method

This study adopted a qualitative case study to document the ways school leaders and teachers make sense of the STEM ALP programme. The cases selected for this study using purposeful unique sampling, for it is an effective type of sampling that provides "rare attributes or occurrences of the phenomenon of interest" (Merriam & Tisdell, 2015, p. 97). We investigated two Singapore secondary schools which implemented the STEM ALP programme. The two case schools that were selected were based on their involvement in the programme and have emphasised the importance of making centred activities or hands-on learning in their schools. In both the schools, STEM lessons were conducted for 3 periods over 2 weeks for 6 months. Within the cases, the selection of interview samples depended on the school leaders and teachers who had been involved in the programme.

3.1. Research context

Since the early 2000s, the Singapore education ministry has tried to broaden the notion of success beyond good academic results (Ng, 2003). Although the need of change from a result-oriented system to one that stimulates creativity and innovation has been supported by the government, schools and students still find themselves stuck in a pressurised exam-driven culture where the primary emphasis is still on students' exam results (Wu & He, 2018). The ministry has highlighted that success in education should not be measured by academic results alone and that more opportunities and multiple skills-based progression pathways should be available to all students of varying abilities.

STEM ALP was introduced in 2013, as a programme to provide authentic learning based on real-world situations in STEM learning (Teo, 2019). The programme draws out content from STEM disciplines that are relevant to existing and projected trends and needs of Singapore's economy (Teo, 2019). In this study, the two schools involved focused on robotics, to highlight how Science and Engineering could work in tandem. The delivery of the STEM ALP programme shared similar objectives with the pedagogy of making in its intention of helping students understand the relevance of what they learn in class to the real world through interactive and hands-on experiences. This programme used educational technologies and hands-on activities that integrate conceptual understanding within the curriculum to applications of real-world scenarios in a non-formal context. STEM ALPs are organised by schools and conducted after formal curriculum time, and students are not formally assessed. It is a big shift away from the examination-dominant culture Singapore is commonly associated with.

Two STEM educators, trained by the Science Centre, were assigned to each school. The STEM educators helped to customise the programme to the school and help with the facilitation of the lessons. After two years, the Science Centre would pull out the STEM educators from the school and the teachers would have to facilitate the lessons on their own. In this study, the Arduino, an open-source electronics platform, was utilised as a tool to control the sea perch. The Arduino platform enabled students to build, program and control electronics. The user would ideally need some basic understanding of electronics and programming although it was not absolutely necessary, as the main idea behind it was that the user would start learning how to use the platform by doing and by experimentation. Most of the teachers did not have prior experience. Yet teachers were encouraged to look for training on their own. There was a budget set aside for teachers to go for external training, but they were required to get approval from their school.

3.2. Participants and school sites

School A is a boy's school. The school is active in organising activities related to Design and Technology (D&T) and robotics within the school and frequently hosts other schools in their zone. During their STEM ALP lessons, students used the Arduino to build the seas perch (an underwater robotic to build an underwater Remotely Operated Vehicle). School B is a Mainstream co-educational school. The school started offering computer studies in 2006 and is now offering computing as an 'O' level subject. The STEM ALP lessons at School B were planned based on the school's niche area in clean energy and environmental technology. Their students also used the Arduino to build the seas perch in STEM APL lessons.

As shown in Table 1, A.D is the vice-principal of School A and has been in the school since 2014. A.T is Head of the Department of Design & Technology and has been teaching in School A for 12 years. Teachers A.J and A.S have had 16 and 9 years of teaching experience respectively. For School B, B.R is in charge of computing and the year head for the lower secondary and has been in the teaching service for more than 15 years. B.W is a teacher at School B has more than 6 years of teaching experience.

Table 1. Research participant profiles

School	Name (Pseudonym)	Role	Years of experience	Sex	Leader or not
A	A.D	Vice-principal	20	M	Yes
A	A.T	Head of Department	> 14	M	Yes
A	A.J	Teacher	16	M	No
A	A.S	Teacher	9	M	No
B	B.R	Year Head	>15	M	Yes
B	B.W	Teacher	> 6	F	No

3.3. Data collection and analysis

Data collection and analysis occurred simultaneously throughout the study year. Four semi-structured interviews and focus group discussions were conducted with three school leaders and three school teachers to identify their understandings of school culture, interpretations of the programme, shared interactions. A sensemaking process could reflect a complex interaction between policy messages, teacher beliefs, and practices (Coburn, 2001;

Gherardi et al., 2017). Therefore, in addition to collecting interviewee's personal information, the guiding questions of the interviews mainly consisted of three aspects: (1) interplay between policy messages and practices: questions related to participants' understandings of the programme and the role they played; (2) interplay between beliefs and policy: questions about participants' understandings and attitudes towards STEM and life-long learning; (3) practices and perceptions: elaboration on the supports they provided or received, challenges they faced in the process of implementation, as well as how they sought to overcome the difficulties. Every interview or discussion ranged in length from 50 min to 57 min, totalled 218 min. All the interview and focus group discussion were audio-recorded and transcribed verbatim. Extensive field notes were taken during the initial classroom observations and during the focus group discussions to ensure that data could be cross-checked with the audio and video recordings.

Thematic analysis was conducted manually to analyse the collected data. Following the 6 steps of thematic analysis (Braun & Clarke, 2006), two researchers first evaluated the transcribed recordings and field notes, and then familiarized ourselves with the data. From the perspective of sensemaking, the researchers (the first author and the third author) looked for the portions of data that related to school culture, curriculum materials, interactions between school leaders and teachers, as well as their interpretations of the programme. After that, each segment of relevant data was coded by the researchers separately. In contrast to the previous stage, this stage was data-driven but not theory-driven. After capturing the essence of the utterances, the first author clustered similar utterances to generalise their meanings and derive categories by considering the third author's coding. Lastly, the final dimensions of categories were confirmed by all three authors together. Data from school leaders and teachers were coded separated and two cases were analysed individually, and next, they were put together to generate common themes. It was an inductive process to generate themes, grounded in the different perspectives articulated by participants (Rossman & Rallis, 2012).

4. Findings

The findings that emerged from the data analysis indicate that four major themes guided the implementation of STEM ALP in schools. They are (1) vision, (2) flexibility, (3) communication and (4) resources. The data and interpretation are presented in the sections below. In each section, we start with School A's data, and data regarding teachers and students from the same school are put together to illustrate the commonalities and discrepancies.

4.1. Vision

As a general observation, for both the schools, the vision of the school leaders plays a crucial role in the possibilities of establishing and implementing STEM ALP, although these two schools differ in their development track and curriculum culture. The teachers can fully understand their school vision and identify with it.

According to A.D., a vice-principal of School A, the school's strong D&T culture was one of the factors that paved the way in supporting ALP in the school. The strong D&T culture was shaped by the vision and leadership of the former school leader, who viewed D&T as a vital part of education. At school A, D&T was taught with the objective of empowering students and equipping them with problem solving skills and design thinking skills. Problems were presented in class and students were invited to come up with creative solutions in response.

Another factor that influenced the school's development of ALP was the school leaders' analysis of the students' learning styles and choices. To cater to the learning needs of the students, the school had analysed their tertiary choices and discovered that a large percentage of the students ended up in engineering related courses. The school administration decided to take a more deliberate approach to help the students develop their engineering skills and it was by adopting strategies based on the understanding of how boys learn. The basic principle in an all-boys school, as the vice-principal A.D. explained, is to adopt "practices in understanding hearts and minds of boys." Teachers from School A could sense this special culture of the school. Teacher A.J. from school A said,

Our school is quite level headed when it comes to this kind of thing because we see it not so much from the perspective that the school wants to have a lot of achievements, though that is something that every school desires. More importantly, we view it from the student's perspective that we can provide them with a variety so that they can choose.

On the other hand, both teachers (A.J. and A.S.) from school A also expressed concerns about examinations. The following excerpts demonstrate how the examination demands have affected their perceptions.

No matter what we do, we must always remember students are taking their exams and it's the results that bring them to the next phase of their life. They can be very good, but the "O" levels cert won't say this student maybe 25 points but ALP excellent. It's not written there.

The process is important, the deliverables are also important because ultimately they have to meet the exam requirements ………So as educators we must always go back to our KPI. […] Of course, we want to equip them with as many skills as possible. Cannot - results never mind, the government say focus on skills […] They do need the results at last in these few years.

Teachers generally appreciated that STEM ALP is a non-examinable subject and one commented that "students will probably be more receptive towards ALP since they're not being assessed." Still, teachers did feel that a balance was needed in terms of assessment and some form of assessment should be in place to get students "a bit more interested in whatever they are doing. To get them to take it a bit more seriously but also to give them feedback. To let them know if they are on the right track." Teacher B.W from school B commented that some students did not take ALP seriously as it was not graded and would work on developing a qualitative assessment system that would provide some feedback for the students. He explained that

The feedback is very important if not they just play around and then go off. We want them to take away so after going through, playing exploring, understanding what's the takeaway. We want them to internalize, verbalise.

School B's computing background plays a strong role in the school's learning culture. According to B.R, a leader of school B, the role of computing was highlighted in the school and explained how computing can be used as a significant tool in any subject or field of expertise. Since 2009, the school has been trying to integrate computing into core subjects, instead of having computing as a stand-alone subject. B.R highlighted that the students do not study "computing for the sake of computing'' as the students would not know how to apply it. She further explained that they did not want the students to see computing as just another programming tool, but as a platform for creative innovation, to cultivate students' analytical and problem solving skills.

From the teachers' experience of School B, infusing computing into core subjects has been an effective way to engage students. The computing department collaborates with the Science, Math and D&T departments and uses computing tools to help students learn through a hands-on approach. For instance, when the teachers found it hard to engage students during biology lessons, the computing and biology teachers came together and developed a package to teach concepts about digestion. Their students were first taught digestive concepts, followed by the programming tool, scratch. The students, now equipped with both biology concepts and basic programming, were asked to work on a project to create a storyboard on the movement of digestion. The teachers found that it made lessons more interesting and engaged students more effectively. The students had to internalise what they were learning and began to understand the seemingly dry concepts better. More importantly, the teachers can determine if the students have fully understood the topic by looking at their story boarding, and their thinking process.

In sum, the central notion that the school leaders and teachers shared is that the idea of STEM ALP is being explored to meet the learning needs of students with different learning styles and creating a sustainable learning ecology for lifelong learning. Contextual factors ranged from school's culture to examination demands, influence or affect how teachers expressed or enacted their beliefs.

4.2. Flexibility

The implementation of the programme involves changes at the teacher and school levels. Each school possesses its uniqueness in development in the programs, jointly defined by its historical trajectories and contextual conditions. In analysing the focus group responses of teachers and school leaders, we also noticed that schools and teachers have some freedom to implement the policy.

The school leader from school A (A.D.) said they realised that older teachers who were more conventional were more resistant, while younger teachers were more daring and willing to try new approaches, but they were not so experienced and lacked subject knowledge. The school's strategy was to adopt a "community of learning," where they would organise discussions and deliberately break the teachers into groups and mix the young and old teachers. They found that these discussions as a group on teaching methods were effective as the teachers could influence and learn from each other. A.D observed that from the "community of learning," it evolved to "a community of sharing" and from there, a "sharing program" where all departments have teaching packages so they work in groups to develop teaching packages. He cited an example that

[…] the older teachers will say, I don't know computers very well, I am not a digital native, the young teacher will say, never mind I will do this package for the class, I'll share with you […] through the community of learning we also have a community of sharing, so of course […] all should have sharing program and all departments have teaching packages so they work in groups to develop teaching packages.

The teachers of school A stated that they had the freedom to choose the domain and design and preparing learning materials by themselves based on the structure of the design prepared by the vendor (the Science Centre). The school leaders met with the vendors and introduced them to teachers. Teacher A.S. explained that

we need to follow the domain that we've chosen, which is robotics. Key is science and tech, engineering maths. The components or rather the syllabus must have the components engineering design. These are not restricted. These are the instructions given to us. This is the domain the school ticked this domain; these are the requirements we have to follow.

However, Teacher A.S. also mentioned that the risk assessment was very strict in the STEM ALP project implementation. He said,

under the current framework, there're a lot of things we can't do because of the risks involved. Anything we do must undergo risk assessments. School leaders, MOE got to approve before we can proceed.

According to B.R, teacher sharing also played a role in the development of ALP in School B. Some of the teachers were straddling between two subject departments. For instance, a teacher could be teaching both science and computing and collaborating with the math department. The teacher would share resources, experiences and influence other teachers to embark on cross-curricular instruction between multiple subjects. Infusing computing into core subjects was an effective way to engage students. As some teachers were also new to computing, the process of sharing with others would help them to internalise their knowledge. Teacher B.W further explained,

[…] we tweak the timetables so that they coincide at the same time. There are times of course one of us not around but most of them we are there […] we are together.

B.R shared that in the last year due to teacher sharing, the humanities department worked with the computing department and got students to make short animations and games. The teachers of School B were encouraged to not only share within the school but to share with other schools and communities. This culture of sharing also extended beyond the teachers to that of the students. The students were given opportunities to share in other schools and also at other community activities.

On the other hand, because of the close collaboration with external vendors (the Science Center), teachers in School B had limited flexibility in setting learning objectives and content. Teacher B.W said,

the design part was kind of done by the science centre so our own teachers didn't really have that much of a role in the design of the package, the whole ALP package. It's just the conducting. […] like me, science teacher, I had no background on computing and till now, even though it's our second year that we are doing it, I also have kind of struggle with programming part, which is why we decided to collaborate with the computing department because the teachers there have more experience.

Schools implemented the programme in diverse approaches, but the collaboration culture is the common vision we captured. The collaboration includes internal collaboration across departments, as well as collaboration between schools and external vendors. Both teachers and schools have some autonomy in deciding who to work with and how to work, though the process of risk assessment of curriculum content is strict.

4.3. Communication

The ways in which school leaders communicate with teachers are instrumental in the teachers' execution of initiatives. A.T., the head of the department of D&T in School A, shared that having dialogue sessions with the teachers are important and that the school is very "mindful" before rolling out any changes. He said, Teachers experience school leaders first. MOE has a lot of policies but how we want to roll it out in the school is something we can take …. Because if you don't think through and you are very careless in rolling out certain policies, you will affect the teachers. And that will affect the students.

The communication between schools and parents is also emphasised. As B.R. of School B stated,

It's also communication. We do send letters, during parent teacher's session we do talk about it and then also for example for scratch we want to be a bit more serious in not just play around.

Additionally, she also highlighted the role of government, saying that

It's good now we have a nationwide initiative, and they engage parents. Thru all this sharing and also in schools we do a lot of sharing. The awareness is there but still, parents are a bit reluctant […] for a start the government is doing a good job in terms of pushing it.

4.4. Resources

As the Arduino is an open-source platform used for building electronics projects, the user would ideally need some basic understanding of electronics and programming although it was not totally necessary. The main idea behind it was that the user would start learning how to use the platform by doing and by experimentation. Most of the teachers did not have prior experience and most were uncomfortable with not having basic knowledge of both electronics and programming. Not only preparing for lessons time-intensive, but they also did not have the time to start experimenting on their own. As a result, they needed the support of STEM educators. Teacher B.W. from school B was worried that once the science centre pulled out the STEM educators from the school, they would have trouble coping.

School A leader A.T. described how the school tried to manage teacher training, by starting small with one department and conduct regular training sessions with not only the students but also with the teachers. They started by introducing scratch. A.T said,

To be a whole-school approach we started small with the science department. … but we not only trained the students, we also trained the teachers on how to use this (scratch), how it is important. The process we go through is mind mapping, storyboarding, analysing data, so there are some of the things the teachers go through to understand. Of course, it takes time for them to pick so it took about 2, 3 years before most of the teachers become fluent in using scratch.

Of crucial pedagogical importance in the STEM ALP approach is a shift away from dispensing ready-made knowledge to an environment that facilitates exploration. It appeared that not all teachers were ready for this pedagogical shift. Some teachers adopted a more task-oriented approach and were conservative in giving the students autonomy. However, in school A, the teachers felt that there were insufficient training and support for conducting STEM ALP lessons. According to them, for each topic, they only received a single training session within one afternoon, and this was inadequate for them to be proficient enough to conduct ALP lessons on their own. Although STEM educators were assigned to support teachers in conducting lessons, the turnover rate of these educators was very high. As a result, teachers often have to figure out how the lessons should be conducted in their absence. Furthermore, materials for lessons were not provided in advance before the lesson, and teachers have to put in substantial time on top of their regular workload to prepare the required materials for ALP lessons. Teacher A.S commented that

ALP is not like teaching in class, (where) we take the textbook and we just start teaching. We need to prepare the materials but it is not given to us, and I spend most of the afternoons preparing for the next day's lesson.

In School B, support from STEM educators was good and the STEM educators helped with facilitating and preparing the materials well. However, the organization providing the STEM educators would be pulling out next year. Teachers were going to face logistical and time issues and to prepare and test the equipment before each lesson.

All the teachers have expressed that they were overwhelmed with a large number of maker-centred programmes in the school and have insufficient time and energy to focus and do a good job with the programmes. A teacher commented, Right now, we have so many programs going on […] all these things take up resources, time and space, and there is no one particular envelope under which they all come under.

Cost constraint is another issue. The costs of equipment and materials needed to conduct ALP lessons are substantial, and this places constraints on what can be done during lessons. The program budget only allows an additional 10% of excess materials, hence there are not enough resources to allow students the freedom to make mistakes, iterate and learn from the process. Teachers expressed that they would like the students to experiment a lot more, however, they are forced to put in "controls and boundaries" during the lessons. "If 50% (of the students) make mistakes then we can't run the programme" teacher A.S explained.

5. Discussion

This paper presents the results of school culture, resources and connections between actions and understandings of school leaders and teachers in the implementation of the STEM ALP programme in two Singapore secondary schools. The research question that guided the study was how school leaders and teachers perceive and enact their implementation role in the programme. In this section, we will revisit the findings and discuss the affordance and tensions in the programme from the practitioners' sensemaking.

Our findings show all the school leaders and teachers participating in this study share a common idea about the essence of STEM ALP, which is meeting the learning needs of students with different learning styles and creating a sustainable learning ecology for supporting lifelong learning. It appears that by capitalising on and catering to students' varying abilities, a learning environment can be instrumental in paving opportunities for students to learn based on their interests, with an emphasis on ownership and relevancy. In doing so, students develop skills and competencies that go beyond routine cognitive tasks, such as the ability to critically seek and synthesise information, the ability to create and innovate (Dede, 2010). However, the findings also reveal that teachers perceived the conflict between examination demands and the designed learning outcome of STEM ALP. STEM ALP is a means not just for students to develop and cultivate interests, but also for the MOE to lessen the stress and emphasis on summative high stakes exams. It has been supported in existing studies (e.g., Coburn, 2005; Penuel et al., 2008) when the reform initiative is coupled with an intense and pervasive message about their importance and meanings, teachers are more likely to transform their practice. Our study further confirms the positive role of the national initiative of lifelong learning and the non-examination of STEM ALP in the implementation of STEM. The effectiveness is not only reflected in teachers' enactment but also in the communication between schools and parents.

On the other hand, our qualitative analysis of interviews also indicates that the approaches to implementing STEM ALP are very different in schools. As shown in the findings, each school possesses its uniqueness in development in the programme, and it is the result of sensemaking by school leaders taking account of historical trajectories and local resources. As shown in the findings, School leaders expressed the opinion that they should use their discretion as leaders of a unique setting. School leaders are sense-makers who enact their interpretation to promote their local interests (Bridwell-Mitchell, 2015), which affects how the programme is implemented. This practice is congruent with the suggestions drawn from the existing studies that school leaders make key decisions which they should emphasis to teachers and which they should filter out (Honig & Hatch, 2004; Ganon-Shilon, & Schechter, 2018). With the school leaders' understanding of the importance of the programme, they ensure that the involvement and empowerment of staff are necessary, and where necessary to provide support for changes to grow from the willing participation of all teachers.

Meanwhile, in both schools, the ways school leaders communicate with teachers are instrumental in the teachers' execution of initiatives. This echoes previous research that suggests the key role in setting a tone of openness and communication and encouragement of collaboration culture among teachers (Coburn, 2001; Wen & Wu, 2017). The requirement of collaboration across disciplines and professional boundaries in STEM education has been widely acknowledged. However, collaboration is not straightforward (Edwards, 2011). It is pointed out in Christensen and Laegreid's study (2007) that this collaboration effort cannot be easily imposed from the top down. Evidence from our studies support this analysis and also suggest that the collaboration culture is nurtured maybe because of the natural complexity of STEM. Future studies could investigate how teachers' agency increase when they are involving a STEM programme, or how the co-design of STEM activities may support teachers' collective agency.

In addition to collaboration across disciplines and professional boundaries, the need for teachers to undergo appropriate professional development is also emphasised in the field of STEM education. Studies have indicated that teachers' subject knowledge of STEM is positively correlated to their ability and confidence levels in teaching STEM (Nadelson et al., 2013; Lee & Houseal, 2003). In addition to possessing strong content proficiency and multidisciplinary knowledge across the STEM domains, educators require adequate professional development to inform their pedagogical practices to develop and plan a holistic STEM integrated curriculum (Kelley & Knowles 2016; Sanders 2009; El Nagdi, Leammukda & Roehrig, 2018). In the study, we also observed that beyond subjective knowledge, teachers also can or should benefit from pedagogical knowledge training. In the STEM ALP class, there is a need for change in classroom culture and pedagogy that supports students as producers, rather than consumers of knowledge, and the affordances of technology cannot be well appropriated without substantial teacher training and development. In building the teachers' practice in their pedagogical enactment, sufficient training should be designed to support teachers in actively responding to such a change. Teachers who have never experienced these making-centred practices in their own education will have difficulty in making sense of them in their classrooms.

Our study extends the literature on STEM education, providing teachers opportunities for active learning and collective reflection also contribute to their sensemaking of the programme. Similar to findings from Holmlund's et al. study (2018), even when teachers experience similar professional development sessions and work in the same context, they may make sense of what the new pedagogy means quite differently. Studies have indicated that teachers' professional development should provide regular opportunities for teachers to be involved in active learning and reflection with their colleagues (Garet et al., 2001; Looi et al., 2018). In STEM education, teachers need to be provided opportunities to experience active learning, and they need opportunities to engage in collaborative and sustained sensemaking to see, understand, and work through incongruities they perceive between goals and strategies promoted in professional development (Allen & Penuel, 2015).

Teachers' sensemaking is a collaborative, reflective, and interactive process that can surface the differences and commonalities in their understandings to better ensure consistency (Holmlund et al., 2018). Though existing studies have revealed that teachers' sensemaking may be affected by wider contextual factors, such as school culture (Gawlik, 2015), examination demands or curricular constraints (Allen & Penuel, 2015). Our study shows that teachers' and school leaders' sensemaking of the programme, associated with school vision and culture, flexibility of implementation and professional development, curriculum resources, communication with colleagues. The findings also show that there is still some inconsistency between school leaders' and teachers' perceptions of the programme. This inconsistency may be caused by school leaders' and teachers' different roles and responsibilities. Yet the findings of this study underscore that the discrepancy is mainly reflected in the allocation of resources rather than teaching beliefs. The presence of contradictions related to time echoes findings in other teacher education studies, as constraints on time due to competing demands (Lee & Tan, 2019). Therefore, in addition to the quality and access to external support and professional development available for teachers, teachers and school leaders should also pay close attention to a two-way communication on arrangements of cost and logistical issues of preparing and implementing STEM ALP curricula.

6. Conclusion

This study was undertaken to contribute towards how the larger system goals influence STEM practitioners' perceptions and enactment in the practice, and during the process what affordances and tensions the innovative programme provides. Based on the sensemaking theory, we examined school leaders' and teachers' understandings and responses to the STEM ALP programme within two schools in Singapore. In sum, the affordances for STEM implementation in schools, including a common understanding about the essence of the programme shared by school leaders and teachers, the positive effect of the national initiative of lifelong learning and the non-examination mechanism in the implementation of STEM, as well as the flexibility and authority of school implementation. Furthermore, both internal and external collaborations are essential, and collaboration culture is not only emphasized by school leaders but also by teachers. The tensions are mainly reflected in the conflict between examination demands and designed learning outcomes of STEM, received professional development, as well as the allocation of curriculum time and cost of materials. Hence, more appropriate professional development with opportunities for active learning and collection reflection should be provided for STEM teachers. As the discrepancy between school leaders and teachers is mainly reflected in their perceptions of resources but not beliefs, teachers and school leaders should also pay close attention to a two-way communication on arrangements regarding curriculum time and costs of equipment and materials. Future studies could pay attention to how to promote this two-way communication.

The study is subject to several limitations as well. First, the study concentrates on the STEM ALP programme, not accounting for other interdisciplinary and multidisciplinary STEM majors. Second, though two cases were reported in the study, only 3 school leaders and 3 teachers were interviewed and this study mainly investigated the interpretation and enactment of the programme in 6 months. Given the process of sensemaking is continuous and ongoing (Maitlis & Christianson, 2014), further studies should take into account the change of teachers' perceptions and enactments over longer periods. Third, the main data source was the practitioners' interview data. Further research should involve class observation data to elaborate on how teachers design and enact activities around their sensemaking processes.

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Building STEM in Schools: An Australian Cross-case Analysis

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ABSTRACT: The Principals as STEM Leaders (PASL) project was an Australian Government-funded national research and professional learning programme for principals, aimed at building STEM leadership capacity. The project involved cluster-based delivery of six learning modules and generation of case studies outlining schools' different approaches to STEM education and STEM leadership. This article analyses factors contributing to the development of four contrasting schools' STEM profiles, identifying the unique approaches and leadership strategies each adopted in designing STEM curriculum for meeting the learning needs of their diverse students. It positions these schools' endeavours within the broader PASL professional learning programme, adding to the limited body of empirical work detailing different approaches schools take to the "STEM challenge," which, for most, presents a disruptive innovation to traditional curriculum and structures. The vital role of school leaders in communicating a clear, evidence-based vision for STEM and also "walking the talk" and being highly engaged in STEM programmes, was a common feature across the cases. This built relational trust, and a strong whole-of-school commitment to and understanding of STEM, to some extent mitigating the challenges of rigid curriculum and external assessment requirements. The study highlights the complex interaction of professional learning, leadership, curriculum design, pedagogy, and school culture in establishing innovative STEM programmes in schools.

Keywords: Principal, STEM, Leadership, Curriculum, Professional learning

1. Introduction

The Principals as STEM Leaders (PASL, the scope of this article precludes detailing this project in depth. Detailed information can be found at https://www.utas.edu.au/education/research/research-groups/maths-education/pasl/pasl) project was a three-year, Australian government-funded initiative launched in 2017, to "strengthen the foundation for greater participation and engagement, and ultimately better learning outcomes, in STEM subjects" (Birmingham, 2017, p. 1). PASL involved over 150 principals, and focused on building school leadership in STEM by "develop(ing) and pilot(ing) new approaches to support principals to provide high quality STEM leadership in schools" (DESE, 2018, np). The project was led by the University of Tasmania, with collaborators from six other universities. PASL was responsible for delivering professional learning (PL) and associated initiatives in each Australian state, through bespoke modules designed to build principals' knowledge and professional leadership in STEM capability dimensions (Beswick, Fraser & Geiger, 2017). The dimensions were STEM discipline and integrated knowledge and practices; contexts for STEM teaching and learning; STEM-supportive dispositions; STEM tools and resources (digital and non-digital), and critical orientation towards STEM leadership. The modules were designed for delivery face-to-face, online, and in blended format, and were supported by research that explored current STEM teaching and leadership practices, and the influence of the professional learning on school programmes. Aligned with the learning modules were four school case studies, developed to "identify the leadership and teaching practices in STEM that are currently working well with the aim of rolling these practices out more broadly in our classrooms" (Birmingham, 2017, p. 1). Case studies informed the PL and the revision of modules between iterations, providing practical illustration of how introduced concepts could be implemented in schools, and their related leadership practices. The four case studies reflected a range of schools from different states, each forging their own pathways in meeting the STEM subject requirements of local and national curricula (e.g., ACARA, 2019; NESA, 2019).

This article analyses the approach each case study school took towards building students' STEM knowledge and capabilities, and supporting overall STEM literacy development. Valuable knowledge was generated that highlighted the complex interaction between professional learning, leadership, curriculum, pedagogy and contextual factors, in establishing each school's unique STEM profile. For that reason this article does not advocate a singular approach to STEM or compare one school's efforts as being better or worse than others. Furthermore, it adopts a broad perspective of STEM education as both separate-subject based, and "a cross-disciplinary approach to teaching that increases student interest in STEM-related fields and improves students' problem-solving and critical analysis skills." (ACARA, 2016, p. 4). In Australia, while some schools' STEM curricula may engage advanced technology, it is not a necessary requirement. Indeed, this perspective is consistent with literature that suggests there are many different approaches to STEM, each one reflecting different priorities, resources and constraints (e.g., Falloon et al., 2020; Honey et al., 2014). The analysis revealed insights into the schools' approaches, and how each developed their STEM programmes reflecting different emphases on professional learning, leadership, curriculum, pedagogy, and contextual factors - such as access to digital and community resources. Findings add to the limited research base concerning how schools in different contexts address the challenge of designing and sustaining STEM programmes, which can present considerable disruption to existing curriculum, pedagogy and organisational systems (Asghar et al., 2012; Zollman, 2012). It is anticipated these outcomes will benefit other schools planning their STEM trajectories.

2. Research questions

Data were analysed responding to these questions:

- What factors influenced the development of STEM education programmes in four Australian schools?
- What can be learnt from these schools about the complexity of establishing effective STEM education programmes?

3. A review of literature

3.1. Understandings of STEM and its relevance to education

Emerging in the 1990s from the early work of U.S National Science Foundation (English, 2016), the term "STEM" simply refers to the subject disciplines of Science, Technology, Engineering and Mathematics. However, their combination in the acronym STEM "was a strategic decision made by scientists, technologists, engineers and mathematicians to combine forces and create a stronger political voice" (STEM Task Force, 2014, p. 9), and also acknowledges the interdependence of the disciplines in making joint contributions to solving complex problems. Furthermore, the development of STEM capabilities is seen worldwide as a priority for supporting economic goals, particularly in knowledge-based economies. In Australia, the need to attract greater numbers into STEM careers is viewed as essential, "if the future workforce is to maintain and grow the reputation of Australia at the forefront of scientific knowledge and expertise" (Edwards et al., 2015, p.1). Beyond workplace readiness, the importance of improving 'STEM literacy' has been aligned with the development of essential skills, competencies, and dispositions needed to function effectively and productively in rapidly-changing future environments (English, 2016). These skills include critical and creative thinking, solving complex and ill-structured problems, autonomy, collaboration, and a growth mindset. Such capabilities are also viewed positively by employers, who identify employees' lack of interpersonal skills, critical thinking and continuous learning engagement, as major workplace challenges (Deloitte Access Economics, 2014). Increasingly, governments and employers are looking to education to improve the STEM performance of economies and businesses, through more engaging and authentic curricula that attract more young people to STEM study and careers.

3.2. STEM education

Despite acceptance and understanding of the acronym STEM, there is limited agreement on how teaching and learning in STEM should be approached in schools (Holmlund, Lesseig & Slavit, 2018). Generally, STEM is still defined by its separate disciplines, and is represented as such in official curriculum statements (e.g., Australian Curriculum, Assessment and Reporting Authority, 2015). While curriculum authorities seek improved STEM instruction, debate persists about if and how the STEM disciplines should be integrated into learning programmes, and the curriculum, pedagogical and organisational structures that best support this. While different approaches to STEM education have been identified (e.g., Falloon et al. 2020; Vasquez, 2014), interdisciplinary models are seen as the most effective (e.g., Bybee, 2010; LaForce et al., 2014; Zollman, 2012). In these, students construct and apply STEM knowledge and skills by developing or modelling solutions to "real world"' problems, needs or opportunities, often using problem or project-based learning models aligned with design thinking principles. However, while these approaches may enhance and make STEM knowledge more relevant to students, they present a significant challenge to prevailing single subject curriculum and assessment methods (Zeidler, 2016). Interdisciplinary STEM necessitates teaching across disciplines using strategies that support knowledge integration in authentic tasks, often utilising group, cooperative, or collaborative organisational structures. Such methods also demand a rethink of conventional assessment approaches, that traditionally prioritise individual over collective contribution and performance. Additionally, interdisciplinary project and problem-based structures are often seen as incompatible with secondary schools' existing emphases on discrete subject blocks. In many countries, these challenges are compounded by the absence of a STEM curriculum with system-level guidelines for planning and teaching. As Holmlund et al. (2018) points out, "without some shared understandings across a system, it is difficult to design and implement curriculum and instruction to promote successful STEM learning for all students" (p. 2). While some emerging examples detail schools' successful efforts to transition to alternative structures (e.g., Sleap, 2019), these are rare.

3.3. School leadership and STEM

Significant research highlights the importance of leadership to implementing changes and innovations in schools (e.g., Fullan, 2003; Minckler, 2014). Cohen et al. (2009) point to two factors that can aid or hinder the adoption of innovations like interdisciplinary STEM - namely school climate, and school culture. According to Cohen et al. (2009) climate reflects "the quality and character of school life, and reflect(s) norms, goals, values interpersonal relationships, teaching and learning practices, and organizational structures" (p. 180). It influences the day-to-day function of the school, establishing the 'tone and feel' of the school environment. Studies indicate a positive school climate improves teachers' engagement and performance, builds morale, and enhances student achievement (e.g., Donaldson, 2008). For Schein (2004), culture is established over time, and defined by the accepted ways in which the organisation operates and solves its problems. Put simply, culture defines how we do things around here, and is powerful when inducting new staff in an organisation "as to the correct way you perceive, think and feel in relation to (those) problems" (Schein, 2004, p. 17). Drago-Severson (2012) comments that over time school climate can influence culture, through leadership that promotes growth by providing opportunities for staff to embrace new initiatives and innovations.

Studies reveal that leadership is fundamental to the success of school STEM initiatives (e.g., Ford, 2017; Likourezos et al., 2020). Ford's cross-case analysis of the leadership practices in four STEM-focused high schools highlights the value of distributed and transformational approaches that empower individuals and groups within and external to the school to lead innovative, STEM-focused change. These approaches "inspired both teachers and students, raised the collective capacity of the school, provided leadership opportunities for teachers, engaged the entire school community, supported positive school culture and values, and addressed the needs of students underrepresented in STEM" (Ford, 2017, p. 198). In all schools, the work of principals in building positive change climates was critical to STEM development. Principals achieved this through securing commitment to a coherent STEM vision, fostering relational trust, strategic management of professional capital, establishing STEM-supportive networks beyond the school, and facilitating access to resources, infrastructure, and appropriate professional development.

4. Conceptual framework

There are multiple ways schools can approach the "STEM challenge," each involving pragmatic judgements about school climate and culture, readiness and support for STEM curriculum, resourcing, and teacher capability (Falloon et al., 2020). A flexible conceptual "lens" and accompanying methodology was therefore needed to accommodate the different approaches the four case study schools took to developing their STEM programmes. To support this, the OECD's (2013) generic learning environment model was used to understand the interacting elements that influenced each school's STEM trajectory. Figure 1 depicts the key elements of the model which interpret a learning environment as "a holistic ecosystem that functions over time and in contexts, and includes the activities and outcomes of learning" (OECD, 2013, p. 23). For analysing data from this study, elements of the model were interpreted into these code categories:

Organisation(al): Leadership of STEM, School context and culture;
Content: STEM curriculum;
Learners: (students), STEM outcomes;
Pedagogy: STEM pedagogy;
Educators (teachers, principals), School context and culture, Leadership of STEM;
Resources (material and non-material), School culture and context, STEM curriculum, Leadership of STEM.

Of note is that some code categories appear in multiple elements. This resulted from evidence in data of, for example, Leadership of STEM, being relevant to more than one element. That is, data indicated leadership as particularly important in Organisational, Resourcing, and Educator support and decision-making, and to a lesser extent in other elements, such as Content (STEM curriculum). Therefore, to support more precise reporting and discussion of data, the context-specific categories were used in place of the broader OECD elements in the analysis framework (see Appendix C). The interacting and overlapping nature of the code categories and their relationship with elements of the OECD model, is further discussed in the final section.

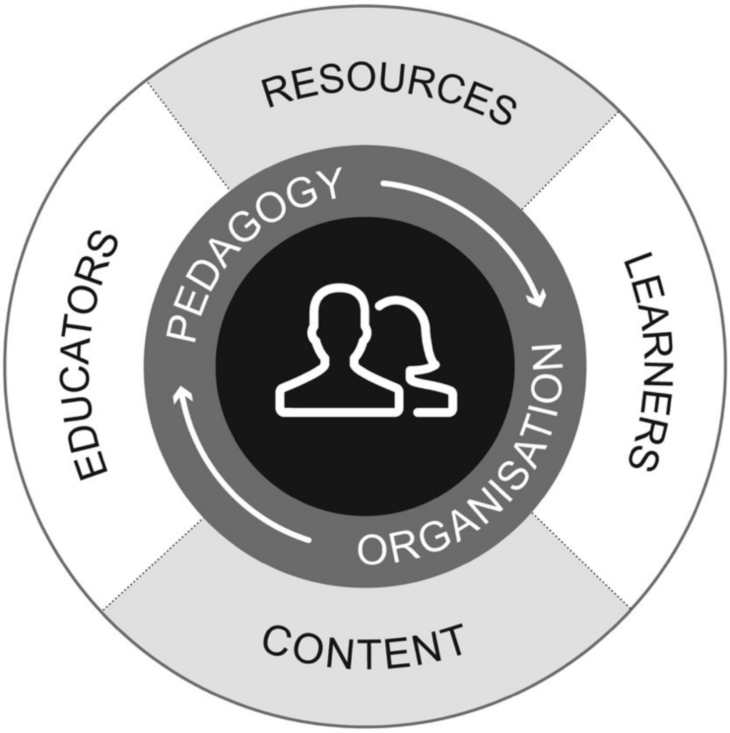

Figure 1. The OECD (2013) Learning Environment Model (See https://read.oecd-ilibrary.org/education/innovative-learning-environments_9789264203488-en#page27)

5. Research design

5.1. The case study schools

The schools were purposively selected as offering effective STEM programmes, and identified through education system and research network nominations as having strong commitment to STEM education. School selection broadly aligned with the OECD's approach, where cases were "chosen based on an understanding of 'innovation' in their own context… [which] left the nature and extent of innovation open to interpretation" (OECD, 2013, p. 25). Final selections ensured a balance of school profiles (location – city, rural/remote/regional), education systems (government, independent, religious) and types (coeducational, single sex, K-12, primary and secondary). Appendix A summarises deidentified participant and profile information for each school. Members of the research team gathered data from each site at different times across the project's lifecycle, using the methods outlined below.

5.2. Data methods and coding

Data were gathered via staff interviews (those with STEM leadership or teaching responsibility), student focus groups (students engaged in STEM programmes), and classroom observations. Interviews followed a standard protocol and question schedule. Data focuses are detailed and aligned with instruments, participants and number of items analysed, in Appendix B. Qualitative data were transcribed and coded using a hybrid method that combined inductive and template approaches to maintain fidelity, while providing a semantic structure for deeper analysis (Fereday & Muir-Cochrane, 2006). Transcripts were manually checked for accuracy and consistency, before a random selection was inductively coded to generate a draft primary and secondary theme template to be applied to all data. This was checked against the sample by a second author, and adjustments were made including conflating some primary codes to accommodate data that crossed over between categories, and refining coding decisions to better align with sub-categorisations. Five primary categories were agreed to: Leadership of STEM; STEM pedagogy; STEM curriculum; STEM outcomes; School context and culture. The subcategories were used to code data, as they provided a finer-grained "lens" supporting more accurate decisions. During analysis of the full dataset these were refined by adding, combining, and removing some subcategories, reflecting their close and at times overlapping association. A summary of the primary and subcategories, a description of each, and sample data is provided in Appendix C. Primary categories were defined as:

- Leadership of STEM: how STEM programmes were conceptualised (rationale and "vision"), leadership responsibility and teaching expectations, principal/teacher backgrounds and partnerships;
- STEM pedagogy: principals' and teachers' beliefs about how STEM should be taught;
- STEM curriculum: different interpretations of learning design and planning, and challenges to implementation;
- STEM outcomes: how learning is assessed, and indicators of beneficial outcomes from STEM programmes;
- School context and culture: climate, culture and environment reflecting support for STEM, and understanding of its role and importance to students' learning, social and work needs.

Coding followed a systematic process whereby data units aligned with each subcategory were identified using keywords/strings - samples of which are recorded in Appendix D. Units varied in length, with selections made based on the extent of evidence needed to support defensible decisions. In inductive coding, it is common to vary the length of coding units. Some units can be relatively short because the concept is clearly conveyed in a single sentence or clause, while others need to be longer where a participant is explaining something in greater depth. Illustrative longer excerpts are included in the discussion of findings, while shorter examples aligned with the subcategories are recorded in Appendix C.

5.3. Analysis

After coding against first and second-order themes using the template (Appendix C), data were enumerated to calculate frequencies associated with keywords, strings, and coded references. The research team revisited all coded references (ref.) and listed the commonly occurring keywords and strings related to each code. To determine the number of keywords and strings across the dataset, by using Boolean search functionality in Nvivo and entering all previously identified strings and keywords for each code in the one search box, it was possible to calculate frequencies against each code. A customised report generated the number of references associated with each code, as well as the number of words coded for each. A final variable was calculated to determine the average number of words per coded reference (total words coded divided by the number of coded references). These calculations are included in Appendix D, columns 4-8. This method revealed the emphasis given to different aspects of the schools' STEM developments, as discussed below. Longer data excerpts have been included in the discussion, where considered beneficial for illustrating participants' perspectives and priorities in greater detail.

6. Findings

Appendix D summarises how data were coded with respect to keywords and strings (columns 4 and 5), and coded references and words coded (columns 6-8). The keywords and strings variables reflect participants' choice of words when communicating perspectives (precision) and the range used across data (breadth). This approach enabled coding of data representative of broader concepts, rather than relying solely on exact word matches that may have missed more nuanced descriptions. The number of coded references (column 6) records the prevalence of data aligned with each subcategory, indicating some concepts attracted greater attention than others. For example, the fewer coded references for Professional Background (25) were almost entirely linked to the first interview question, while participants revisited Curriculum Planning (145) multiple times across several questions. The total words coded and average number of words per coded reference (columns 7 and 8) thus helps to better reveal the depth of detail in responses, particularly in subcategories where there were fewer strings and coded references but higher total and average numbers of coded words. For example, in the subcategory STEM Vision there were few strings (9) and coded references (54) but relatively more words coded (4685), thus yielding the highest average number of words per coded reference (91.86). Larger numbers of both total words coded and average number of words per coded reference typically indicated participants provided greater depth in their explanations and responses.

Figure 2 provides a side-by-side statistical representation of data in each primary category (i.e., collapsed subcategories) by number of strings present (column 5), total coded references (column 6), and average words per code (column 8). Except for STEM Curriculum and Leadership of STEM, all categories returned significantly more strings than coded references, typically reflecting multiple strings used to refer to each concept and greater breadth of detail or explanation. For example, in School Culture and Context, 955 strings were used in only 292 coded references. Participants' responses in this category were often broadly defined and referenced multiple examples. By illustration, responses in Resourcing for STEM often yielded multiple examples of STEM resources in a single coded reference, for example "... we have a lot of resources at our disposal. We have an ideation lab - it's got a lot of laser cutters, 3D printers, tools we can use, materials if we don't want to buy everything ourselves" (School 1, Student 3). Other categories showed only minor variation, suggesting participants were less inclined to elaborate on responses. Leadership of STEM, for example, registered 265 strings and 226 coded references, and in subcategories such as Beliefs about STEM, few examples or details were offered e.g., "I feel like a lot of the skills you develop in STEM can be applied in many other areas" (School 3, Student 1). Moreover, these subcategories often yielded instances where a perspective was expressed without clearly signposted keywords or phrases. For example, as one student commented, "...it's the problem solving… you look at something and you think it's going to be so straightforward… [but] you have to uncover so many layers, and it's like… it's calculated decisions every single time…" (School 3, Student 5). In such cases, coding had no associated keywords or strings. STEM Curriculum was the other category reflecting relative parity between keywords/strings and coded references, returning 603 strings and 583 coded references. The comparatively high number and close alignment of coded references and strings, and low average words per coded reference, suggests that although participants were keen to comment on STEM curriculum, typically their responses were brief. This coding method therefore provided some tentative indications of the understandings, priorities, interests and concerns guiding participants' STEM developments in their schools.

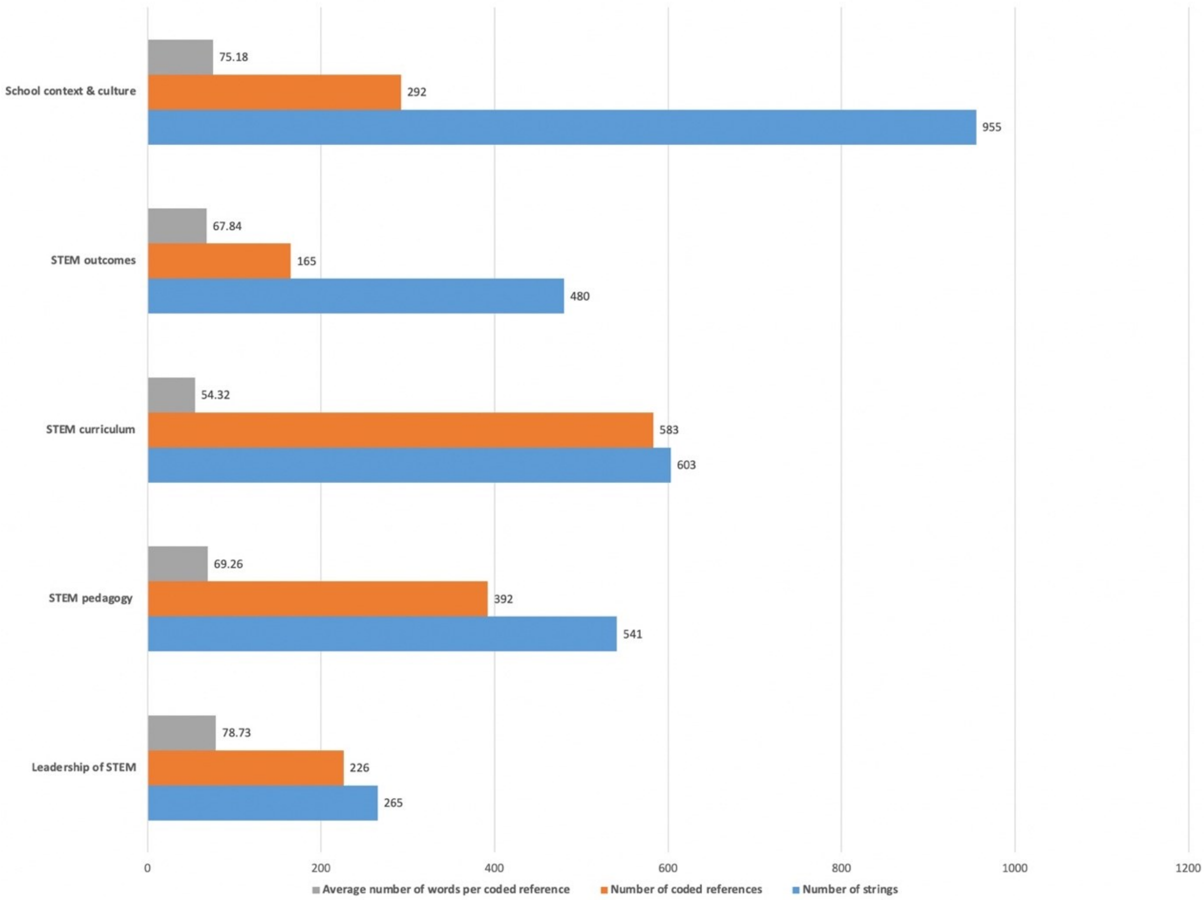

Figure 2. Side-by-side analysis: number of strings, coded references, and average words per coded reference

7. Discussion of findings

Responding to question 1, findings are discussed using the broad categories outlined in the OECD model. In this study, Organisational elements relate to Leadership of STEM and STEM-supportive school Culture and Climate;

Content and Pedagogy refer to STEM curriculum and approaches to teaching; Educators are the teachers and principals, Learners are the students, and Resources are the materials, equipment, infrastructure and professional learning supporting STEM programmes. In reporting data below, schools are denoted (S*n*), teachers (T*n*), principals (P) and students (St*n*).

7.1. Leadership of STEM

Data indicated some teachers and principals linked their professional background to their decision to pursue STEM in their schools (25 refs.), often reflecting a change of career from a STEM profession such as architecture, graphic design, or IT - to teaching in schools. Teachers' STEM industry experience was an asset in each school. As one teacher commented, having two ex-engineers on staff was like having "all the building blocks in place" (S3, T2). Several teachers with STEM leadership responsibility had non-STEM backgrounds - for example, as teachers of English and Geography. However, they considered it beneficial to further their disciplinary knowledge by looking for creative ways to integrate their discipline expertise with STEM. This also applied to two principals, with one commenting, "I don't come from a farming background … but I suppose my skills were in strategy, and so I'd been aware that really what I just needed was to support and to implement strategic approaches to (STEM) improvement" (S4, P).

Across all schools, staff and students were acutely aware of principals' expectations relating to STEM achievement (95 refs). The high string count (n = 112) for the Leadership of STEM category reflected the presence of keywords and phrases such as *they should*, *we have to*, and *it's important to*, which were used to reference STEM initiatives across the 12 strings mapped to these codes. The importance of high expectations - often described as a "push" - was viewed as an enabler of success. Students spoke of their teachers' encouragement to participate in STEM opportunities, with one commenting "if they believe we can do it, that in itself pushes us to want to do it" (S3, St1) and another referring to "a big push for women in engineering" (S3, St5). Two principals identified changes between the previous and current school "STEM culture." One noted when she started "students weren't being challenged in mathematics" (S3, P), while another mentioned the resistance of staff who were previously "left alone to do their own thing" (S4, P). However, teachers were generally pragmatic when setting and managing expectations, such as "starting off with expectations in the middle" (S4, T2) and ensuring they were transparently communicated to students and parents. All staff viewed STEM as a priority area, and a significant contributor to holistic student development.

Approaches to leadership of STEM reflected views about the importance of leadership stability, leadership style, trust, professional capital and student empowerment (29 refs). Teachers valued leaders who were approachable, forward thinking, and not afraid to push back against system-level directives. Principals were unanimous that "leadership density" was key to STEM initiative success, which one principal described as "leadership that is deep and solid, distributed across the school, that enables our young people… and has the support of our parent community" (S1, P). Staff in School 1 recognised that empowerment of their colleagues and students involved a balance between trust, forward planning, and leveraging individual and collective knowledge and skills. As one teacher commented, "I will be completely turned off if I don't get the opportunity to really tap into the things I really want to do as a teacher" (S1, T1).

Participants recognised the importance of partnerships for supporting STEM in their schools (26 refs). These included links to the tertiary sector and local council and industry, as well as participation in festivals and public events. Universities were frequently viewed as a source of STEM opportunities, mentors, and authentic learning experiences, often playing a key role in broadening students' understanding of STEM practices and careers:

We got to go to the [local university]… and they put lab coats on and they were scientists and they got to do some hands-on experiments. But the power for them to actually… just seeing what it's all about and talk to young scientists who were explaining to them about some of the things that they were doing at university… (S4, T1).

Partnerships were deemed important, as one principal described, for "making sure that we have impact and influence beyond our school" (S1, P). However, staff in School 3 acknowledged the difficulty of developing and maintaining industry partnerships. As one teacher explained, willing industry leaders often lacked more nuanced understandings of how schools operate, and how their businesses might best contribute to meeting students' learning needs. This sometimes manifested in tensions between school and business priorities (S3, T2).

Teachers and students unequivocally valued clear, visionary STEM leadership. Although the vision in each school took a different form, high expectations - variously referred to as *great heights*, *extraordinary learning*, *improving outcomes*, and *best practice*, was a uniting theme (11 refs). Evidence played a critical role in determining the attributes of STEM learning excellence, but both teachers and students strongly regarded 'shared ownership' of the vision for STEM as necessary for achieving such excellence. As one principal described, the school's collective vision was instrumental in the empowerment of students:

[Our] vision is *extraordinary learning driven by curiosity and challenge and inspiring confidence and passion*. So that drives our work… [and] is actually what we live and breathe. Our hope here is actually around providing opportunities for students to be curious and to work together to try and come up with their perspectives, their solutions, their ideas (S1, P).

All principals believed that teachers' professional capital and collective efficacy were integral to the success of STEM curriculum, while teachers and students valued their principal's vision for STEM, and the support they received to align this with classroom programmes and practices.

7.2. STEM pedagogy

Experiential learning was widely supported as an effective way to develop STEM knowledge, skills, and dispositions (109 refs). Students viewed STEM as immersive, fun, and involving experimentation, problem-solving, and teamwork, with some suggesting the authentic and "open ended" nature of experiences enhanced interest and motivation. Classroom observations supported the experiential nature of many STEM learning activities such as designing powered paper aircraft (S3) and improving gold mining tools (S2). In School 4, the principal commented on the school's farm as an ideal context for experience-based STEM learning:

So we're really embedding it [the farm] in the STEM work that they do. And this year it's become even more interactive, so the kids get up, they are over there, they touch the animals, they talk about why they're warm, why they're soft... listening to their heart, feeling their heartbeat… (S4, P).

Teachers in three schools viewed experiential approaches to STEM as an alternative to rigid, assessment-driven curriculum. One of these schools had implemented a weekly, 100-minute STEM challenge, where "we just play, we just have fun … there's no assessments, there's no curriculum, there's just us delivering what we think the kids can really benefit from" (S1, T1). Classroom observations identified numerous extracurricular activities such as robotics, Lego, coding, and Makerspaces for students to experience working with tools and materials in practical programming and making tasks (e.g., S3).

Despite teacher modelling being less represented in data (7 refs), the depth of detail indicated it was a valued approach for illustrating methods, dispositions and success criteria for STEM learning. In particular, teachers with industry backgrounds recognised the importance of being seen by their students as "model" STEM learners themselves. As another commented in relation to an industry-background colleague, "he's so passionate about what he does with the science and STEM… [and] it's been really powerful having and instilling that passion in the children" (S4, T1). Modelling also aligned with leadership of STEM and setting high expectations for staff. As one principal explained, "what you think you might be aiming for is not what you actually get, but it has taught me the importance at times of things like modelling and coaching and mentoring people" (S3, P).

Student-led Inquiry (35 refs) principally referred to research-based activities formed around 'investigable' questions or problems, which required students to use various information sources to develop and present defensible responses. This was evidenced in two schools via classroom observations where students explored advanced scientific principles without explicit instruction (S1, S3). To be effective, teachers in these schools considered STEM Inquiry tasks should focus on authentic problems of immediate relevance (e.g., S1 - designing a can-crushing machine to assist school rubbish recycling). Students favoured this approach, with some commenting on the motivating effect of this on work quality and output - e.g., (with reference to a peer) "one day (she) finished a whole page of research (on her STEM topic) - like, this big… full page of writing!" (S4, St8). Others considered Inquiry approaches directly aligned with learner competencies such as autonomy, problem solving, and research skills (S2, S4).

Collaborative partnerships (42 refs) were often based on student learning preferences, and adopted flexible pedagogies that encouraged teamwork, risk taking and innovation. Partnerships extended to colleagues, where teachers valued sharing STEM practices to build collective expertise and efficacy. Teachers commented in detail about how STEM initiatives represented a form of *reciprocal causality* - both emerging from, and further supporting, their STEM efficacy (109 refs). Celebrating successes was important to building STEM efficacy, and often involved sharing "not only *what they're doing* (students and teachers), but also the *outcomes of what they're doing*" (S1, P). Collective STEM efficacy was built on collaboration – as one teacher explained, "you get ideas from everyone… you still get the freedom to do what you want while also seeing what everyone else is doing" (S1, T1). Collaboration was particularly valued in interdisciplinary approaches where students were able to call on the knowledge of multiple teachers during STEM projects, supporting more individualised learning. As one commented, "teachers (are) always floating around, so it's not particularly hard to find a teacher who knows what you need to know" (S1, St4). Individualisation was supported by student-centred pedagogies that recognised student agency in decision-making. This extended to the selection and structuring of STEM learning units, through strategies such as "(getting) a group of students who want to contribute… their point of view about what they really want and what they like… and what is important" (S1, T1).

STEM pedagogies often reflected schools' socio-economically diverse and multicultural student populations (62 refs). Project-based pedagogies were seen to support equity, and principals were keen to use these to ensure *all* students had access to STEM opportunities considered valuable for their future lives. As one principal stated, "we ride every wave of refugee students that come… [and] you want to make sure that they get the opportunities that they deserve in terms of their (STEM) learning" (S3, P). Principals further understood the importance of teachers modelling dispositions they considered essential to STEM learning. As one stated, "it does the kids good to see that we're prepared to fail and [sometimes] can't do well, what they can do…" (S3, P). However, they also recognised the inadequacy of a single pedagogical method, identifying the need for "a multiplicity of styles to meet the particular situation - from direct instruction, through to inquiry-based, project-based, challenge-based, to mastery attention" (S3, P). Individualisation ensured STEM curriculum was relevant and beneficial for students who, due to cultural or socio-economic background, may not otherwise have considered STEM-related study or careers. There was strong commitment to equity and inclusion through pedagogy and curriculum that made STEM opportunities available to all, including staff without direct subject responsibility (44 refs).

7.3. STEM curriculum

Data indicates participants held variable understandings of, and motivations for, interdisciplinary STEM. Results for this category returned a high number of coded references (583) but low average words per reference (54.32), as participants tended to provide fewer details about interdisciplinary STEM in their school. Views and motivations for interdisciplinary STEM varied between schools. In two schools, specific advantages were identified for deepening discipline knowledge and supporting transfer across subjects: "the opportunities are there that we can really strengthen the transfer that students are able to make of their knowledge, their understanding, their skills - from one context to another" (S1, P). In others, interdisciplinarity served as a mechanism to co-plan and co-teach units, some of which had evolved into transdisciplinary units planned around authentic, problem-based tasks. As one teacher described, "we've come so far that the students don't actually know what subject they're being delivered" (S1, T1). Some tasks incorporated design thinking (16 refs), where students were introduced to the role of design through authentic, problem-based experiences: "you go through the whole cycle… you design something, you build something, you iterate it, you change it, then go back to the beginning" (S3, St4). Teachers in three schools associated design-based STEM with development of critical and creative thinking, problem solving, and risk taking. The iterative nature of design processes allowed students to "apply past knowledge to new situations" (S1, T1) and learn through reflecting on mistakes. In one school, design-based STEM extended to participation in community events including an "Innovation Expo," where a group designed, prototyped, trialled and presented, an ultrasonic sensor system to assist blind people's navigation (S1, St3).

While principals and teachers identified the importance of student engagement in authentic or 'real world' STEM (59 refs), the low average word count (41.49) indicated they provided limited detail or elaboration. Three principals mentioned the value of tapping into local businesses or community organisations, or using facilities owned by the school, as a means of adding authenticity to STEM learning. An illustration of this was one school's ownership of a farm, where students learnt about animal care and productivity, irrigation practices, factors affecting pasture growth, and automation opportunities and economics. The farm had "evolved from a very, very separate farm to a place that our students, as well as the visiting students, can engage in all elements (of STEM)" (S4, P). However, principals acknowledged difficulties sustaining external partnerships where commercial and educational priorities did not always align.

Other STEM curriculum challenges were noted by staff (92 refs), including students' "STEM readiness" and the need to "retrain" them in the different skills, dispositions, and competencies demanded by more independent, project-based curriculum. As one principal commented, "when I first came, we had kids who were good at the mindless drilling and skilling type thing, but not good at thinking" (S3, P). Another principal aligned this phenomenon with "the (dis)connection between a STEM strategy and the current improvement agenda" (S1, P), suggesting high stakes assessment, curriculum crowding, and teacher workload, worked against innovative interdisciplinary designs and students' STEM skill development. This awareness reflected in an explicit focus on transferable STEM skills, particularly in Schools 3 and 4.

In two schools, to develop interdisciplinary programmes principals provided release time for teachers to work in teams, where learning units were written and coordinated across disciplines (S1, S3). While in-the-classroom implementation was an individual responsibility, teachers in these schools noted this departure from traditional planning methods: "(this is) quite different from anything I've been involved in before, because… we're in interdisciplinary teams, and we plan as a group" (S1, T3). The blend of 'collaboration, autonomy and responsibility' linked to principals' leadership of STEM, where distributed approaches supported teachers' decision-making about the design of programmes that best met the needs of students. As one commented,

… teachers are actually given the license and the responsibility to make collective decisions about their timetable, their learning design, their assessment, the moderation of that assessment, the timing of those assessment tasks, the timing of the scope and sequence and the pacing of those learning designs (S1, P).

In all schools, extracurricular opportunities were important adjuncts to STEM curriculum (158 refs). These included clubs in robotics, engineering basics and electronics, in addition to participation in local and national STEM challenges and competitions. School 3 aligned some of these with interdisciplinary curriculum units at years 9 and 10, enabling students to link school-based with extracurricular STEM learning. Students appreciated "the freedom we (they) are given" (S3, St9) though this approach, which allowed them flexible access to equipment such as 3D printing, laser cutting and design studios to further their STEM projects.

7.4. STEM outcomes

Principals and teachers identified assessment of interdisciplinary STEM as challenging, and at-times oppositional to conventional assessment requirements that focus heavily of external examinations (75 refs). Although they saw potential for assessment of interdisciplinary STEM via rich, project-based tasks, teachers were realistic about their capacity to do this, with one commenting, "the best place is to put an assessment and bring in the content that we're required to deliver" (S1, T1). The tension between mandated assessment and interdisciplinary STEM was apparent in all schools and viewed as an ongoing concern: "the challenge we've got as educators is to keep the good and not to be become overly sensitive about results in NAPLAN (Australia's National Assessment Programme — Literacy and Numeracy) [since] they're just a measure at one point in time" (S3, P). Teachers nonetheless recognised the value of interdisciplinary STEM for engaging for all students, highlighting evidence beyond standardised assessment as examples of this (90 refs). These included higher numbers of students studying STEM subjects at university (S1, S3), improved academic achievement of students who struggled in other subjects (S2), and self-efficacy (S4). These outcomes were strongly linked to the engaging and authentic nature of learning in interdisciplinary STEM. As one teacher described, "they're investigating their own learning abilities, their own attitudes, dispositions, that growth mindset and understanding how the brain works …[and] it becomes really empowering to them" (S1, T1).

7.5. School culture and context

All schools showed commitment to establishing a STEM culture supportive of risk-taking and learning from failure (18 refs, av. 4.25 words/code). One principal described this as "failing forward" (S3, P), where students take risks and view failures as valuable learning opportunities. However, teachers described challenges working with risk-averse students, noting that some were inclined to "opt out" due to difficulties experienced transitioning to environments demanding more independence: "I caution them against that (leaving) because even though they find it very difficult … they just feel uncomfortable most of the time because they're learning" (S1, T2). Regardless, principals and teachers understood the importance of STEM knowledge and skills for their students' futures, recognising the value of practical, problem-based approaches for building valued 'soft skills' such as creativity, autonomy, critical thinking, teamwork, and problem solving (35 refs). As one principal commented, "the problem we face is [that] no one's quite sure of what the future and jobs are going to be" (S2, P). The suitability of project-based STEM as preparation for the future was also well understood by students, who appreciated the opportunities it presented to exercise their talents. As one explained, "I think I would like to do a job in STEM because [it's where] I'm using my imagination and my creativity" (S2, St1).

Professional learning in all schools supported staff capabilities by providing internal and external mentoring and training (59 refs, av. 83.81 words/code). Some of this occurred through attendance at courses and conferences, while other opportunities were accessed online using synchronous and asynchronous technologies (e.g., S3). All teachers and principals used technology to network with remote colleagues, further supporting the sharing of ideas and generation of new knowledge enhancing their STEM curriculum. In two schools professional learning mainly took the form of internal peer-learning and co-teaching through sharing of successful STEM experiences and knowledge, or working alongside colleagues in co-taught units (S1, S4). Peer-learning was particularly effective in School 4, where colleagues mentored new teachers to build knowledge embedding farm-based STEM experiences in their curriculum. As the principal commented, (our STEM leader) "takes teachers out onto the farm so that they become more aware of what it looks like out there and what they can do [STEM-wise]" (S4, P). Other schools leveraged external professional learning provided by state authorities, or accessed training through collaborative partnerships with nearby universities (S 2, S3).

Schools invested heavily in equipment and infrastructure to support STEM programmes (113 refs, av. 74.36 words/code), but also accessed free resources such as a local wildlife sanctuary, a museum visitors' centre, and a government research agency. Principal leadership was critical to resourcing STEM, and teachers acknowledged the freedom and support they were given to resource new initiatives. As one commented, (the principal's) "really good at saying, 'yes, this is something we need to build on, here's the money to do it, and we're going to support you in making the changes'" (S2, T3). Although parents represented an important resource, all schools struggled to engage them meaningfully with their interdisciplinary programmes (23 refs). Principals noted parents' preconceptions about integrated STEM curricula being less demanding and less effective than single discipline approaches: "the biggest challenge is our students and our families understanding the value of having a more interdisciplinary STEM curriculum, versus having a purer discipline-based grounding" (S1, P). Despite this, all principals saw this as "work in progress," and were keen to communicate to parents at every opportunity the positive outcomes from their interdisciplinary programmes, often using social media to demonstrate the breadth and depth of learning that occurred in them.

8. Summary and conclusion

Responding to question 2 and consistent with much literature (e.g., English, 2016; Falloon et al., 2020; Holmlund et al., 2018; Timms et al., 2018), these four schools pursued very different approaches to STEM. However, in each case the elements of the OECD model were valuable for understanding the interaction between, and overlapping nature of school culture, curriculum, pedagogy and leadership in the formation of practices and programmes, and revealed the challenges that some schools experienced - especially secondary schools, in attempting to transition to interdisciplinary STEM curriculum. Consistent with research (e.g., Fullan, 2003; Rose et al., 2019), leadership that created school cultures and climates supporting risk taking and innovation, was at the core of effective STEM education. The leadership capacity of principals to communicate a strong purpose and vision for STEM based on well-developed understandings of the current and likely future needs of students, was critical. Purpose was a consistent and unifying factor driving STEM, and was influential in decision-making relating to professional learning, resourcing (digital and non-digital), curriculum, and pedagogy supporting programmes. Interestingly, all schools adopted some form of distributed leadership of STEM, with teachers holding significant autonomy and often financial delegation to design programmes they saw as best meeting the needs of their students. However, principals were still central to establishing a "STEM culture" based on solid understandings of the importance of STEM knowledge, skills and dispositions (and modelling these themselves), high levels of relational trust, professional belief in the capabilities of teachers and students, providing autonomy with accountability, and support for risk taking and "failing forward." However, it was also clear, especially in the secondary schools, that enacting this vision was complex and challenging. The OECD model elements helped understand the significant tension schools experienced between external "high stakes" assessment (Content) and their transition to preferred interdisciplinary STEM (STEM curriculum). It also revealed the need for major organisational and system changes (Organisation), and specific professional learning in new pedagogies and assessment methods to allow teachers to plan, teach and assess project-based units in teams (Pedagogy, Resources). In these respects STEM presented a disruptive innovation, generally resulting in interdisciplinary approaches being limited to the junior school where constraints could be mitigated, or occasional units being designed around mandated content knowledge.

Notably, leadership of STEM in these schools involved much more than simply espousing a vision. While distributed leadership was common across schools, this did not mean principals delegated complete responsibility for STEM to teachers. In all cases, principals fully engaged with STEM programmes, often providing classroom assistance or helping coordinate external STEM events or competitions. Through this "hands on" approach, these principals set high expectations and modelled the type of behaviours and dispositions they expected from staff and students. Consistent with other recent studies (e.g., Rose et al., 2019), active principal engagement was fundamental to forming and enacting a clear purpose and vision for STEM. It also supported professional learning, resource and staffing decisions, through building better 'first hand' knowledge of the needs of teachers and the progress of students. Additionally, principal modelling served as a powerful motivator, creating confidence in teachers to try new approaches to curriculum and teaching that departed from conventional methods. Furthermore, principal modelling supported teachers' efforts to educate parents about the nature and value of learning using interdisciplinary approaches. As in other studies (e.g., Hutchinson, 2013), meaningfully engaging parents in STEM curriculum was an ongoing challenge, but recognised as one that needed to be addressed and could potentially yield substantial benefits. All principals actively communicated with parents to promote positive outcomes from STEM and build external partnerships and support for initiatives.

Finally, in this study rich data from multiple perspectives were innovatively analysed to better understand the most influential factors on schools' STEM trajectories. This was supported by classroom observations which indicated a high degree of fidelity and consistency with the interviews, providing confidence that details communicated were consistent with actual classroom experiences. However, these schools were not chosen because they displayed "exemplary" approaches to STEM. Indeed, literature indicates little is known about what exemplary practice actually is, or what and how outcomes from particularly interdisciplinary STEM can be recognised and evaluated. Instead, they were selected because they were identified as delivering STEM curricula that were deemed effective for meeting students' learning needs in their local context. While leadership was the unifying factor, each school programme was quite different in nature, suggesting what is effective STEM in one context may not apply to others. This highlights the need for further studies specifically connected to different contexts and environments, that will provide deeper insights into common factors that promote effective school STEM curriculum.

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Appendix

Appendix is available here.

Lai, C.-L. (2021). Exploring Taiwanese Teachers' Preferences for STEM Teaching in Relation to Their Perceptions of STEM Learning. *Educational Technology & Society*, *24* (4), 123–135.

Exploring Taiwanese Teachers' Preferences for STEM Teaching in Relation to their Perceptions of STEM Learning

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ABSTRACT: Educators believe that STEM activities allow students to use multiple skills to solve real-world problems; therefore, it has been recognized as an effective way to apply academic knowledge to life's problems. While many studies have examined the effectiveness and perceptions of students' learning through STEM activities, little research has been conducted on teachers' perceptions of STEM activities. In particular, there has been little research on teachers' preferences for STEM learning. Therefore, in this study, two questionnaires were employed to investigate the teachers' preferences for and perceptions of STEM learning and teaching. The questionnaire of teachers' preferences for STEM learning consisted of four scales, namely, activity flexibility, technology support, classroom interaction and teaching assistance, while the questionnaire of perceptions of STEM learning included higher order thinking, collaboration, and attitude toward STEM learning. A total of 307 teachers from 25 high schools in Taiwan filled in the questionnaire after conducting STEM activities. From the result of structural equation modeling it was found that teachers' perception of collaboration was the key element connecting the teachers' preference for STEM activities and attitude toward STEM learning. In addition, the teachers' preference for technical support and classroom interaction positively correlated with their perceptions of higher order thinking and collaboration, while activity flexibility and teaching assistance positively correlated with their attitude toward STEM learning. According to the results, it was found that teachers' perceptions of STEM learning were pluralistic and differed according to their preferences.

Keywords: STEM education, Teacher professional development, Teaching preference, Attitude toward STEM education

1. Introduction

In recent years, STEM education has been recognized as an important educational issue (Wahono et al., 2020). In general, STEM education refers to integrating the disciplines and skills of science, technology, mathematics, and engineering. It has placed great emphasis on students' practical skills, and has developed their competitive ability to face complex problems through hands-on experience in the process (Chang & Chen, 2020). According to the results of a literature analysis based on Wahono et al. (2020), STEM activities can also motivate students to progress to a higher level of thinking, which in turn affects their academic performance. Researchers believe that STEM education is well suited for developing soft skills such as problem solving, higher order thinking, and collaborative communication skills (Lin et al., 2020).

Much of the research has practiced the spirit of STEM, guiding students to integrate and apply concepts from science, mathematics, technology, and engineering to solve problems themselves (Century et al., 2020; Kelley et al., 2020). For example, Hu et al. (2020) investigated the impact of using the Knowledge, Skills, and Attitudes (KSA) instructional mode on students' learning effectiveness when making an electronic musical pencil. The results showed that the use of the KSA mode can positively enhance students' attitudes towards STEM, and improve their learning outcomes. Besides, some studies investigated the effectiveness of technology on students' hands-on activities. Altmeyer et al. (2020) developed a tablet-based AR application to support hands-on experimentation in physics science. It was found that the students could gain more conceptual knowledge through effective technological assistance. Although the integration of technology and content is necessary, the role of the teacher in STEM learning may also be an important factor in determining the quality of the learning outcomes (Dong et al., 2020). In Lin's et al. (2020) research, they explored the role of teachers in teaching and learning in a web-based collaborative problem-solving system (wCPSS) learning environment. According to their results, even if the e-learning system benefits students' STEM problem solving, if the teachers do not provide guidance during the learning process, it is still hard to highlight the effectiveness of students' STEM learning.

Researchers are also interested in teachers' perceptions of STEM education, research has shown that teachers' attitudes are a key aspect of successful teaching and learning (Wu & Albion, 2019; Yeh & Tseng, 2019). Adov et al. (2020) explored STEM teachers' attitudes toward using mobile devices for teaching, and investigated what factors might help to increase teachers' willingness to conduct STEM activities. The results of the questionnaire analysis showed that teachers' expectations and effort expectancy of activities were highly correlated to the teachers' attitude toward using mobile technology. Affouneh et al. (2020) also explored teachers' perceptions of professional development in STEM teaching and learning. The factors that teachers perceived as influencing their STEM professional development included the availability of teaching resources, teachers' professional competence and beliefs, and the operation of the teacher community. As Gosling and Moon (2002) stated, the teacher's expectations of the teaching objectives and outcomes would determine the effectiveness of student learning in the process. Therefore, it is important to explore teachers' perspectives on that approach to teaching and learning.

However, teachers face many challenges when developing STEM activities (Wahono & Chang, 2019). For example, they may be unfamiliar with how to connect different curricula, they may not understand effective assessment methods for STEM outcomes, and there may be few exemplars to emulate (Brand, 2020). The reasons for these difficulties stem from a number of external factors including restricted classroom environments, limitations of the curriculum framework, and inadequate teaching resources. Therefore, researchers have pointed out that teachers' preferences need to be considered (Chuang & Tsai, 2005), since they determine the teachers' needs from several external perspectives (e.g., technology needs, environmental needs, and content needs). In the meantime, an investigation exploring the relationship between these external perspectives and internal perspectives (e.g., attitudes) is needed (Angel-Alvarado et al., 2020). Without overall consideration of teachers' internal and external needs, it is likely to result in unsuccessful curricula, which might reduce the opportunity for students to practice solving complex problems (Kelley et al., 2020). Therefore, to effectively encourage teachers to develop STEM activities, educators and school managers need to understand the teachers' considerations and preferences for conducting STEM activities.

The purpose of this study was, therefore, to investigate the teachers' perspectives on STEM learning by examining their preferences for and perceptions of STEM learning. This study examined the contextual preferences of teachers when conducting STEM activities. Meanwhile, we also investigated how these preferences are related to the teachers' perceptions of STEM learning. In this way, school managers and teachers can develop meaningful STEM teaching activities based on the teachers' preferences.

2. Literature review

2.1. Learning outcomes of STEM activities

Learning outcomes are often used as a reference to measure the effectiveness of a learning approach (Beege et al., 2020). Students' perceptions and cognitive development of the learning process are usually reflected in the learning outcomes (Cedefop, 2017). At the same time, learning outcomes are also a reference basis for teachers' teaching quality; teachers' expectations of students' learning outcomes can also be reflected in their teaching effectiveness (Kong et al., 2020; Song & Hwang, 2020).

In the field of STEM education research, in addition to students' learning achievement, researchers are more concerned about the development of students' higher level skills (Simeon et al., 2020). This is because STEM emphasizes not only effective knowledge application, but also problem solving, teamwork, and critical thinking in the process (Kong et al., 2014). Two important skills that the researchers have identified as important for students are higher order thinking skills and collaboration (Wahono et al., 2020).

Higher order thinking has been recognized as a concept of education reform based on Bloom's taxonomy (Hu et al., 2020). It involves cognitive processing such as analysis, evaluation, and synthesis (Bloom et al., 1956). It is believed that higher order thinking skills play a very important role in knowledge acquisition in students' STEM activities. For instance, Yu et al. (2020) examined the influence of students' scientific knowledge and higher order thinking tendency on their design of engineering projects. The results showed that the students' higher order thinking ability (e.g., deduce, explain, and evaluate) was an important ability when they attempted to apply scientific knowledge during the design process. On the other hand, Wahono et al. (2020) reviewed 54 STEM studies and found that effective STEM activities begin with encouraging students' higher order thinking, then move to their academic achievement, and end with students' motivation.

On the other hand, collaboration is considered to be an important competitive skill (Wang et al., 2020). It is related to the ability of learners to integrate into a group of people or to communicate effectively once they enter the community (Patten et al., 2006). Researchers have also stated that the design of STEM instructional activities that consist of collaboration and communication can enhance the development of students' skills (Lou et al., 2014). Many studies have found that doing projects is a successful way to stimulate students to conduct collaboration and communication activities (Mustafa et al., 2016; Siew et al., 2015).

From the aforementioned literature, it was known that the instructional strategies and the development of activities have a great potential to help students develop higher order thinking and collaboration skills (Martín-Páez et al., 2019). However, not all teachers who implement STEM activities know how to design STEM activities and incorporate instructional strategies (Martín-Páez et al., 2019). If the outcome of the implementation is the intended goal, teachers need to devote a great deal of effort and time to designing the curriculum (Kelley et al., 2020). This is because such an approach is very different from the past; some external factors have influenced the teachers' identification of STEM learning. Therefore, understanding teachers' perspectives on STEM education and their perceived potential of students' learning outcomes in STEM activities needs to be taken seriously.

2.2. Preference of STEM activities

The integration of technology and instructional strategies into teaching has been recognized as a critical issue (Ogbuanya & Efuwape, 2018). How teaching resources and contexts adapt to learning needs to be reconsidered when introducing new modes or activities (Sandholtz & Ringstaff, 2020). It requires consideration of teachers' basic technological knowledge and pedagogical expertise (Wei, 2020; Ng & Chan, 2021). Mishra and Koehler (2006) proposed three components of the learning environment: content, pedagogy, and technology; these three components would interact and influence each other. In the case of STEM education, it was found that many projects are still limited to technology-oriented projects, such as robotics education and programming education (Lin et al., 2020). This indicated that there may be more barriers than content, pedagogy, and technology, which may be related to teachers' preferences or perceptions (Okumus et al., 2016). As Ertmer (2005) and McElearney et al. (2019) suggested, investigating teachers' perceptions and preferences may be a way to provide important references for teacher professional development.

Preference has been considered as a crucial foundation for the further development of learning environments (Chuang & Tsai, 2005; Franquesa-Soler et al., 2019). Researchers have frequently investigated teachers' and learners' preferences in various learning contexts, such as conventional learning environments, web-based learning environments, and mobile learning contexts (Hwang et al., 2018; Liu, 2020). For instance, Liang and Tsai (2008) explored college students' preferences in Internet-based learning environments. According to their investigation, they found that the students with high Internet self-efficacy presented higher preference for Internet-based learning environments, such as exploring real-life problems, displaying multiple sources of information, and conducting open-ended inquiry activities. Li et al. (2019) examined pre-service teachers' preferences for smart learning contexts. Their results revealed that connectedness was positively associated with all smart classroom features, such as inquiry learning, student negotiation, multiple sources, usefulness, and ease of use. Those studies not only pointed out the factors that need to be considered when developing or conducting activities, but revealed the importance of considering preferences when designing activities or implementation of certain policies.

For the development of STEM activities, researchers have also discussed teachers' preference for STEM education. For instance, Gardner and Tillotson (2020) interviewed a teacher who developed STEM activities, and identified three important factors that the teacher considered. The first was the flexibility of the activities and spaces. The second was the replicability of the instructional models, which indicated the low technical threshold of the curriculum, making it easy for teachers to imitate. The last one was the improvement of teaching deficiencies, indicating that strong teacher teams and administrative support were needed. Through interviews, El Nagdi and Roehrig (2020) also found that STEM teachers valued the level of team support in the curriculum design process; they cited this as a factor that motivated them to develop the curriculum. Wang et al. (2020) also noted that teaching goals and collaboration structure were highly associated with the successful STEM mode.

According to previous studies (Gale et al., 2020; Kelley et al., 2020), the factors that teachers considered when designing STEM instructional activities included activity flexibility, technology support, classroom interaction, and teaching assistance. Activity flexibility refers to the contexts that allow the teacher to have more flexibility in their learning activities. Good flexibility not only allows teachers to create meaningful learning activities, but also enhances the interaction between teachers and students (El Nagdi et al., 2018). At the same time, the flexible curriculum allows teachers to design cross-curricular activities. Technology support refers to the teachers' technology need for conducting learning activities. In particular, in STEM learning environments, learning activities are often complex and lengthy; students or teachers often need technology for recording, communicating, and searching for information (Holmlund et al., 2018). On the other hand, teachers also have expectations about the level of classroom interaction in the activities. This refers to peer discussion or interaction between teachers and students in learning activities (El Nagdi et al., 2018; Stehle & Peters-Burton, 2019). In STEM activities, in addition to the wealth of information, peer cooperation, competition, or communication is also a key factor reflected in the success of instructional activities. In addition to the three influencing factors of learning, technology, and interpersonal interaction, many researchers have recently found that the level of support from the school also affected whether teachers developed their instructional activities (Siew et al., 2019). Therefore, teaching assistance is also important when considering teachers' preferences for instructional activities.

How teachers perceive and what they expect from learning activities also affect the development of the whole activity (Dong et al., 2020; Kelley et al., 2020). Many researchers have taken into account students' preferences for learning patterns and their propensity to perform well (Wahono et al., 2020). Teachers' perceptions of and preferences for instructional modes also affect students' learning and the quality of instruction. Therefore, it is also important and urgent to explore teachers' preferences for and perceptions of the implementation of STEM activities. Therefore, in this study, a survey exploring teachers' preferences for and perceptions of STEM activities was administered. The research questions explored in this study were as follows:

- What are the teachers' preferences for STEM activities?
- What are the teachers' perceptions of STEM activities?
- What is the relationship between teachers' preferences for and perceptions of STEM activities?
- What are the direct and indirect indicators in the model of teachers' preferences for and perceptions of STEM activities?

3. Theoretical framework

In this study, an investigation of teachers' preferences for and perceptions of STEM activities was conducted. To answer the research questions, the research mode was developed based on previous studies' suggestions, as shown in Figure 1.

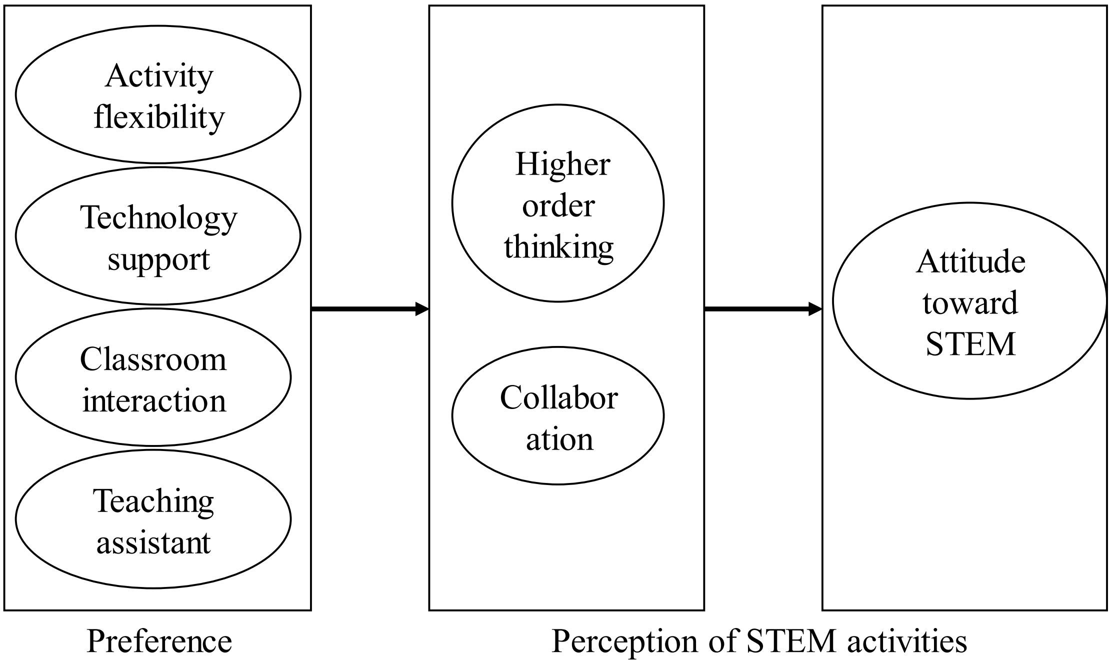

Figure 1. Research model of the teachers' preferences for and perceptions of STEM activities

Many researchers have argued that individual preferences in the teaching and learning process affect learning and teaching outcomes, and that contexts that allow users to engage in relevant activities can be effective (Lin et al., 2019; Liu, 2020). Therefore, two elements were considered in the study: preferences and perceptions. Preferences indicate the teachers' preferences for STEM activities, while perceptions refer to the teachers' perceptions of the effectiveness of STEM activities. As previous studies have suggested (Gale et al., 2020), the factors included in the teachers' preferences for STEM activities consisted of activity flexibility, technology support, classroom interaction, and teaching assistance. On the other hand, the factors included in the teachers' perceptions of STEM activities were higher order thinking, collaboration, and attitude toward STEM activities.

Researchers have also noted that preference for teaching or learning is positively related to learning outcomes (Brand, 2020). By understanding teaching and learning preferences, the learners' or teachers' perceptions of learning can be enhanced, for instance, preferences for technology and students' interaction have been found to be highly related to students' performance of higher order thinking and collaboration (El Nagdi et al., 2018; Holmlund et al., 2018). In addition, the perceptions of learning or teaching were positively correlated to their attitude toward learning or teaching (Wang et al., 2020).

4. Method

4.1. Participants

In this study, an investigation of teachers' preferences for and perceptions of STEM activities was conducted. The teachers who participated in this study had to meet two criteria: (1) they had all conducted mobile technology-assisted learning in the classroom. The mobile learning training was based on the mobile learning training model proposed by Hwang et al. (2017) and Garet et al. (2001); and (2) They all had basic concepts of STEM education or had already conducted STEM activities in the classroom.

To ensure that the activities implemented by the teachers were in line with STEM education principles, the study provided six training workshops and eight regular meetings, as shown in Figure 2. Each session averaged about 2.5 hours, with an average of 50 teachers attending each session. In the training workshops, the study explained the definition of STEM education and teaching examples to help the teachers understand the teaching goals of STEM teaching. The sources of these STEM teaching examples were drawn from the teaching examples of mobile technology-assisted STEM education designed by Hwang et al. (2020); these teaching plans were provided to teachers to help them design distinctive and pedagogically meaningful STEM teaching activities. In the training workshops, this study also guided teachers to co-develop STEM teaching activities. The researcher proposed several educational topics (e.g., using VR for STEM education or developing STEM activities related to environmental conservation), and experienced STEM teachers led teachers without STEM teaching experience to co-create teaching plans. This helped teachers understand the meaning of STEM education and curriculum development methods.

Regular meetings were also arranged to provide teachers with the opportunity to adjust the quality of their teaching. The study invited all participating teachers to physical meetings, and invited experts experienced in promoting STEM and technology-enhanced learning to attend. In addition to teaching experience sharing, the teachers were invited to share the problems they met during the teaching activities, and the experts provided them with practical help. Therefore, through this sharing forum, each teacher could listen to the experiences of other teachers, which encouraged exchanges and inspired the design of teaching.

Figure 2. Training workshops and meetings for teachers to develop their STEM activities

After the teachers had implemented STEM activities, they were encouraged to complete the questionnaire. Finally, a total of 307 questionnaires were returned. These teachers were from 25 high schools and senior high schools in Taiwan. The distribution of the teachers in northern, central, southern, and eastern Taiwan was 42%, 42%, 9%, and 6%, respectively. The percentages of male and female teachers were 42% and 58% respectively.

4.2. Instruments

To achieve the purpose of this study, the questionnaires of teachers' preferences for and perceptions of STEM activities were adopted to measure the teachers' perceptions of conducting STEM activities. All items in the questionnaire were on a 5-point Likert scale ranging from "1 - *Strongly Disagree*" to "5 - *Strongly Agree*."

The teachers' preference for the STEM activities questionnaire consisted of four dimensions, that is, activity flexibility, technology support, classroom interaction, and teaching assistance, with four, five, five, and five items, respectively. The activity flexibility factor was developed by Paechter and Maier (2010), and measures the extent to which teachers prefer that STEM activities provide more learner control. For example, "I prefer STEM activities that provide learners with opportunities for self-directed learning." The technology factor was developed by Sun et al. (2008), and measures teachers' preference for technology in STEM. For example, "I prefer the quality of wireless internet provided by the school to help me with my teaching activities." The classroom interaction and teaching assistance factor were revised from Arbaugh (2002). Classroom interaction was used to measure the teachers' preference that STEM activities provide more peer and teacher interaction. For example, "I prefer the STEM learning environments that effectively support me in guiding students through discussions." Lastly, the teaching assistance measured the teachers' preference for a STEM teaching community. For example, "I prefer that my school's STEM teaching community can help me fix my own teaching activity weaknesses."

The perception of STEM activities consisted of three dimensions, that is, higher order thinking (10 items), collaboration (7 items), and attitude toward STEM activities (6 items). The factor of higher order thinking was revised from the measures developed by Chai et al. (2015) and Schraw and Dennison (1994). It was used to measure teachers' expectations of STEM learning to enhance students' critical thinking or metacognitive skills. For example, "I expect that when students engage in STEM learning they can ask themselves questions to test their level of proficiency." On the other hand, the factor of collaboration was revised from the measures developed by Lin and Tsai (2013) and Lee et al. (2014). It was used to measure teachers' expectations that STEM teaching would enhance students' teamwork and communication. For instance, "I expect students to be proactive in discussing STEM learning with their classmates and come up with new ideas." Lastly, the attitude toward STEM activities was revised from the measure developed by Lee and Tsai (2010). It measured the extent of teachers' attitude toward conducting STEM activities, for example, "STEM learning can enhance students' learning motivation."

4.3. Data analysis

This study involved two phases of the data analysis procedure, that is confirmatory factor analysis (CFA), and structural equation modeling (SEM).

The finalization of the questionnaires was conducted through confirmatory factor analysis (CFA), which clarified the structure of each dimension and examined the construct validity of the questionnaires. The CFA employed the IBM SPSS Amos software to confirm the validity of the scales in the questionnaires (Jöreskog & Sörbom, 1993).

Second, the structure relationships existing between the three dimensions were explored through a structural equation modeling (SEM) analysis. All analyses of SEM in this study were based on a significance level of $p = 0.05$. First, the descriptive statistics were performed to verify the skewness and kurtosis of the values and to establish the data's univariate normality. The critical values were ± 3 and ± 8, respectively (Kline, 2010). Also, we measured the multivariate normality using Mardia's normalized multivariate kurtosis (Mardia, 1970).

5. Result

5.1. Test of the measurement model

First, CFA was conducted to verify the construct validity of the three questionnaires in this study. The construct (scale) and measurement (item), the descriptive data (mean and SD), the item factor loadings, *t* value, average variance extracted (AVE), composite reliability (CR), and alpha value are shown in the tables to evaluate the convergent validity of the two questionnaires' constructs.

In Table 1, the result shows that each scale in Preparation of STEM activity consists of four to five items. All the values of factor loadings are significant ($p < .05$) and higher than 0.5. The AVE values range from 0.45 to 0.68; the CR values are all higher than 0.7 and range from 0.77 to 0.91; and the alpha values range from .75 to .91 with an overall alpha of .95. The convergent validity of the construct is adequate (Fornell & Larcker, 1981). With respect to the goodness-of-fit of the construct measurement, the ratio of the Chi-square to degree of freedom = 2.18, GFI = 0.90, AGFI = 0.87, CFI = 0.96, RMSEA = 0.06, and SRMR = 0.04, showing a good model fit for this construct.

Table 1. The confirmatory factor analysis for the preference of STEM activity questionnaire

Construct and measurement items	Mean	*SD*	Factor loading	*t*-value	AVE	CR	Alpha value
Activity flexibility	4.38	0.46			0.45	0.77	0.75
AF1			0.51	8.69^{***}			
AF2			0.70	12.72^{***}			
AF3			0.72	13.25^{***}			
AF4			0.74	13.83^{***}			
Technology support	4.25	0.62			0.67	0.91	0.91
TS1			0.76	15.33^{***}			
TS2			0.88	16.49^{***}			
TS3			0.88	19.00^{***}			
TS4			0.81	16.73^{***}			
TS5			0.85	18.12^{***}			
Classroom interaction	4.28	0.54			0.67	0.91	0.91
CI1			0.86	18.34^{***}			
CI2			0.84	17.89^{***}			
CI3			0.78	15.95^{***}			
CI4			0.79	16.31^{***}			
CI5			0.82	17.19^{***}			
Teaching assistance	4.39	0.55			0.68	0.91	0.91
TA1			0.78	16.02^{***}			
TA2			0.79	16.30^{***}			
TA3			0.81	16.83^{***}			
TA4			0.85	18.15^{***}			
TA5			0.87	18.84^{***}			

Note. Overall alpha, 0.95; AVE, average variance extracted; CR, composite reliability. $^{***}p < .001$.

Similarly, CFAs were conducted to verify the construct validity of the perception of STEM activities. In Table 2, the result shows that each construct consisted of 10 and seven items. All of the factor loading values are significant ($p < .05$) and higher than 0.7. The AVE values are all higher than 0.6 and range from 0.62 to 0.70, the CR values are all higher than 0.9 and range from 0.92 to 0.96, and the alpha values range from .92 to .96 with an overall alpha of .97. With respect to the goodness-of-fit of the constructs, the ratio of the Chi-square to degree of freedom = 2.71, GFI = 0.88, AGFI = 0.85, CFI = 0.96, RMSEA = 0.08, and SRMR = 0.03, showing a good model fit.

CFA was also conducted to verify the construct validity of the attitude toward STEM activities with only one construct (six items). In Table 3, the results show that all the factor loading values are significant ($p < .05$) and higher than 0.5. The AVE value is 0.70 which is higher than 0.5, the CR value is 0.93 which is higher than 0.7, and the alpha value is also .93. With respect to the goodness-of-fit of the constructs, the ratio of the Chi-square to degree of freedom = 3.07, GFI = 0.98, AGFI = 0.94, CFI = 0.99, RMSEA = 0.08, and SRMR = 0.02, showing a good model fit.

In addition, the overall CFA shows that all the factor loadings of the measured items are higher than the threshold value of 0.51. The range of composite reliability (CR) is 0.76~0.96, and the range of average variance extracted (AVE) is 0.45~0.72, indicating that the present study has good convergence validity of the adopted variables. In addition, the study further compared the correlation coefficient of each variable with its square root of AVE. If the square root of AVE is larger than its correlation coefficient, this shows that each construct has close correlation with the theory itself rather than other theories. In the current study, most of the square roots of AVE are larger than their correlation coefficient. As a result, each variable adopted in the present study has its discriminant validity (Yang et al., 2000).

Table 2. The confirmatory factor analysis for the perception of STEM questionnaire

Construct and measurement items	Mean	*SD*	Factor loading	*t*-value	AVE	CR	Alpha value
Higher order thinking	4.00	0.66			0.70	0.96	0.96
HT1			0.84	17.90^{***}			
HT2			0.82	17.54^{***}			
HT3			0.84	18.11^{***}			
HT4			0.84	18.06^{***}			
HT5			0.84	18.16^{***}			
HT6			0.85	18.47^{***}			
HT7			0.81	17.05^{***}			
HT8			0.82	17.46^{***}			
HT9			0.84	17.93^{***}			
HT10			0.86	18.67^{***}			
Collaboration	4.19	0.59			0.62	0.92	0.92
CL1			0.75	15.20^{***}			
CL2			0.68	13.35^{***}			
CL3			0.77	15.65^{***}			
CL4			0.89	19.64^{***}			
CL5			0.88	19.17^{***}			
CL6			0.74	14.91^{***}			
CL7			0.78	15.98^{***}			

Note. Overall alpha, .97; AVE, average variance extracted; CR, composite reliability. $^{***}p < .001$.

Table 3. The confirmatory factor analysis for the satisfaction of STEM

Construct and measurement items	Mean	*SD*	Factor loading	*t*-value	AVE	CR	Alpha value
Attitude toward of STEM activities	4.37	0.59			0.72	0.93	0.93
AT1			0.86	18.37^{***}			
AT2			0.88	19.29^{***}			
AT3			0.81	16.91^{***}			
AT4			0.86	18.45^{***}			
AT5			0.83	17.51^{***}			

Note. AVE, average variance extracted; CR, composite reliability. $^{***}p < .001$.

5.2. Test of the structural model

Path analysis was utilized to measure the structural model in the second stage of SEM analysis. With respect to the goodness-of-fit of the model, the ratio of the Chi-square to degree of freedom = 1.76, GFI = 0.83, AGFI = 0.80, CFI = 0.95, RMSEA = 0.05, and SRMR = 0.04. The GFI and AGFI values of this sample, 0.83 and 0.80, are below 0.9, but could be deemed as a moderate fit (Doll et al., 1994). The CFI value is close to 0.9, which shows a relatively acceptable fit (Norberg et al., 2007).

The structural relationships among Preference and perception of STEM activities are revealed in Figure 3. The conception of Preference of STEM activities as "Technology Support" and "Classroom Interaction" are significant and positive factors explaining "Higher order thinking" in Perception of STEM activities ($\gamma = 0.22$ and 0.60, $p < .01$ and .001). The two factors are also significant and positive factors explaining "Collaboration" in Perception of STEM activities ($\gamma = 0.15$ and 0.71, $p < .05$ and .001). The conception of Preference of STEM activity as "Activity flexibility" and "Teaching assistance" is significant and positive in explaining "Attitude toward STEM activities" in Perception of STEM activities ($\gamma = 0.22$ and 0.23, $p < .01$ and .001). In addition, "Collaboration" in Perception of STEM activities is a significant and positive factor which relates to "Attitude toward STEM activities" ($\gamma = 0.49$, $p < .001$).

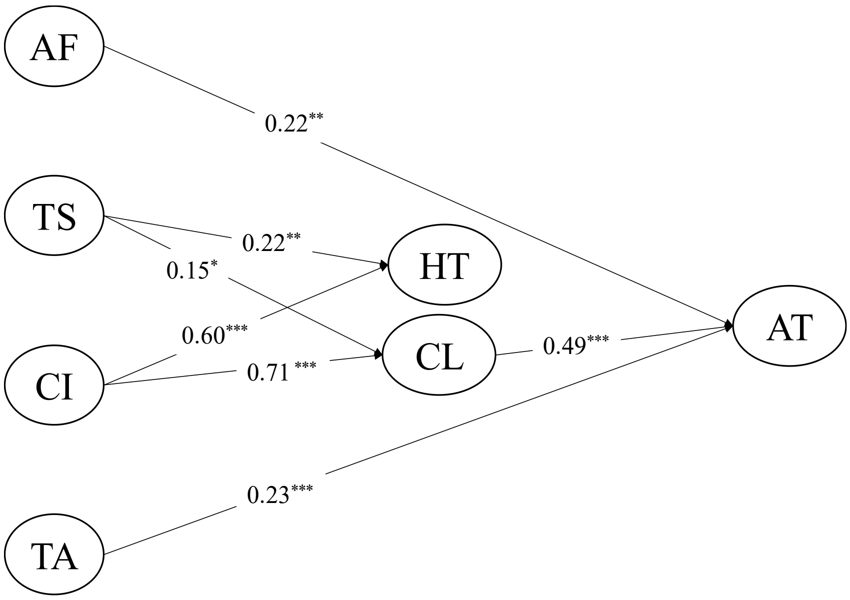

Figure 3. Structural model of the relationships to the teachers' preferences for and perceptions of STEM activities. *Note.* AF = Activity flexibility; TS = Technology support; CI = Classroom interaction; TA = Teaching assistance; HT = Higher order thinking; CL = Collaboration; AT = Attitude toward STEM activities.

In summary, teachers' Preference for STEM activities links to their perceptions of STEM activities. Only two scales of Preference for STEM activity, "activity flexibility" and "teaching assistance," directly link to their attitude toward STEM activities. However, by testing the mediation effect through bootstrapping, teachers' preferences for SEM activities as "Technology support" and "Classroom interaction" play indirect-only mediating roles in their attitude toward STEM activities (standard regression weight = 0.15, $p < .05$, and 0.71, $p < .001$) through their "collaboration" perception of STEM activities.

Table 4 shows the standardized total effect, direct and indirect effects of each variable in the model. The range of the standardized total effect of the predicted variables on the dependent variables in this research model is 0.07-0.60. According to the research model, three endogenous constructs were tested: TS and CI jointly explained HT and CL; the explanatory power was 60% and 68%, respectively, which belonged to the medium to large explanatory power. On the other hand, AF, TS, CI and TA together explained 70% of the variation in AT, which belonged to the medium to large explanatory power. According to the result, it was found that the teachers believed that CI and CL play an important role in STEM activities.

Table 4. Tests of direct and indirect effects

Endogenous variable	Determinant	Direct effect	Indirect effect	Total effect
HT ($R^2 = 0.60$)	TS	0.22		0.22
	CI	0.60		0.60
CL ($R^2 = 0.68$)	TS	0.15		0.15
	CI	0.71		0.71
AT ($R^2 = 0.70$)	AF	0.23		0.23
	TS	-	0.07	0.07
	CI	-	0.35	0.35
	TA	0.22		0.22
	CL	0.49		0.49

Note. AF = Activity flexibility; TS = Technology support; CI = Classroom interaction; TA = Teaching assistance; HT = Higher order thinking; CL = Collaboration; AT = Attitude toward STEM activities.

6. Discussion and conclusion

In this study, the teachers' preferences for and perceptions of STEM activities were investigated. According to the structural equation model, the positive predictive link from "Technology support" and "Classroom interaction" indicated the importance of providing hardware support for teachers. For example, students have access to a smooth wireless network and easy-to-use mobile devices for learning activities. The classroom environment was ideal for group work and discussion. The provision of two environmental and equipment factors was correlated with teachers' perceptions of STEM activities. In fact, this also reflected the teachers' perception of teaching infrastructure and hardware. They considered that while professional training for activity development was important, there should also be an effective mix of teaching hardware and environment.

A positive predictor was also found from "collaboration" to the teachers' attitude toward STEM activities. In other words, the teachers' perception of collaboration is an important mediator between their preferences for STEM activities and attitude toward STEM activities. This study not only reflected the importance of collaboration in teaching and learning, which has been emphasized in many studies in the past (Brand, 2020; Lin et al., 2020), but also illustrated the importance of team problem solving and teacher-student interaction in STEM education. Therefore, when designing STEM activities in the future, it is important to consider not only how well the curriculum is structured for learning, but also whether the students' roles in the activities are clearly defined.

On the other hand, "activity flexibility" and "teaching assistance" performed positive correlation with "attitude toward STEM activities." This result suggested that soft support (e.g., curriculum training and teacher community functioning) can enhance teachers' belief in STEM teaching. Although these two types of support were not directly related to teachers' perceptions of higher order thinking and collaboration, they did have some degree of effectiveness in terms of increasing teachers' beliefs about STEM teaching and learning.

Based on the above findings, the following recommendations are made for future education practitioners:

- School managers should provide support to teachers according to their needs during the curriculum development and teaching process (Adov et al., 2020). For example, teachers should be encouraged to form a community of teachers to develop STEM activities that are unique and sustainable to enhance their attitude in teaching. Friendly collaborative learning spaces and teacher-student interaction can enhance teachers' satisfaction in their teaching.
- It is important to provide a good hardware environment. Including the aforementioned wireless networks and collaborative learning spaces, and encouraging teachers to design activities that make use of collaborative learning strategies can also enhance teachers' perception of STEM education.
- School administrators can organize in-school discussion sessions or cross-school experience sharing sessions. Facilitators can use issue-based discussions and arrange for teachers to co-design teaching plans, for example, discussing the design of cross-curricular activities for the health and science curriculum under COVID-19. By discussing common issues in their lives, teachers can contribute their expertise and creativity to each other.

However, there are still some limitations to this study that should be noted, such as the lack of discussion of students' STEM learning preferences, making it difficult to compare differences in the teachers' and students' preferences. Also, this study only discussed the teachers' self-presentation scales but not their actual teaching effectiveness. Therefore, this study also provides research recommendations for future interested researchers, as follows.

- Researchers can consider comparing the preferences of teachers and students for STEM education, and examine the needs of both samples for teaching and learning through qualitative research.
- Relevant research can also take teachers' teaching plans and actual teaching effectiveness into account to understand teachers' demands for STEM from multiple perspectives.
- It is suggested that students' learning achievement as well as their higher order thinking performance in the context of technology-assisted classroom interaction be evaluated.

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Lo, C. K. (2021). Design Principles for Effective Teacher Professional Development in Integrated STEM Education: A Systematic Review. *Educational Technology & Society*, *24* (4), 136–152.

Design Principles for Effective Teacher Professional Development in Integrated STEM Education: A Systematic Review

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ABSTRACT: In recent years, there has been increasing emphasis on integrated STEM education, reflecting the fact that the four STEM disciplines (i.e., science, technology, engineering, and mathematics) are often integrated in real-world applications. However, most K-12 teachers are trained within their own subject discipline and may not be capable of implementing an integrated approach to STEM education. There is therefore a need to develop teacher professional development (TPD) programs that can provide high-quality learning opportunities and support for teachers. The overarching goal of this research synthesis is to develop a set of design principles for effective TPD for integrated STEM education. To this end, this paper reviews 48 empirical studies and identifies the elements of effective TPD and potential challenges to implementing integrated STEM education. Content knowledge, pedagogical content knowledge, and sample STEM instructional materials are the three most frequently reported elements of effective TPD programs. However, even with TPD, teachers encounter various obstacles to the implementation of integrated STEM education, including pedagogical challenges (e.g., teachers' limited STEM knowledge) and structural challenges (e.g., teachers' lack of preparation time and resources). Based on the findings of this review, a set of design principles (e.g., allocate TPD time for teachers' micro-teaching) is proposed. This review contributes to the design and implementation of TPD programs by leveraging studies of the effective elements of TPD and addressing the potential challenges to integrated STEM education.

Keywords: STEM education, STEM integration, Professional development, Teacher education, Literature review

1. Introduction

In today's information-based and highly technological society, STEM (science, technology, engineering, and mathematics) education is becoming increasingly important (Hauze & French, 2017; Li et al., 2020; Thibaut et al., 2018). Although STEM is four separate subject disciplines in K-12 educational contexts, real-life applications of STEM are naturally integrated (Honey et al., 2014). For example, engineers often need an in-depth understanding of various science disciplines, mathematics, and technology to support their engineering designs and applications (Breiner et al., 2012). Therefore, recent reform initiatives advocate for integrated STEM education in which K-12 students learn to solve problems by drawing on the knowledge and skills of multiple STEM disciplines (see Committee on STEM Education, 2018; Honey et al., 2014; NGSS Lead States, 2013 for a review).

However, most K-12 teachers in STEM subjects are trained within their own subject discipline, and they may not be capable of implementing an integrated and holistic approach to STEM education (Cavlazoglu & Stuessy, 2017; Margot & Kettler, 2019; Rich et al., 2018). Teacher professional development (TPD) is thus a critical strategy for helping in-service teachers to teach STEM subjects using integrated approaches (Brand, 2020; Chai et al., 2019; Williams et al., 2019b). Researchers (e.g., Brenneman et al., 2019; Dyehouse et al., 2019; Goodnough, 2018) have explored the elements of effective TPD for integrated STEM education. However, some of the recommendations made by these studies may not be generalizable, because they are limited to the researchers' TPD interventions in a single context. Therefore, the goal of this research synthesis is to develop a generalizable set of design principles for TPD programs that support integrated STEM education. In addition to effective elements, understanding how TPD facilitators design their programs and teacher challenges can inform the development of the design principles (Lesseig et al., 2016). The following research questions (RQ1 to RQ3) are thus formulated:

- RQ1: How do TPD facilitators design TPD programs for integrated STEM education?
- RQ2: What are the key elements of TPD programs for integrated STEM education?
- RQ3: What are the major challenges perceived or encountered by teachers who have taken the TPD training programs in their implementation of integrated STEM education?

2. Conceptual background

The conceptual background of this review is threefold. First, the theoretical foundation of integrated STEM education is described. Second, previous reviews of TPD for STEM education and their findings (e.g., effective elements and challenges) are highlighted. Third, the model of effective TPD developed by Darling-Hammond et al. (2017) is adopted as a lens for analyzing the empirical studies in this review.

2.1. Integrated STEM education

Integrated STEM education mirrors the real-world work of engineers and scientists (STEM Task Force Report, 2014). Students can experience the interconnected nature of these subject disciplines. English (2016) and Vasquez et al. (2013) defined a spectrum of STEM integration from non-integrated to fully integrated.

- Disciplinary: Concepts and skills are learned separately in each discipline.
- Multidisciplinary: Concepts and skills are still learned separately in each discipline but linked by a common theme.
- Interdisciplinary: Closely linked concepts and skills are learned in two or more disciplines with the aim of deepening student learning.
- Transdisciplinary: Knowledge and skills learned in two or more disciplines are applied to real-world problems and projects, and thus shape the learning experience.
- Progression along this continuum indicates greater levels of STEM integration (English, 2016; Vasquez et al., 2013).

The commitment to the interdisciplinary and transdisciplinary STEM integration is increasing in the education sector (English, 2016). In the United States, for example, NGSS Lead States (2013) established the Next Generation Science Standards (NGSS), which promote more in-depth connections among the STEM disciplines. The NGSS has further emphasized the integration of engineering design and practices into K-12 STEM subjects (see NGSS Lead States, 2013 for a review). According to Kelley et al. (2020), "Engineering design provides an ideal platform for situated learning because it provides a context situated in a problem that is authentic and bound by science and engineering practices" (p. 3). They proposed a conceptual framework for STEM learning (Kelley & Knowles, 2016). In their framework, the connections between science inquiry, technology literacy, mathematical thinking, and engineering design are established by engaging with a community of practice. Various STEM partners, such as practicing scientists, engineers, and technologists, can help teachers and students focus on learning in real-life STEM contexts. However, Kelley and Knowles (2016) cautioned that using a community of practice approach to integrated STEM education can be challenging because it is difficult for teachers to network with STEM professionals. They therefore suggested that a sustainable community of practice (e.g., STEM teachers, researchers, and industry partners) be established through TPD programs.

2.2. Previous reviews of TPD for STEM education

Although there have been quite a few reviews (e.g., Ibáñez & Delgado-Kloos, 2018; Martín-Páez et al., 2019; Thibaut et al., 2018) of STEM education (not necessarily integrated education), a scarcity of reviews has been published on TPD for STEM education. Margot and Kettler (2019) reviewed 25 articles on teachers' perceptions of STEM integration and education. They summarized the barriers reported by teachers, such as curriculum challenges (e.g., difficult to integrate STEM curriculum into existing curricula), structural challenges (e.g., no platforms for teachers from different subject disciplines to collaborate), and concerns about students. Teachers generally believed that well organized and effective TPD could improve their effort to implement integrated STEM education (Margot & Kettler, 2019). In their meta-analysis of 95 TPD programs in STEM disciplines, Lynch et al. (2019) found significantly positive effects of TPD on student achievement (mean pooled effect size = +0.21 *SD*) across studies. They further identified the following characteristics of TPD programs as being associated with improved student achievement (p. 284):

- focusing on improving teachers' content/pedagogical content knowledge;
- focusing on how to use of new curriculum materials; and
- providing summer workshops to begin the TPD learning process, followed by meetings to troubleshoot and discuss teaching practice.

According to Darling-Hammond et al. (2017), however, these characteristics are only few elements (i.e., content focus, use of models and modeling, and sustained duration) of effective TPD. How can we design an overall approach to TPD programs for integrated STEM education? As Margot and Kettler (2019) stated, there is a need to develop a mechanism for TPD that can provide high-quality learning opportunities for teachers.

2.3. Effective teacher professional development

In a frequently cited research synthesis, Darling-Hammond et al. (2017) identified seven design elements of effective TPD: (a) content focus; (b) use of models and modeling; (c) active learning; (d) collaboration; (e) coaching and expert support; (f) feedback and reflection; and (g) sustained duration (Table 1). The TPD program of Roth et al. (2011) was one of their reviewed studies. It began with a three-week summer program focusing on science content (i.e., content focus). The teacher participants engaged in video analysis of teaching practices (i.e., use of models and modeling). They then used what they had learned to plan and deliver their own lessons (i.e., active learning). In follow-up sessions throughout the school year (i.e., sustained duration), they met in small groups facilitated by a program leader to discuss their teaching practice (i.e., coaching and expert support). The groups would collaboratively analyze their teaching practice and student work (i.e., collaboration). The collaborative analysis and subsequent revisions were scaffolded by TPD facilitators (i.e., feedback and reflection). Roth et al. (2011) found that their TPD program significantly improved teachers' content knowledge and their ability to analyze their teaching practice. Most importantly, the participants were more able to facilitate students' science learning. The framework developed by Darling-Hammond et al. (2017) has been used in TPD across contexts. Table 1 shows some new examples from integrated STEM education. Their framework provided an analytical lens for this review.

Table 1. Design elements of effective TPD identified by Darling-Hammond et al. (2017)

Design elements	Description	Examples
Content focus	TPD activities focus on the content that teachers teach in their classroom and context.	Brenneman et al. (2019) built teachers' content knowledge by covering the topics in mathematics (e.g., counting) and science (e.g., animal adaptations).
Use of models and modeling	Teacher participants are provided with instructional models (e.g., demonstration lessons and sample materials) as a vision of practice.	Brenneman et al. (2019) provided model lesson guides with suggestions for modification to fit teachers' school context, such as their available resources and student ability.
Active learning	Teacher participants are directly engaged in the practices which are connected to their classrooms and students.	Williams et al. (2019b) engaged their teacher participants as students in various integrated STEM activities, such as performing design-, build-, and test-based engineering activities.
Collaboration	Teacher collaboration is facilitated at the teacher, department, school, and/or district levels.	Singer et al. (2016) encouraged interactions between teacher participants and community members to share information/designs, negotiate meaning, and build consensus.
Coaching and expert support	Coaching and expert scaffolding support teacher participants' implementation of new curricula, tools, and instructional approaches.	The district coaches of Brenneman et al. (2019) supported their teacher participants in lesson planning, such as adopting integrated STEM activities into their existing curriculum and teaching schedule.
Feedback and reflection	Teacher participants are provided with time to think about, received input on, and make changes to their practice.	Singer et al. (2016) used lesson videos to support teacher reflection on teaching practice. Feedback was provided focusing on both positive exemplars and aspects worthy of improvement.
Sustained duration	Teacher participants are offered multiple opportunities to engage in learning.	The TPD program of Herro et al. (2019) included a year-long field placement, during which the TPD facilitators observed teachers' lessons and offered suggestions for improvement.

3. Method

The methodology of experiential (qualitative) reviews was employed. According to Munn et al. (2018), this systematic review methodology can explore why interventions are or are not effective using qualitative evidence as well as quantitative data of the reviewed studies.

3.1. Search strategies

The process of selecting relevant studies followed the preferred reporting of items for systematic reviews and meta-analyses (PRISMA) statement (Moher et al., 2009). Following Margot and Kettler (2019), four electronic databases were searched: (1) Academic Search Ultimate; (2) ERIC; (3) PsychINFO; and (4) Web of Science. The search string with Boolean operators was as follows: ("professional development" OR "professional learning" OR "teacher education" OR "teacher training") AND STEM AND integrat*. The asterisk was used as a wildcard to include most of the common expressions of integrated STEM education (e.g., STEM integration). The last search was run on July 15, 2020.

3.2. Inclusion and exclusion criteria

Empirical studies published between January 2015 and June 2020 (five and a half years) were reviewed. To be included in this review, the studies had to report on TPD intervention(s) in integrated STEM education and include a description of their TPD programs. The articles without these details were excluded. No constraints were imposed on subject disciplines, but the TPD content had to be in STEM fields, such as life sciences or engineering design (Guzey et al., 2019). Moreover, the authors had to mention the approaches they used to bring "together at least two STEM disciplines through the integration of both content topics and disciplinary practices" (Brown & Bogiages, 2019, p. 116). Thus, studies of single-discipline TPD programs were excluded. As PreK-12 education was the scope of this review, the participants of the TPD programs had to include PreK-12 in-service teachers. Thus, programs restricted to other participants (e.g., pre-service teachers) were excluded. Finally, no constraints were imposed on the language of instruction or the location of the studies. However, the manuscripts had to be written in English and published in peer-reviewed journals because peer review is a useful criterion for including methodologically sound studies (Korpershoek et al., 2016).

3.3. Data extraction and analysis

The following data were extracted from each article: author(s), year of publication, participants, location, subject disciplines, and duration of TPD programs (RQ1); effective TPD elements (RQ2); and challenges that teacher participants perceived or encountered in their implementation of integrated STEM education (RQ3). To answer RQ2 and RQ3, all of the findings/results, discussions, and conclusions of the reviewed studies were coded. In other words, the count of effective TPD elements and challenges was based upon the actual empirical evidence reported in each article (Akçayır & Akçayır, 2017; Akçayır & Akçayır, 2018).

To analyze the data, Miles and Huberman (1994) suggested "creating a provisional 'start list' of codes" (p. 58). Coffey and Atkinson (1996) explained that this is a useful way to begin coding. The framework of Darling-Hammond et al. (2017), shown in Table 1, provided a basis for a thematic analysis of effective TPD elements. To recall, Margot and Kettler (2019) identified challenges to STEM integration and education across 25 articles. Their categories were thus used to develop the initial framework for coding teacher challenges: (a) pedagogical challenges; (b) curriculum challenges; (c) assessment challenges; (d) structural challenges; and (e) student-related challenges. To enhance the consistency of coding, several exemplary quotes (Tables 2 and 3) that could clearly illustrate each constructed theme were identified. Multiple reviews of the data were done to ensure the understanding of each theme (Creswell, 2012). It is important to note that although these frameworks were used a priori, this review did not forcefully impose any of the coding categories onto the data set. New categories (e.g., socio-emotional challenges) were allowed to emerge inductively during the coding process.

To establish coding reliability, 25% of the articles were randomly selected and double coded by a second member of the research team. The percent agreement method was used to calculate a consensus estimate of interrater reliability using the formula given by Stemler (2004). Interrater reliability was greater than 80%. In the event of disagreements, the author and the team member re-examined the articles in question together to come to a consensus.

4. Findings

4.1. Study selection and characteristics of the reviewed studies

As of July 15, 2020, the search string described above had identified 361 journal articles published between January 2015 and June 2020. Some of the articles were removed due to duplication across databases. After analyzing the titles and abstracts of the search outcomes, quite a few articles were excluded because they were not relevant to this review (i.e., TPD in integrated STEM education). Ultimately, 81 full-text articles were assessed for eligibility. Some of them did not meet the criteria outlined above (e.g., no empirical data were provided; no details of their TPD programs were reported). Nevertheless, some of the excluded articles were used for background reference. The final sample included 48 articles. Among them, the following researchers reported on their TPD programs in multiple articles:

- Guzey and her colleagues (i.e., Guzey et al., 2016, 2019; Johnston et al., 2019; Lie et al., 2019);
- Herro and her colleagues (i.e., Herro & Quigley, 2017; Herro et al., 2018, 2019; Quigley & Herro, 2016);
- Kelley and his colleagues (i.e., Kelley et al., 2020; Knowles et al., 2018);
- Rich and his colleagues (i.e., Rich et al., 2017, 2018);
- Ríordáin and her colleagues (i.e., Johnston et al., 2020; Ríordáin et al., 2016); and
- Singer and his colleagues (i.e., Singer et al., 2016; Williams et al., 2019a, 2019b).

Therefore, a total of 37 unique TPD programs (the unit of analysis) for integrated STEM education were analyzed. Figure 1 outlines the process of article selection.

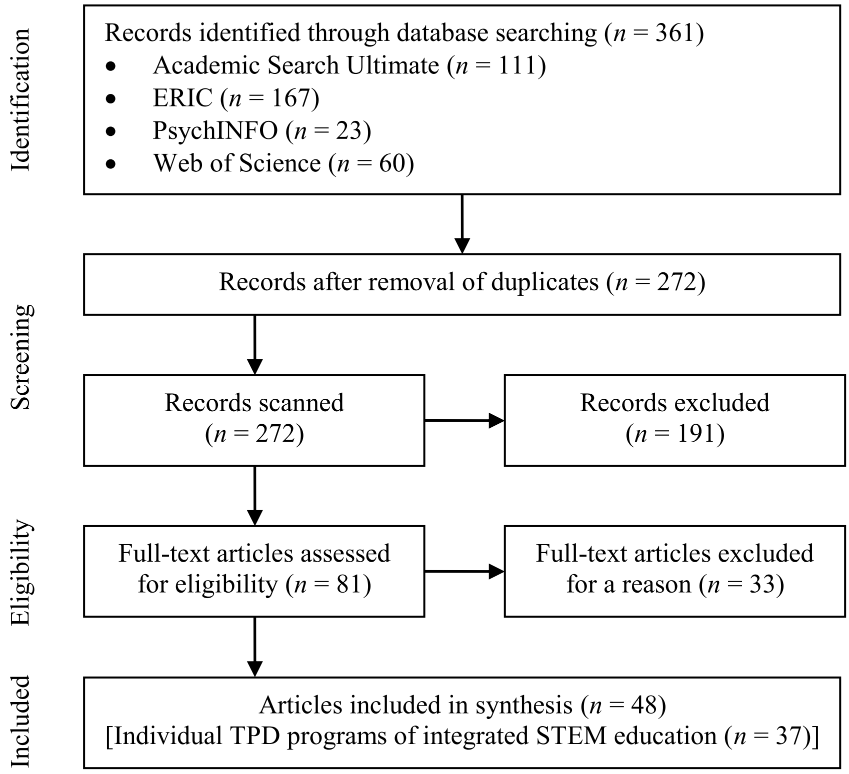

Figure 1. PRISMA flow diagram of article selection

Thirty-one of the 37 TPD programs (83.8%) were conducted in the United States; the others were from Canada (n = 2), Australia (n = 1), Ireland (n = 1), Israel (n = 1), and Saudi Arabia (n = 1). It is worth noting that the number of teacher participants in the TPD programs were not always provided. Besides, researchers might not recruit all teacher participants as their research participants. The available information indicated that the number of teacher research participants (M = 23.3; SD = 17.7) varied across the 48 reviewed studies, ranging from one (e.g., Johnston et al., 2019; Meyer, 2017) to 75 (DeCoito & Myszkal, 2018). Five studies also involved student research participants (M = 716.8; SD = 621.2), ranging from 58 (Kermani & Aldemir, 2015) to 1695 (McHugh et al., 2018). Figure 2 shows that more than half (n = 19) of the 37 TPD programs involved secondary school teachers only (e.g., Aldahmash et al., 2019). Some TPD programs recruited teachers from different school levels, such as elementary and middle schools (e.g., Mathis et al., 2017). In contrast, relatively few TPD programs involved early childhood educators (e.g., Marksbury, 2017).

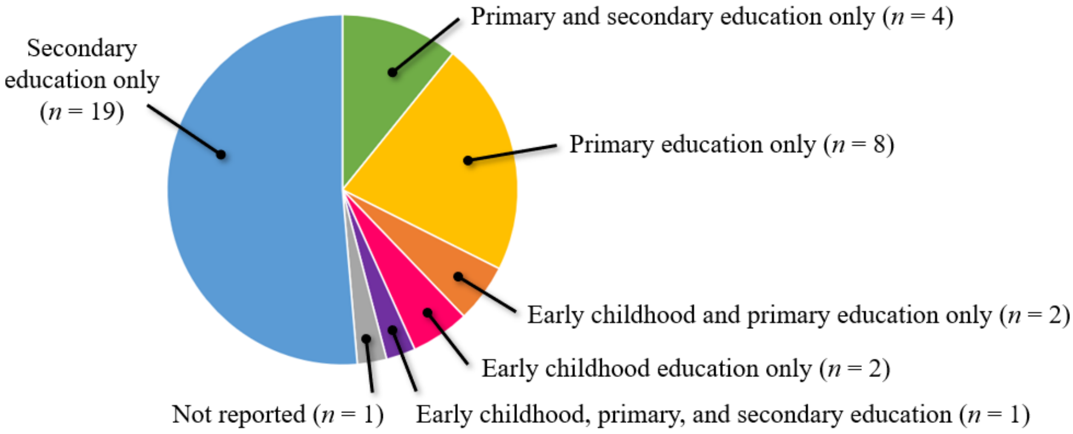

Figure 2. Teaching contexts of the teacher participants (Remarks: Early childhood education includes preschools and kindergartens; primary education includes elementary and primary schools; secondary education includes middle, high, and secondary schools)

4.2. Design of TPD programs for integrated STEM education (RQ1)

Reports on 20 TPD programs explicitly mentioned that the main TPD activities were conducted during the summer (e.g., Ring et al., 2017). However, most of the reviewed studies did not report the exact training hours and days. The available information indicated that in 22 TPD programs the main TPD activities lasted within two weeks (e.g., Constantine et al., 2017), and about 60% of the TPD programs (n = 22) provided ongoing support throughout a semester or academic year (e.g., Baker & Galanti, 2017; McFadden & Roehrig, 2017).

Figure 3 summarizes the findings on TPD content. Seven TPD programs (18.9%) integrated knowledge from all four STEM subjects. For example, Du et al. (2019) focused on "scientific inquiry, engineering and technological design, and mathematical analysis" (p. 107). Fifteen TPD programs (40.5%) integrated knowledge from three STEM subjects, such as "engineering, mathematics, and biology in a biomedical engineering theme" (Al Salami et al., 2017, p. 69). Eleven of the 37 TPD programs (29.7%) focused on two of the four STEM subjects. For example, the TPD program of Murcia and Pepper (2018) aimed to develop teachers' scientific and technological literacy skills. Other TPD programs emphasized pedagogical approaches to integrated STEM education, such as project-based learning (e.g., Herro & Quigley, 2017), or simply stated that they had covered STEM knowledge.

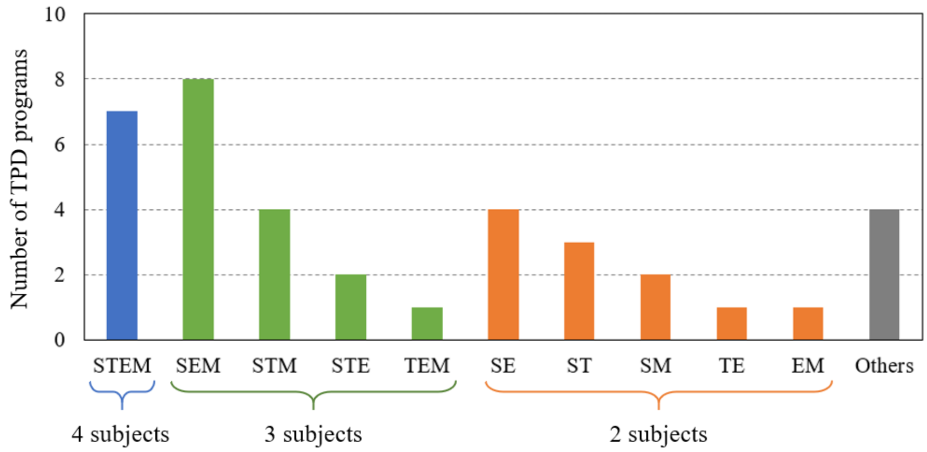

Figure 3. Subject integration in the 37 TPD programs

Figure 4 summarizes the major instructional activities, apart from facilitator presentations, of the 37 TPD programs. Facilitators from 25 TPD programs explicitly mentioned the use of small-group activities (e.g., Ortiz et al., 2015). Nearly two thirds of the TPD programs (n = 24) engaged teacher participants in model activities/lessons that they could use in their classrooms. For example, the teacher participants of McFadden and Roehrig (2017) "experienced STEM-integrated curriculum as learners" (p. 5). In about 60% of the TPD programs (n = 22), teacher participants designed and developed their own instructional materials. In other words, they "were tasked with developing activities for their classrooms" (Brand, 2020, p. 5). In addition, facilitators from 22 TPD programs arranged ongoing meetings with teacher participants. In-school coaching (Smith et al., 2018), virtual meetings (Wang et al., 2020), and attending teachers' planning meetings (Goodnough, 2018) were some of the formats used. A few notable TPD programs (n = 6) used micro-teaching, during which teacher participants piloted their integrated STEM lessons with a small group of summer camp students (e.g., Lie et al., 2019) or graduate students (e.g., Brand, 2020). They could thus revise their teaching plan and instructional materials based on the feedback and reflection on micro-teaching. As shown in Figure 4, other instructional activities of the TPD programs included reflection (n = 15), expert sharing (n = 9), and STEM site visits (n = 4).

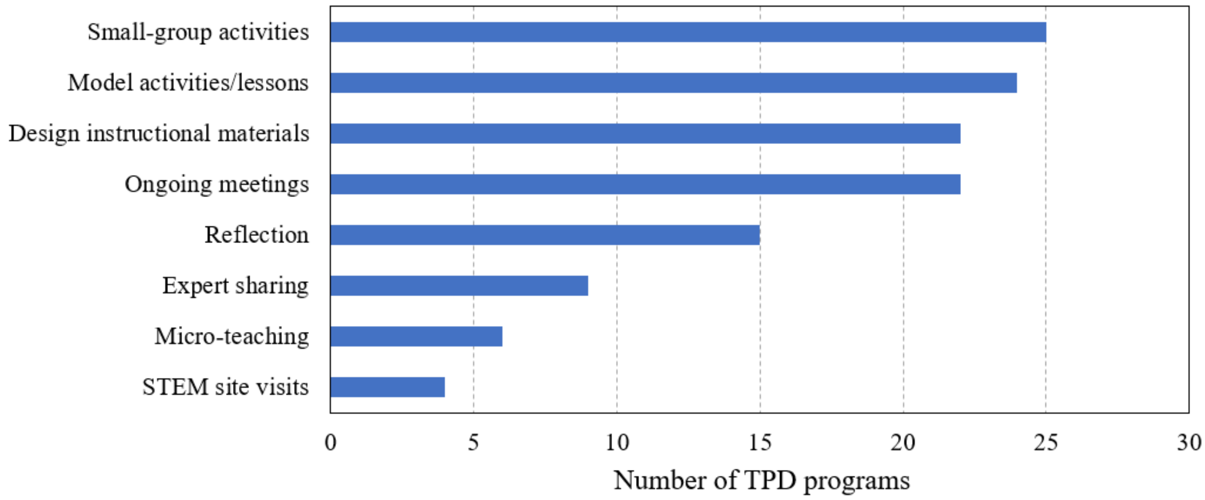

Figure 4. Major instructional activities in the 37 TPD programs (Remark: Totals are greater than 37 because most TPD programs provided multiple instructional activities)

4.3. Elements of effective TPD for integrated STEM education (RQ2)

This review identified a number of elements that contributed to the effectiveness of the TPD programs. These elements were organized using the framework developed by Darling-Hammond et al. (2017) and are summarized in Table 2. First, content focus was the most frequently mentioned element. Following Singer et al. (2016), this theme was further classified into two sub-themes, content knowledge (n = 16) and pedagogical content knowledge (n = 15). The researchers found that building teachers' content knowledge and pedagogical content knowledge improved their implementation of integrated STEM education. Second, nearly 40% of the TPD programs (n = 14) provided evidence to support the use of models and modeling. More specifically, teacher participants stated that sample STEM instructional materials, such as lesson plans (Rich et al., 2018) and hands-on activities (Brenneman et al., 2019), provided ideas and/or became resources for their teaching practice. Third, seven TPD programs found that engaging teacher participants in sample STEM activities/lessons, such as laboratory experience (Wang et al., 2020) and problem-solving activities (Herro & Quigley, 2017), enhanced their understanding of integrated STEM education.

Collaboration was another frequently mentioned element of effective TPD programs, which was divided into in-school interdisciplinary collaboration (n = 7) and beyond school collaboration (n = 6). Taking in-school interdisciplinary collaboration as an example, Wang et al. (2020) found that interdisciplinary collaboration involving teachers from different subject areas facilitated the implementation of integrated STEM education in both classroom and extracurricular activity settings. Furthermore, coaching and expert support for teachers' knowledge of STEM practice (n = 8) and instructional strategies for teaching STEM (n = 3) were essential. According to Herro and Quigley (2017), "the majority of [teacher] participants talked about the value of connecting to experts (via Google Hangout) to assist in teaching content, explaining that they were a bridge to understanding 'problem-based learning in action in their classroom'" (p. 428). Some researchers also provided evidence for the benefits of feedback (n = 7) and teacher reflection (n = 4). One district coach working with Brenneman et al. (2019) said that "the feedback we shared was constructive as they [teacher participants] often applied the suggestions given" (p. 23). Furthermore, their teacher participants recognized the value of reflection. Finally, seven of the TPD programs found that sustained duration was valuable. In Meyer's (2017) 2-year TPD program, the teacher participants set their own goal in the second year of learning. As a result, they were better able to integrate science and engineering in their teaching.

Table 2. Elements of effective TPD in integrated STEM education across the 37 TPD programs

Themes and sub-themes	Count	Representative citations
Content focus		
• Content knowledge	16	"I felt like the task today really pushed my math content knowledge and allowed me to pull more information to create new understandings" (Teacher participant, quoted in Brown & Bogiages, 2019, p. 122).
• Pedagogical content knowledge	15	"[Teacher participants] attempted, liked, or used inquiry-based approaches in their practice … the majority of teachers reported that the STEM-OP [STEM outreach program] workshops influenced their teaching and provided them with new teaching ideas" (DeCoito & Myszkal, 2018, p. 497).
Use of models and modeling		
• Sample STEM instructional materials	14	"Hands-on activities are helpful to me as we share and gather info to bring back to our classrooms" (Teacher participant, quoted in Brenneman et al., 2019, p. 23).
• Active learning		
• Engaging in sample STEM activities/lessons	7	"Going through the process as a student [using the technology] helped me to better understand what I need to do as teacher in my classroom" (Teacher participant, quoted in Herro & Quigley, 2017, p. 430).
Collaboration		
• In-school interdisciplinary collaboration	7	"Ray [one teacher participant] believed that the interdisciplinary approach allowed teachers to use their strengths to teach a more complex idea to students. … Ray was amazed to see Josh and Melvin [two teacher participants in the same school] using analytical skills to solve problems with their hydroponics systems" (Wang et al., 2020, p. 8).
• Beyond school collaboration	6	"[Teacher] participants also noted that collaboration, oftentimes enabled by technology, allowed them an opportunity to connect with experts in the field in content areas outside of their specialty" (Herro & Quigley, 2017, p. 429).
Coaching and expert support		
• Knowledge of STEM practice	8	"TRAILS teachers experienced a blend of science and technology practices during professional development and learned how these practices are used in industry and scientific research from guest speakers. These experiences may have impacted teachers' increase in self-efficacy in teaching STEM" (Kelley et al., 2020, p. 10).
• Instructional strategies for teaching STEM	3	"[T]he coaches' helpfulness—pedagogical instructional assistance, materials instructional assistance, and role as reflective practitioners and encouragers—was evident in how prepared the coaches were to transfer content knowledge to the teachers" (Parker et al., 2015, p. 297).
Feedback and reflection		
• Feedback	7	"[Teacher participants] demonstrated that the feedback we shared was constructive as they often applied the suggestions given" (District coach, quoted in Brenneman et al., 2019, p. 23).
• Reflection	4	"The findings indicated that the teachers' continuous reflections on their practice and the framework initially presented to them, led to an understanding of the value of activities integrating inquiry and engineering design for their students" (Brand, 2020, p. 7).
Sustained duration		
• Sustained TPD	7	"The long-term, sustained professional development model resulted in consistent results in a variety of classroom settings. Student outcomes were measured and indicated improvements in science mastery and positive attitudes" (McHugh et al., 2018, p. 820).

4.4. Teacher challenges to integrated STEM education (RQ3)

Teachers who received the training in TPD programs reported challenges to the implementation of integrated STEM education. Using the framework of Margot and Kettler (2019), the major challenges were organized into five main themes. As shown in Table 3, some of these themes were further categorized into sub-themes. First, pedagogical challenges were frequently reported. Researchers discovered that even after participating in TPD programs, some teachers lacked the necessary knowledge of STEM (n = 20) and level of comfort to implement integrated STEM education (n = 12). In fact, these two sub-themes could be interrelated. As Rich et al. (2017) argued, "Their lack of background in these [STEM materials] and related fields heavily influenced their lower self-efficacy for teaching computing and engineering" (p. 15). Another frequently mentioned theme was curriculum challenges, including time constraints (n = 16) and the discrepancy between STEM and curriculum requirements (n = 7). Herro et al. (2019) pointed out that "The challenge was not in meeting standards per se but instead in meeting standards by timelines" (p. 182). One related theme was assessment challenges. More specifically, the use of class activities was limited by the need to prepare for mandated exams (n = 7). One teacher lamented that "Testing for Educational Progress takes the fun out of what we do as teachers" (Wang et al., 2020, p. 10), although she had the goal of teaching STEM using an integrated approach.

Table 3. Challenges to integrated STEM education identified in the 37 TPD programs

Themes and sub-themes	Count	Representative citations
Pedagogical challenges		
• Teachers' limited STEM knowledge	20	"All three teachers had limited knowledge about technological electronic components such as resistors, diodes, transistors and their functions in an electric circuit" (Awad et al., 2019, p. 5).
• Teachers' discomfort	12	"One of the key disconnects evident in the activity system was the teachers' lack of comfort with teaching in STEM areas" (Goodnough, 2018, p. 2192).
Curriculum challenges		
• Time constraints	16	"[S]he [one teacher participant] was indeed aware of the importance of the mathematics component, but time constraints were hindering greater exploration of the concepts" (Johnston et al., 2020, p. 1409).
• Discrepancy between STEM and curriculum requirements	7	"Mr. Ferroni and Ms. Williams [two teacher participants] both highlighted the fact that the inclusion of angles at this particular time of the school year was not in alignment with the mathematics scope and sequence as set by the district" (Smith et al., 2018, p. 162).
Assessment challenges		
• Confined by mandated exams	7	"Despite the values Malcom [one teacher participant] perceived of STEM integration, he was required to use the standards and teach according to the state exams. This prevented him from using hands-on experiences in teaching STEM because he did not think they fit together" (Wang et al., 2020, p. 11).
Structural challenges		
• Teachers' lack of preparation time	10	"Adapting these new lessons to incorporate either engineering or computing did not just involve having to take time to create the lesson, but also take the time to learn the material for themselves" (Rich et al., 2018, p. 458).
• Teachers' lack of resources	10	"I think for me one of the challenges is going to be … coming up with hands-on things, because budgets are tight in the public school system" (Teacher participant, quoted in Fore et al., 2015, p. 108).
• Absence of school planning	6	"The teachers saw the benefits of integrating both subjects but felt that school structures and supports need to be flexible in terms of accommodating and achieving integration, particularly in relation to timetabling and subject planning" (Ríordáin et al., 2016, pp. 246-247).
Student-related challenges		
• Unable to understand STEM materials	12	"[H]e [one teacher participant] believed the topic was too complicated and too advanced for students at the freshman level and lower, which was the majority of his students" (Wang et al., 2020, p. 11).
• Negative attitudes toward STEM learning	5	"Students not convinced of curricular tie-in" (Teacher reflection, quoted in Al Salami et al., 2017, p. 79).

In the reviewed studies, three types of structural challenges to integrated STEM education were identified: lack of teachers' preparation time (n = 10); lack of resources (n = 10); and absence of school planning (n = 6). In particular, when TPD programs involved the use of specific equipment (e.g., 3D printers), the implementation of their STEM activities might not be feasible in some schools (see Dyehouse et al., 2019; Schelly et al., 2015 for a review). Finally, the studies identified a few challenges related to students. Some teachers reported that their students were unable to understand the STEM materials introduced in the TPD programs (n = 12). One teacher even asserted that "his students would find such problems to be profoundly troublesome" (Fore et al., 2015, p. 106). In addition to student ability, some students might have negative attitudes toward STEM learning (n = 5). For example, teachers might not have a broad buy-in from their students (Al Salami et al., 2017).

5. Discussion

This review analyzed 48 articles reporting on 37 TPD programs for integrated STEM education. Consistent with Lynch et al. (2019), the major themes in this literature were content focus, use of models and modeling, and sustained duration. In fact, content knowledge, pedagogical content knowledge (content focus), and sample STEM instructional materials (use of models and modeling) were the three most frequently reported elements of effective TPD programs (Table 2). Resonated with Margot and Kettler (2019), this review also identified various challenges to the implementation of integrated STEM education in schools. Some challenges (e.g., time constraints and teachers' lack of resources) appear to be generic for non-STEM contexts. TPD facilitators should therefore leverage the literature of teaching and teacher education when designing their TPD programs. In STEM contexts, however, one should pay particular attention to pedagogical and structural challenges – the two most frequently reported challenges (Table 3). Drawing on these findings and the framework of Darling-Hammond et al. (2017), this section develops a set of 10 design principles for effective TPD for integrated STEM education.

5.1. Content focus

5.1.1. Principle 1: Develop a connected foundation of content knowledge and pedagogical content knowledge across disciplines for STEM integration

The inclusion of content knowledge and pedagogical content knowledge is vitally important to TPD programs (Table 2). However, this review indicated that even after training, quite a few teachers lack the necessary knowledge (Table 3). For example, Smith et al. (2018) found that "the teachers did not understand the 'big' picture with regards to either the science or mathematics contents" (p. 164). Without understanding the interconnected nature of STEM disciplines, teachers are not able to achieve greater levels of STEM integration (English, 2016; Vasquez et al., 2013). Therefore, TPD facilitators should (1) develop a connected foundation of content knowledge and pedagogical content knowledge across disciplines for STEM integration, and (2) engage teacher participants in integrating the STEM concepts. Cavlazoglu and Stuessy (2017) used concept maps to facilitate this process. They first identified a list of essential earthquake engineering and related STEM concepts through a discussion with experts in the field. The overall structure and connections among the concepts were then represented using a concept map. In addition to the acquisition of TPD content, Cavlazoglu and Stuessy (2017) emphasized the need to provide teacher participants with concept mapping experience during their TPD program. They asked their teacher participants to develop their own concept maps and establish connections among earthquake engineering and STEM concepts. In this way, they could see how the STEM concepts were integrated.

5.2. Use of models and modeling

5.2.1. Principle 2: Provide exemplars of instructional materials and deliver model activities/lessons

TPD facilitators can provide teacher participants with exemplars of instructional materials (Table 2). These materials can provide ideas or frameworks for their design and implementation of integrated STEM activities (Estapa & Tank, 2017; Guzey et al., 2016). Teachers in some TPD even adopted the materials as their teaching resources. In Rich et al. (2018), for example, "These resources included (but were not limited to): mobile applications, online modules, printed lesson plans, interactive robots, and other resources that they [teachers] could take into their classroom" (p. 453). With these resources, the challenge of teachers' lack of preparation time for STEM activities (Table 3) can be remedied. TPD facilitators should further introduce the design and use of new instructional materials (Lynch et al., 2019). By doing so, Estapa and Tank (2017) found that most teacher participants were able to develop quality lesson plans through reference to their sample activities. As Sias et al. (2017) observed, however, some teachers did not practice what they had learned in their TPD program because they had no personal experience with these educational innovations (Table 3). Therefore, TPD facilitators can demonstrate how to deliver their STEM activities/lessons. Teacher participants in different TPD programs (e.g., Herro & Quigley, 2017; Rich et al., 2017) confirmed that going through the learning process as students increased their understanding and self-efficacy in using those STEM activities/lessons in their classrooms (Table 2).

5.3. Active learning

5.3.1. Principle 3: Allocate TPD time for teachers to develop their own instructional materials

Ríordáin et al. (2016) observed that some teachers did not take ownership of the STEM materials developed by TPD facilitators. The teachers thought that the materials were not suitable for their students and school context (e.g., teaching schedule and lecture hour). In fact, students' difficulty in learning STEM subjects is one of the major challenges to integrated STEM education (Table 3). Viewed from another perspective, this may be the result of teachers failing to provide suitable learning tasks for facilitating their STEM learning. Therefore, TPD facilitators should allocate time for teacher participants to create their own instructional materials. As Fore et al. (2015) stated, teachers understand their students' capabilities as well as the realities of their classrooms. These understandings can inform the development of their own instructional materials. They can tailor the materials for their students and share them with their colleagues. During the development process, TPD facilitators can provide additional supporting recourses as well as feedback for improvement (McFadden & Roehrig, 2017).

5.3.2. Principle 4: Allocate TPD time for teachers' micro-teaching

Consistent with the finding of Margot and Kettler (2019), teachers' lack of comfort was one of the challenges to integrated STEM education identified in this review (Table 3). Rich et al. (2018) found that providing their teacher participants with instructional resources and learning opportunities was insufficient for making them feel comfortable in teaching integrated STEM. Moreover, although the teachers were able to design quality instructional materials for STEM integration, they did not always use the materials and enact their lessons satisfactorily (Estapa & Tank, 2017). To bridge the gap between planning and implementing lessons, TPD facilitators can allocate time for teachers' micro-teaching. For example, the teacher participants in Brand's (2020) program piloted their lessons with a group of graduate student volunteers. At the end of each pilot lesson, the teachers and audience evaluated the quality of teaching using an established rubric (i.e., Science Teaching Inquiry Rubric). They could thus have a more focused discussion on the lesson design and teaching performance. Based on the feedback and reflection on their micro-teaching, the teacher participants could make necessary revisions to their lesson plans and instructional materials before implementing them in their own classrooms. Most importantly, they gained experience delivering integrated STEM activities, which increased their familiarity with the new instructional materials and their self-efficacy (Parker et al., 2015; Rich et al., 2017).

5.4. Collaboration

5.4.1. Principle 5: Facilitate teachers' in-school interdisciplinary collaboration for integrated STEM education

This review confirmed the importance of in-school interdisciplinary collaboration for integrated STEM education (Table 2). Teachers from different subject disciplines can use their strengths and expertise to design instructional materials for students (Johnston et al., 2020). To facilitate such collaboration, TPD facilitators can recruit a team of teachers from the same school (Dyehouse et al., 2019). For example, Kelley et al. (2020) encouraged the participation of two teachers from a school. They could collaborate on lesson plans and implementation according to their school context. Goodnough (2018) further supported a team of teachers in each participating school. Her teams designed and implemented their integrated STEM activities using a collaborative action research approach. The teacher participants thus had the opportunity to share ideas and discuss their practice. This kind of collaboration enables teachers to determine feasible and sustainable ways of implementing integrated STEM education in schools (Dyehouse et al., 2019; Goodnough, 2018).

5.4.2. Principle 6: Familiarize school leaders with the strategies for supporting integrated STEM education

Fore et al. (2015) pointed out that the involvement of school leaders has often been overlooked in integrated STEM education. If school leaders lack a background in STEM, they may not provide relevant support and resources for teaching STEM. In fact, the structural challenges identified in this review (Table 3) must be resolved at the school level (Ríordáin et al., 2016). First, some teachers discussed the difficulty of finding meeting times that suited colleagues from different departments (Quigley & Herro, 2016; Wang et al., 2020). In addition, quite a few teachers did not have sufficient preparation time and resources to design and implement integrated STEM activities (Fore et al., 2015; Ríordáin et al., 2016). To reduce or avoid these problems, school leaders can schedule meetings for interdisciplinary collaboration and allocate additional resources (e.g., budget and manpower) to support the development of new instructional materials. In future TPD programs, an orientation session for the leaders of participating schools can be offered to increase their familiarity with integrated STEM education (Al Salami et al., 2017) and to help them establish a detailed implementation plan (Rich et al., 2017).

5.4.3. Principle 7: Connect teachers to a community of practice that supports integrated STEM education

Kelley and Knowles (2016) emphasized the vital role of a community of practice in integrated STEM education. However, this review found that not all TPD programs connected their teacher participants to a community of practice (Figure 4). STEM teachers from different schools, industry partners, and college faculty can offer insights into a school's teaching practices (Table 2). In particular, STEM professionals can share not only their practice and current job challenges (Dyehouse et al., 2019) but also their career pathways (Knowles et al., 2018). Such sharing allows teacher participants to provide students with authentic learning experiences based on recent STEM practice (Knowles et al., 2018). Herro and Quigley (2017) found that the majority of teacher participants confirmed the value of connecting with experts when developing teaching content and instructional approaches such as problem-based learning. With these connections, teachers can invite STEM professionals to their classrooms as guest speakers, which broadens students' understanding of STEM practice and careers (Knowles et al., 2018).

5.5. Coaching and expert support

5.5.1. Principle 8: Understand the context and needs of teachers and provide relevant support

This review suggested that coaching and expert support in both subject knowledge and instructional strategies for teaching STEM contributed to the effectiveness of TPD programs (Table 2). There are some strategies to ensure the relevance and effectiveness of the support. For example, Williams et al. (2019b) met with district personnel and teacher participants at the design and development phase of their program. In this way, the TPD facilitators and teacher participants could "develop a common vision and design, including the establishment of goals, strategies, needs assessment, targets, and contextual factors" (p. 180). In addition, some STEM professionals and experts may not have the knowledge of the education field and the experience of working with teachers. As the teacher participants in the study by Parker et al. (2015) said, some STEM coaches seemed unapproachable. In future practice, TPD facilitators can brief their coaches on the best coaching practice before the start of their TPD programs (Brenneman et al., 2019). Estapa and Tank (2017) even took a few days to train their engineering fellows in how to support teachers' instructional practice. Using lesson videos and instructional materials, the fellows were familiarized with school contexts and existing curriculums. This kind of preparation can enhance the relevance and effectiveness of coaching and expert support.

5.6. Feedback and reflection

5.6.1. Principle 9: Facilitate teacher reflection on their understanding of STEM integration and teaching practice

Bandura's (1994) theory on improving self-efficacy emphasizes the role of continuous input and feedback throughout the three stages of learning new knowledge, putting the knowledge into practice, and reviewing the outcome of practices (Kelley et al., 2020). As integrated STEM education is new to some teachers (Table 3), Ring et al. (2017) allowed time for teacher participants to reflect on their own concepts both individually and with peers after learning new materials. They found that the reflective and collaborative nature of these TPD activities enabled the teachers to gain a deeper understanding of STEM integration. Furthermore, feedback from coaches or TPD facilitators can guide teacher reflection and inform their instructional improvement (Table 2). Brenneman et al. (2019) adopted a reflective coaching model in their TPD program. During each reflective coaching cycle, a district coach and a member of the research team first observed and videotaped a lesson of a teacher participant. Then, their conversation started with the teacher's self-evaluation of his/her teaching practice, followed by the coach's suggestions based on specific evidence from the lesson. Most of their teacher participants highly valued the reflective coaching sessions and improved their teaching practice.

5.7. Sustained duration

5.7.1. Principle 10: Use summer programs to begin the TPD learning process and provide ongoing support across several years

More than half of the TPD programs in this review were offered in the summer, a time when teachers were relatively less occupied by their teaching load. Echoing Lynch et al. (2019), the findings of this review suggested that ongoing support from TPD facilitators benefited teachers' implementation of integrated STEM education (Table 2). Lie et al. (2019) allowed their teacher participants to enroll in their TPD program repeatedly. They found that the number of years of teacher participation was positively associated with student attitudes toward engineering. Observing one of their teacher participants over a three-year period, Johnston et al. (2019) found that the teacher progressively increased his mastery of integrating science, mathematics, and engineering through engineering talk. The researchers explained that teachers' consecutive participation in the TPD program and ongoing support developed their confidence and increased their ability to teach STEM. However, it is worth noting that TPD facilitators' drop-ins (e.g., school visits) can "create a lot of work" (Al Salami et al., 2017, p. 79) for teachers. In addition to face-to-face formats, TPD facilitators can consider using approaches that have greater flexibility and sustainability, such as virtual meetings (Wang et al., 2020) and online asynchronous coaching (Brenneman et al., 2019).

6. Conclusion and limitations

This review was motivated by the need to develop TPD for integrated STEM education that provides high-quality learning opportunities and support for teachers. A systematic review of 48 empirical studies was conducted to identify the effective elements of TPD for integrated STEM education and the potential challenges to teaching integrated STEM in schools. The importance of content knowledge, pedagogical content knowledge, and sample STEM instructional materials was frequently stressed across studies. However, pedagogical challenges (e.g., teachers' limited STEM knowledge) and structure challenges (e.g., teachers' lack of preparation time and resources) hindered the implementation of integrated STEM education in schools. Based on these findings, this review proposed a set of 10 design principles for TPD programs for integrated STEM education. The principles were established by leveraging the elements of TPD identified as effective in this review, and addressing the potential challenges to teaching STEM. For example, Principle 4 suggests allocating TPD time for teachers' micro-teaching which allows teachers to customize their STEM materials and receive feedback on teaching performance. Although this set of design principles provides a potential agenda for TPD programs, further studies should be conducted to examine the efficacy of each principle. Based on their empirical findings, TPD facilitators can identify the principles that are most relevant to their programs.

Before the design principles are applied, several limitations of this review must be acknowledged. First, this review only considered the topics discussed in the published articles. Therefore, the absence of some types of TPD activities and/or findings does not necessarily imply the absence of these attributes. It only indicates that these topics were not explicitly explored in the published articles. Second, most of the TPD programs in this review were conducted in the United States. Besides, the scope of this review was limited to PreK-12 education. One should therefore consider whether the design principles are context specific. Further research is required to modify or extend them before applying them to other educational contexts, such as Asian counties. Finally, the findings of this review suggest that existing curriculum and assessment requirements still limit the implementation of integrated STEM education in schools. However, these challenges cannot be resolved at a TPD level. These findings thus have implications for policymakers, suggesting the need of significant and long-term reform to the current disciplinary curriculum and assessment practices.

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Teacher Professional Development on Self-Determination Theory–Based Design Thinking in STEM Education

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ABSTRACT: Design thinking has become increasingly important in the context of the current movement toward integrated STEM education. Allied teaching practices often take the form of project-based learning, which represents a major shift in the teaching and learning process and poses challenges for many teachers during implementation. Many professional development programmes for STEM teachers focus on the development of teacher beliefs and content or technological knowledge. Teachers may not have enough opportunities to gain sufficient knowledge of how to foster students' intrinsic motivation for project-based learning. The teacher-support dimensions – autonomy, structure and involvement – distinguished in self-determination theory (SDT) can foster student motivation, and the teaching experience can allow for feedback and reflection. Accordingly, this study aimed to investigate how to design a PD programme consisting of a workshop and actual teaching experience as a way of using SDT-based design thinking in teaching STEM project-based learning. Specifically, the study comprised two interventions designed to examine how teacher/student learning is affected by workshops alone and actual teaching experience, respectively. The participants were 60 teachers and 358 secondary school students. The findings revealed that it is beneficial for teachers to apply what they learned from workshops in classroom teaching and that SDT-based design thinking benefits students more than non-SDT-based design thinking. Hence, this study suggests that professional development should occur over a sustained period, enhance teacher capacity to support students' needs, and offer multiple opportunities for feedback and reflection. Consequently, a model of pedagogical design thinking for professional development programmes is proposed.

Keywords: Teacher professional development, STEM education, Self-Determination theory, Motivation, Design thinking

1. Introduction

In the current movement to develop and implement integrated Science, Technology, Engineering and Mathematics (STEM) education, design thinking has become a focus for students to traverse disciplinary boundaries and draw on knowledge from various disciplines to synthesise and apply new knowledge (Henriksen et al., 2020; Li et al., 2019). Many integrated STEM teaching practices implicitly aim to promote design thinking in the form of project-based learning (e.g., Chai et al., 2020; English, 2019). A design-thinking framework that is being increasingly frequently adopted for many STEM education projects is Innovation Design Engineering Organization (IDEO, 2020), which is based on the five stages of empathize, define, ideate, prototype and test. This movement involves a major shift in the teaching and learning process and poses challenges for teachers (Henriksen et al., 2020; Retna, 2016). Many recent professional development (PD) programmes have focused on training teachers to teach STEM in an integrated context (Chai et al., 2020; English, 2019; Honey et al., 2014; Ring et al., 2017). However, many of them have focused on the development of teacher beliefs, content knowledge, new pedagogy, technological skills and curriculum design (Al Salami et al., 2017; Chai, 2019; Chiu & Churchill, 2016; Ring et al., 2017; Thibaut et al., 2018). Teachers, therefore, may not have been provided with enough opportunities to gain sufficient knowledge of how to foster students' intrinsic motivation for design thinking through project-based learning (Kim & Cho, 2014; Ryan & Deci, 2017, 2020). Given that design thinking usually involves students solving ill-defined problems that are complex and cognitively challenging (Johansson-Sköldberg et al., 2013), it seems important for teachers to provide students with adequate support by developing relevant design-thinking competencies, as well as fostering the intrinsic motivation to undertake complex tasks. Although a number of studies have addressed some of the complex issues in the field of STEM education, the specific question of how to adapt motivational theory appropriately to design effective and sustainable pedagogy and learning in an interdisciplinary context is relatively under-investigated (Chiu & Chai, 2020; Li et al., 2019). Moreover, Van Haneghan et al. (2015) reported that some teachers did not possess sufficient confidence to foster intrinsic motivation among students.

Student motivation and engagement in a prolonged project may go through ups and downs (IDEO, 2020). The students may initially feel excited, but then get demotivated by obstacles such as the inability to consolidate and/or implement ideas in the middle of the journey, at which time they need stimuli to gain energy and confidence to move towards project completion. Teachers play an important role in fostering students' intrinsic motivation (Lam et al., 2009; Lam et al., 2010; Lietaert et al., 2015; Sierens et al., 2009). Self-determination theory (SDT) posits that learning environments should support the individual's innate needs for autonomy, competence and relatedness. Such environments can intrinsically motivate student engagement in activities and enhance performance, persistence and creativity (Ryan & Deci, 2017). In addition, the theory posits that environments that do not support these three psychological needs within a social context will have a detrimental impact on learning. The three dimensions of teacher support identified in SDT for classroom practice – autonomy support, structure and involvement (Lietaert et al., 2015; Roorda et al., 2011) – can be used to motivate and engage students effectively in classroom learning.

In addition, the literature on teacher PD has highlighted another challenge. Without the opportunity to apply teaching ideas and obtain and reflect on feedback, the intended outcomes of PD may not be sufficiently integrated into the teacher repertoire to genuinely change practice (Al Salami et al., 2017; Desimone, 2009; Fore et al., 2015). For example, Fore et al. (2015) highlighted how teacher beliefs filter the information they receive during PD and shape their responses to a new curriculum. Thus, although teachers' knowledge is changed, the knowledge may not be converted into practice. In other words, teacher PD is incomplete if it does not involve the teachers in implementing the newly designed lessons and observing students' changes as feedback for reflective refinement (Chai, 2019). Concomitantly, research on teacher PD should provide evidence of students' changes to ascertain the effects of the PD. There have, however, been relatively few studies that have addressed both teachers' and students' concurrent outcomes from PD.

To address the above challenges, this experimental study compared the perceptual outcomes of two groups of teachers and students who experienced learning to design in the context of STEM education with (SDT) and without (non-SDT) the incorporation of the three teacher-support dimensions. In other words, it is important to note here that three contexts for design were involved in this study. The first was that the teachers attended the workshops designed by the researchers; the second was that the teachers taught the students STEM projects using design thinking; and the third was that the students created artefacts related to the STEM projects.

2. Literature review

In this section, we start by discussing the two challenges of design thinking in integrated STEM education, followed by a discussion of SDT-based teacher support that may help students to negotiate the challenges. We then provide an overview of previous studies on PD programmes for STEM teachers. This section culminates with a discussion of how these factors could be incorporated into the designed intervention to address the two challenges.

2.1. Design thinking in STEM-integrated education

Design thinking is one of the key competencies that students need to develop as an outcome of STEM education (Chai et al., 2020). It refers to the cognitive skills and approaches that designers use to address problems (Cross, 2001). The meaning of design thinking is open to diverse interpretations in different professional fields (Li et al., 2019; Johansson-Sköldberg et al., 2013). For example, it means careful thinking and planning for creativity in business management and can be seen as routine actions for innovation in engineering (Johansson-Sköldberg et al., 2013). Design thinking was popularised by David Kelley, the founder of the IDEO design consulting company and Stanford's d.school in the business and education context (McCullagh, 2010). He advocates for design thinking as a human-centric way to provide a solution-based approach to solving complex problems. It is based on understanding human needs and framing the problems to address those needs by creating many ideas in brainstorming sessions and adopting a hands-on approach to prototyping and testing (Stanford d.school, 2009). This method encourages designers to get to know the users and define their needs through different stages. The user-centeredness inspires designers to present innovative ideas using prototypes. Subsequently, the designers conduct testing to improve the ideas. To apply design thinking in education, Stanford's d.school has further suggested five stages of the design-thinking process for addressing complex and ill-defined design problems. The stages are *empathize*: conduct research to develop an understanding of users' needs; *define*: combine the research and articulate where the users' problems lie; *ideate*: generate a range of creative ideas; *prototype*: build real and tactile representations of selected ideas; *test*: present the prototype to users for feedback. These procedures may be useful for informing teachers and students as to how to go about designing real-world projects and resolving problems (Stanford d.school, 2009).

Design thinking that is usually implemented in a project-based approach can have a significant impact on the curriculum and on instruction (Dym et al., 2005; Li et al., 2019). For example, engineering education has evolved from being largely about engineering solutions and models to including reflective practices that are often characterised by project-based learning (Dym et al., 2005). Mathematics is often perceived as a non-experimental subject, and researchers have advocated including more design activities and project-based learning in mathematics education (Li et al., 2019). Nonetheless, design is a complex and ill-structured task, and student rates of progress may not be consistent. When students are engaged in long-term projects involving design thinking, their commitment may go through ups and downs (IDEO, 2020). For example, the students may initially feel excited, but then get demotivated by obstacles such as the inability to consolidate and/or implement ideas in the middle of the journey, at which time they need support to gain energy and confidence to move towards design resolution. Teachers thus play an important role in fostering intrinsic motivation in students (Lam et al., 2009; Lam et al., 2010; Lietaert et al., 2015; Sierens et al., 2009). Without effective support, students may lack the confidence and skills to complete a project. Thus, one major challenge of conducting a project-based approach is fostering students' persistence and motivation (Lam et al., 2009; Lam et al., 2010). To this end, teacher PD associated with designing STEM projects should include strategies to enhance and maintain students' intrinsic motivation over a prolonged learning time.

Design thinking encourages diverse perspectives in viewing and solving problems, which is vital to creativity and innovation. It has become increasingly important in the current movement to develop and implement integrated STEM education (Honey et al., 2014; Li et al., 2019). The research literature suggests that using design thinking as the main pedagogical method benefits students in learning about STEM. For example, practising design thinking significantly improved academic performance in Physics for female and male students (Simeon et al., 2020). English (2019) reported a longitudinal study of Grade 4 students solving a shoe design problem and found that the students were more aware of the STEM knowledge they needed to use and were able to use the knowledge to make decisions and give explanations. Kelley and Sung (2017) revealed that using a design approach fostered students' computational thinking and significantly improved their science knowledge. Although design thinking seems to enhance students' STEM learning, design problems are ill-structured, cognitively challenging and require multiple forms of knowledge to resolve (Johansson-Sköldberg et al., 2013). The demands on both teachers' and students' knowledge, skills and resilience are high, and thus both teachers and students need support. However, there has been little investigation of how teachers implement these innovative practices to foster design thinking in STEM education (Retna, 2016). There are also, apparently, few studies of whether teachers' efforts to sustain students' motivation for STEM education are successful.

In sum, project-based learning requires teachers to support students' psychological needs to maintain their intrinsic motivation. Teacher PD in integrated STEM project-based learning involving design thinking should pay attention to the question of how to foster students' intrinsic motivation over a period of time.

2.2. Student intrinsic motivation and Self-Determination Theory

Multiple theories of motivation have been developed to account for people's behaviour, including expectancy-value theory (Eccles, 2005), social cognitive theory (Bandura, 1994; Zimmerman, 2000) and SDT (Deci & Ryan, 2017, 2020). The first two theories focus mainly on people's efficacy to learn and achieve their goals as the factors influencing their choices and efforts. SDT, however, focuses on intrinsic motivation directed towards the satisfaction of one's interests or desire for mastery. For the long-term development of students, developing intrinsic motivation is arguably the most important factor in learning.

Enhancing and maintaining students' intrinsic motivation is very important for implementing design thinking. Intrinsic motivation can be explained by SDT, proposed by Deci and Ryan (2017, 2020). This theory aims to explicate the dynamics of human needs and motivation within a social context. It suggests that satisfying individuals' three basic psychological needs – autonomy, competence and relatedness – can foster their intrinsic motivation. Autonomy refers to the desire to self-initiate and self-regulate one's own behaviour; competence refers to the desire to feel effective in attaining valued outcomes; and relatedness refers to the desire to feel connected to others and organisations. This theory is widely applied in educational contexts. Learning environments that support individual experiences of autonomy, competence and relatedness can foster high-quality forms of motivation and engagement for activities, including enhanced performance, persistence and creativity (Ryan & Deci, 2017, 2020).

In line with SDT, teacher practices may be analysed based on the dimensions of autonomy support (autonomy), structure (competence) and involvement (relatedness) (Lietaert et al., 2015; Sierens et al., 2009; Vansteenkiste et al., 2009; Chiu, 2021a; Chiu, 2021b). Autonomy-supportive teachers allow for choices around learning, provide explanations when choice is constrained, avoid the use of controlling language and reduce unnecessary stress and demands on students (Katz & Assor, 2007; Chiu, 2021a, 2021b). Students are encouraged to choose and decide their personal goals based on their self-efficacy and to seek assistance when needed, which helps them to feel empowered in their learning (Chiu, 2021a; Chiu, 2021b). Structure involves the communication of clear expectations with respect to student behaviour (Sierens et al., 2009). Teachers who focus on structure will provide good guidance during lessons (Jang et al., 2010), give competence-relevant feedback (Chiu 2021a; Chiu, 2021b) and assemble effective learning materials for achieving desired outcomes. Involved teachers provide students with emotional and motivational support such as pedagogical caring, involvement closeness, acceptance and help (Chiu, 2021a, 2021b). Such teacher practices make students feel welcome, safe, efficacious and autonomous; they internalise the positive experiences and evince engagement (Ryan & Deci, 2017, 2020).

One of the effective STEM instructional approaches is design thinking, which usually adopts a project-based learning approach (Li et al., 2019). Whereas students need teachers' guidance in STEM learning, teachers need to support and foster students' intrinsic motivation throughout the learning process. Teachers who are capable of intrinsically motivating students in project-based learning are more likely to provide students with integrated experiences (Lietaert et al., 2015; Sierens et al., 2009; Vansteenkiste et al., 2009). Although the teacher-support dimensions have been widely applied to optimise student learning in some other contexts (e.g., Ryan & Deci, 2020; Standage et al., 2005), they have largely been overlooked in project-based learning.

2.3. Teaching experience and teacher professional development programmes

The literature on teacher PD programmes for STEM education has focused on the development of teacher beliefs, self-efficacy, content knowledge, pedagogical content knowledge, technological skills and curriculum design (Al Salami et al., 2017; Chiu, 2017; Chiu & Churchill, 2016; Nadelson et al., 2012; Ring et al., 2017). These programmes aim to prepare teachers to teach STEM in an integrated context by enhancing their science, technology, engineering and/or mathematics subject knowledge, introducing innovative teaching methods for interdisciplinary learning and scaffolding learning outcomes. These STEM-related teacher PD programmes are generally successful in the aforementioned aspects. However, PD for teachers is generally episodic and fragmented and does not afford the time necessary for learning that is rigorous and cumulative (Chai, 2019; Darling-Hammond et al., 2017). A handful of researchers (Chai, 2019; Desimone, 2009) have argued that there is a need to require teachers to apply what they have learned in practice when designing effective teacher PD programmes for integrated STEM teaching.

Accordingly, contemporary programmes should offer opportunities for feedback and reflection and be of sustained duration (Darling-Hammond et al., 2017; Desimone, 2009). Feedback and reflection are powerful tools in designing effective PD because they are critical components of adult learning theory (Thurlings et al., 2013; van Diggelen et al., 2013). Both elements are essential for STEM PD, as STEM teaching methods and content knowledge are likely to be novel to the student. Testing the ideas in classrooms and receiving feedback from the students allows teachers to reflect on their current practice, which is essential for teacher growth. Moreover, meaningful PD requires time and high-quality implementation (Darling-Hammond et al., 2017). Teacher PD programmes should be sustained and offer multiple opportunities for teachers to engage in learning. One-off workshops are more likely to fail if their main goal is to change practice. In sum, effective teacher PD programmes for integrated STEM teaching should carefully consider both student motivation in project-based learning and feedback and reflection on innovative practices.

3. The Present study

As discussed, actual teaching experience affords opportunities for feedback and reflection that enhance teacher competence; the teacher-support dimensions based on SDT can foster students' intrinsic motivation, which is important for project-based learning. This experimental study investigated how to design a PD programme for applying SDT-based design thinking in teaching STEM project-based learning. Specifically, two interventions were conducted to examine how a workshop alone and how actual teaching experience affect teacher/student learning, see Figure 1. There were two groups in each of the interventions. That is, the SDT teacher group received training on design thinking with the three teacher-support dimensions, whereas the non-SDT teacher group received training without the dimensions. The SDT and non-SDT student groups were taught by SDT and non-SDT teacher groups, respectively. Intervention 1 aimed to test the effect of the enhancement of the dimensions given from the workshop on teachers' perceived competence and intrinsic motivation towards design thinking; Intervention 2 was intended to examine whether applying the dimensions in design thinking affected (i) teachers' perceived competence and intrinsic motivation towards design thinking, and (ii) students' perceived competence and intrinsic motivation towards design thinking and cognitive engagement in integrated STEM learning.

Accordingly, the three research questions were as follows:

- RQ1: Will the SDT teacher group perceive stronger gains in their learning about design thinking than the non-SDT teacher group from the workshops? (Intervention 1)
- RQ2: Will the SDT teacher group perceive stronger gains in their learning about design thinking than the non-SDT teacher group after classroom teaching? (Intervention 2)
- RQ3: Will the SDT student group perceive stronger gains in their learning about design thinking and in their integrated STEM learning experiences than the non-SDT students after classroom teaching? (Intervention 2)

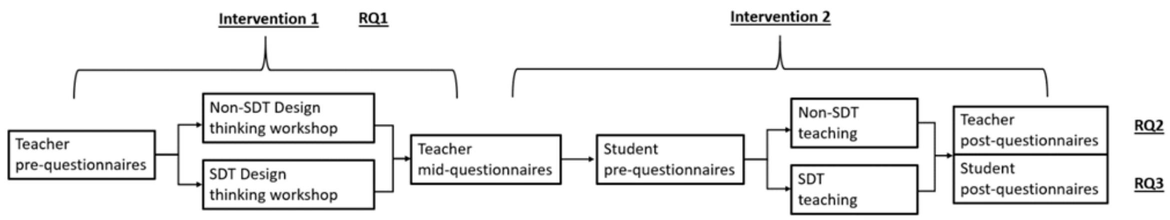

Figure 1. The flow of the interventions in the PD programme

Therefore, we examined three hypotheses:

- (H1) The SDT teacher group will not perceive a significantly stronger sense of competence and intrinsic motivation towards design thinking than the non-SDT teacher group after the workshop (Ring et al., 2017; RQ1);
- (H2) The SDT teacher group will perceive a significantly stronger sense of competence and intrinsic motivation towards design thinking than the non-SDT teacher group after the implementation (Al Salami et al., 2017; Chiu & Churchill, 2016; RQ2); and
- (H3) The SDT student group will perceive a significantly stronger sense of competence and intrinsic motivation towards design thinking, as well as engaging more cognitively in interdisciplinary STEM learning than the non-SDT student group (Chiu, 2021a, 2021b; Chiu & Mok, 2017; Chiu & Lim, 2020; RQ3)

4. Method

4.1. Participants

The participants were 60 teachers and their 358 Secondary Three–level (Grade 9) students from six schools in Hong Kong. The schools were located in different districts and varied in terms of socioeconomic backgrounds and academic standards. The data were collected during a 6-month teacher PD programme. Of the 60 teachers who participated in this study, 60% were male and 40% were female. They were, on average, 33.5 years old (*SD* = 5.4) and had been teaching for an average of 10.5 years (*SD* = 4.8). The student sample was randomly selected and comprised 53% boys and 47% girls. Their mean age was 14.4 years (*SD* = 0.5). The teacher and student participants had not previously taught or learned about design thinking in any subject.

4.2. Procedures

Institutional ethical clearance was followed by participant consent. The study consisted of two interventions – a PD workshop followed by classroom teaching. In Invention 1, the two teacher groups completed an online questionnaire (teacher pre-questionnaire) one week before the workshop and attended four 3-hour PD sessions focused on design thinking over a 2-month period. In the SDT workshop, the roles of three teacher-support dimensions (please see section 2.2 paragraph 3) in design thinking were emphasised, explained and demonstrated, and the teachers explored the SDT pedagogy in STEM teaching. In the first three sessions, a researcher first explained the five stages of design thinking and shared how to teach three STEM topics with design thinking, followed by participant discussions and presentations. In the last session, the researcher discussed with the participants how the three teacher-support dimensions satisfy students' psychological needs in each stage; e.g., avoiding using controlling wordings such as "should or must" to promote autonomy, providing a list of videos that students need for their project, using competence-related feedback to provide a structure that builds students' competence (e.g., advice on what skills and tools are needed for the tasks/ideas) and conducting smaller weekly teacher–student consultation sessions to build relatedness. The teachers created their own support strategies in each stage. In the non-SDT workshops, teacher-support dimensions were not mentioned. We shared and discussed how to use design thinking in teaching STEM in the four sessions. In the last workshop, both groups finished a questionnaire (teacher mid-questionnaire) online. In Intervention 2, the two student groups completed an online questionnaire (student pre-questionnaire) one week before the STEM lessons. The teacher groups applied what they had learned in the workshops to teach their students to take an integrated approach to STEM over 12 weeks. The topic concerned air pollution in Hong Kong. In the final lesson, all of the student and teacher groups finished another online questionnaire (teacher and student post-questionnaire). All of the questionnaires in the interventions were 30 minutes long. All students and teachers were informed that their participation was voluntary and that their answers and identities would remain confidential. They were also informed that their data would be reported collectively and used for research purposes only.

4.3. Instruments

Apart from demographic data, the teacher questionnaire included two variables: perceived competence and intrinsic motivation towards design thinking; the student questionnaire included three variables: perceived competence and intrinsic motivation towards design thinking and cognitive engagement in integrated STEM learning. Each of the variables was measured by five 5-point Likert scale items that had been adapted from previous studies with acceptable reliability and validity (described below). The items were also checked by two experienced teachers to make sure that the wording and language were understandable. Details of the instruments are described below.

Perceived competence toward design thinking was measured using the four items from the perceived competence subscale of the 18-item Intrinsic Motivation Inventory (IMI) (McAuley et al., 1989), with Cronbach's alpha = .80. The items from the competence subscale were: "When I have participated in teaching (for students, teaching is changed to learning) the STEM project, I feel pretty competent with design thinking," "I am pretty skilled at teaching (completing) the STEM project with design thinking," "I am satisfied with my teaching (learning) the STEM project using a design-thinking approach" and "I think I did pretty well at using design thinking in the STEM project." The competence subscale of the IMI showed acceptable reliability with similarly aged groups in a previous study by Standage and colleagues (2005).

Intrinsic motivation towards design thinking was measured using the four items from the perceived competence subscale of the 18-item IMI (McAuley et al., 1989), with Cronbach's alpha = .78. The stem of the items from the intrinsic motivation subscale was modified in this study to ask the question: "When I have participated in teaching (completing) the STEM project." The stem was followed by "because I feel design thinking is fun," "because I enjoy applying design thinking," "because I would describe design thinking as very interesting" and "because design thinking was fun to use." The intrinsic motivation subscale of the IMI showed acceptable reliability with similarly aged groups in two previous studies by Chiu et al. (2020), Chiu and Mok (2017) and Standage and colleagues (2005).

Cognitive engagement was measured using four items adapted from a study by Wang and colleagues (2016), with Cronbach's alpha = .75. They validated and verified items to measure middle and high school students' cognitive engagement in science and mathematics. These items were relevant to our participants and subject domains. For example, "I go through the work for integrated STEM learning and make sure that it's right," "I think about different subjects (science, technology, engineering and mathematics) to solve a problem," "I try to connect what I am learning to things I have learned before" and "I try to understand my mistakes when I get something wrong."

4.4. Research analytic approach

Analysis of covariance (ANCOVA) was used in two observations analyses when assessing the differences in the post-observation means after accounting for the pre-observation values (Bonate, 2000; Chiu & Churchill, 2015). Therefore, we used ANCOVA to analyse the questionnaires to answer the three research questions.

5. Results

5.1. Descriptive statistics

Table 1 presents the descriptive statistics and Cronbach's alpha coefficients (Cronbach, 1951) for all variables. As indicated, the alpha coefficients ranged from .81 to .96, and thus the variables can be considered internally reliable based on the $\alpha = .70$ criterion.

Table 1. Descriptive statistics

Teacher ($N = 60$)	Pre-questionnaire			Mid-questionnaire			Post-questionnaire		
Variables	Mean	*SD*	Cronbach's alpha	Mean	*SD*	Cronbach's alpha	Mean	*SD*	Cronbach's alpha
Perceived competence	3.27	0.44	.82	4.20	0.46	.81	4.17	0.61	.95
Intrinsic motivation	3.37	.47	.94	4.16	.53	.85	4.19	.65	.96

Student ($N = 358$)	Pre-questionnaire			Post-questionnaire		
	Mean	*SD*	Cronbach's alpha	Mean	*SD*	Cronbach's alpha
Perceived competence	3.17	0.43	.90	4.09	0.52	.84
Intrinsic motivation	3.19	0.42	.83	4.14	0.52	.81
Cognitive engagement	3.23	0.42	.84	3.90	0.65	.92

5.2. Analyses of covariance (ANCOVA)

Table 2 shows the ANCOVA results. The analysis of homogeneity of the regression slope showed that (i) the two teacher groups did not differ in perceived competence, $F(1, 56) = 0.16$, $p = .70$, or intrinsic motivation, $F(1, 56) = 1.92$, $p = .17$, on the mid-questionnaire with the pre-questionnaire entered as a covariate; (ii) the two teacher groups did not differ in perceived competence, $F(1, 56) = 2.28$, $p = .14$, or intrinsic motivation, $F(1, 56) = 0.86$, $p = .36$, on the post-questionnaire with the mid-questionnaire entered as a covariate; and (iii) the two student groups did not differ in perceived competence, $F(1, 354) = 0.19$, $p = .17$, intrinsic motivation, $F(1, 354) = 0.55$, $p = .46$, or cognitive engagement, $F(1, 354) = 2.62$, $p = .11$, on the mid-questionnaire with the pre-questionnaire entered as a covariate. These results confirm the homogeneity the data. Next ANCOVAs were conducted to analyse the post-treatment questionnaire scores by excluding the effect of their pre-treatment questionnaire scores.

RQ1 (H1): For the dependent variable perceived competence, there was no significant difference in the mid-questionnaire scores between the SDT ($M = 4.18$, $SD = 0.47$) and non-SDT ($M = 4.23$, $SD = 0.45$) teacher groups, $F(1, 57) = 0.58$, $p = .45$, with a small effect size $\eta^2 = 0.01$. For the dependent variable intrinsic motivation, there was no significant difference in the mid-questionnaire scores between the SDT ($M = 4.25$, $SD = 0.44$) and non-SDT ($M = 4.08$, $SD = 0.60$) teacher groups, $F(1, 57) = 1.66$, $p = .20$, with a small effect size, $\eta^2 = 0.03$.

RQ2 (H2): For the dependent variable perceived competence, the post-questionnaire scores of the SDT teacher group ($M = 4.19$, $SD = 0.49$) were significantly higher than those of the non-SDT teacher group ($M = 3.82$, $SD = 0.57$), $F(1, 57) = 27.51$, $p < .001$, with a large effect size, $\eta^2 = 0.33$. For the dependent variable intrinsic motivation, the post-questionnaire scores of the SDT teacher group ($M = 4.57$, $SD = 0.49$) were significantly higher than those of the non-SDT teacher group ($M = 3.82$, $SD = 0.57$), $F(1, 57) = 30.54$, $p < .001$, with a large effect size, $\eta^2 = 0.35$.

RQ3 (H3): For the dependent variable perceived competence, the post-questionnaire scores of the SDT student group ($M = 4.36$, $SD = 0.43$) were significantly higher than those of the non-SDT student group ($M = 3.83$, $SD = 0.48$), $F(1, 355) = 259.25$, $p < .001$, with a large effect size, $\eta^2 = 0.42$. For the dependent variable intrinsic motivation (H2), the post-questionnaire scores of the SDT student group ($M = 4.35$, $SD = 0.44$) were significantly higher than those of the non-SDT student group ($M = 3.93$, $SD = 0.52$), $F(1, 355) = 135.69$, $p < .001$, with a large effect size, $\eta^2 = 0.28$. For the dependent variable cognitive engagement (H3), the post-questionnaire scores of the SDT student group ($M = 4.27$, $SD = 0.58$) were significantly higher than those of the non-SDT group ($M = 3.53$, $SD = 0.49$), $F(1, 355) = 221.62$, $p < .001$, with a large effect size, $\eta^2 = 0.38$.

We concluded that including teacher-support dimensions in the teacher PD workshop had no significant effect on teachers' perceived competence or intrinsic motivation towards design thinking, and that classroom teaching had an impact on both teachers' and students' perceived competence and intrinsic motivation towards design thinking, and students' integrated STEM learning experience.

Table 2. ANCOVA results of the teacher and student questionnaires

Variable	Group	*N*	Mean	*SD*	*F*	• η^2
Teacher (dependent variables: mid-questionnaire; covariate: pre-questionnaire)						
Perceived competence	SDT	30	4.18	0.47	0.58	0.45
	Non-SDT	30	4.23	0.45		
Intrinsic motivation	SDT	30	4.25	0.44	1.66	0.03
	Non-SDT	30	4.08	0.60		
Teacher (dependent variables: post-questionnaire; covariate: mid-questionnaire)						
Perceived competence	SDT	30	4.19	0.49	27.51^{***}	0.33
	Non-SDT	30	3.82	0.57		
Intrinsic motivation	SDT	30	4.57	0.49	30.54^{***}	0.35
	Non-SDT	30	3.82	0.57		
Student (dependent variables: pre-questionnaire; covariate: post-questionnaire)						
Perceived competence	SDT	178	4.36	0.43	259.25^{***}	0.42
	Non-SDT	180	3.83	0.48		
Intrinsic motivation	SDT	178	4.35	0.44	135.69^{***}	0.28
	Non-SDT	180	3.93	0.52		
Cognitive engagement	SDT	178	4.27	0.58	221.62^{***}	0.38
	Non-SDT	180	3.53	0.49		

Note. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

6. Discussion

The main goal of this study was to investigate how incorporating the three teacher-support dimensions in a STEM teacher PD programme about design thinking affects teacher learning and to determine its implementations for teacher and student learning. The findings afford three major empirical implications and make one theoretical contribution. We offer three practical suggestions for teacher PD programmes.

6.1. Empirical implication

The first implication is that the workshops alone did not result in significant differences among the SDT and non-SDT groups with regard to the participants' perceived competence or intrinsic motivation for SDT-based design thinking (H1). This is not surprising, as such differences move beyond influences on declarative knowledge (Chai, 2019). Insignificant differences may only be evident after teachers have been able to test the ideas in the classroom (Al Salami et al., 2017). This is discussed next for the second implication.

The second implication, as hypothesised in H2, was that after applying what they learned from the workshops in classroom teaching, the SDT group perceived themselves as having a significantly stronger sense of competence and intrinsic motivation towards design thinking than the non-SDT group. This implies that the application of the dimensions boosted the SDT teachers' perceived competence and intrinsic motivation towards design thinking in STEM project-based learning, whereas the non-SDT teachers may not have been able to support project-based learning effectively. These results are aligned with the teacher training research that highlights the importance of teaching experience and practice in changing teacher self-efficacy and attitude. Implementation through experiential teaching is fundamental in preparing teachers to accept new pedagogies (Darling-Hammond et al., 2017; Fore et al., 2015). A plausible explanation for these findings is that while both groups facilitated design thinking, the attention towards the motivational factors may have created a qualitatively different experience for teachers and students. As the teachers in the SDT group were more involved with the students, they would have had a more direct understanding of the students' progress. As they encouraged students' autonomy and provided them with structure, the students were more likely to have been motivated and performed better, which is reflected in the next implication. Significant changes in teachers' perceived design capacity for the motivational design of STEM projects became prominent with a strong effect after actual classroom teaching.

The final implication is that the students in the SDT group reported perceiving themselves as having a stronger sense of competence and intrinsic motivation towards design thinking, and were significantly more cognitively engaged in STEM project-based learning than the non-SDT group (H3). These results align with studies of satisfying autonomy, competence and relatedness needs for intrinsically motivating student engagement (Ryan & Deci, 2017, 2020; Lietaert et al., 2015; Roorda et al., 2011). This intrinsic motivation is very important in activities that involve learning over a period of time, such as during project-based learning. It is essential to build students' efficacy and competence through a structured environment with teachers' encouragement. Educationally, these are the types of experiences that teachers need to foster through their instructional design for project-based learning. Therefore, the teacher-support dimensions play a very important role in learning, particularly over a longer period of time (Ryan & Deci, 2017, 2020; Vansteenkiste et al., 2009).

6.2. Theoretical contribution

The theoretical contribution of this study lies in enriching the literature on STEM education by connecting it with the well-established SDT framework. The findings demonstrate that attending explicitly to autonomy support, structure and involvement during the PD programme is a required dimension for STEM project-based learning. It is thus desirable for future theorisation of STEM education to consider SDT as a foundation for the motivational design of STEM education (Ryan & Deci, 2017, 2020).

As the findings suggest the importance of supporting motivation in design thinking, we propose a framework for pedagogical design thinking to guide teachers to facilitate students' motivational disposition towards design thinking, as shown in Figure 2. Gaining knowledge of design thinking is different from nurturing a design-thinking mindset (H3). School students need inputs from teachers to change how they think about problem-solving over a sustained period. Therefore, we propose to pedagogise design thinking by emphasising that teachers need support. To successfully nurture a design-thinking mindset in students, teachers need to satisfy students' psychological needs – autonomy, competence and relatedness – if students' knowledge of design thinking is to be transformed into a design-thinking mindset. Instead of routinising STEM learning by getting students to complete tasks and create products, teachers should consider applying motivational design to promote intrinsic motivation. In other words, instead of reducing ill-defined design problems to a set of well-defined classroom procedures, teachers should support students in handling the uncertainties through providing choices, resources and possible directions and discussing the alternatives with students. This is crucial to help students to build design dispositions beyond knowledge acquisition.

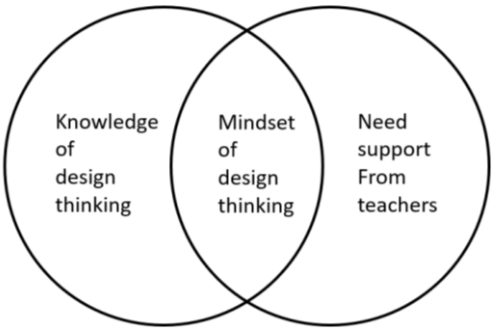

Figure 2. A framework for pedagogical design thinking

6.3. Practical suggestion

This study offers three practical suggestions for teacher PD programmes to enhance teachers' capacity to teach integrated STEM. The first suggestion is that programmes should incorporate time for feedback and reflection (H2 and H3; Darling-Hammond et al., 2017). The programme designers and providers should use co-design, classroom visits and coaching for feedback and reflection, which are critical components of adult learning theory (Thurlings et al., 2013; van Diggelen et al., 2013). They should provide intentional time for teachers to think about, receive input on, and make changes to their new and developing practice.

The second suggestion is that meaningful PD programmes require time for implementation (Darling-Hammond et al., 2017). One-off workshops are more likely to fail if their main purpose is to change practice. Therefore, we suggest that programmes should be held over a sustained period, offering multiple opportunities for teachers to engage in learning a set of concepts or practices in design thinking. Teachers will thus be more likely to transform their teaching practices and student learning (H2 and H3).

Mastering pedagogical practices that facilitate design thinking is crucial to creating positive and empowering learning experiences for students. Because design thinking is often implemented in a project-based approach, enhancing and maintaining students' intrinsic motivation is very important (Lam et al., 2009). In our final practical suggestion, we propose that teacher PD programmes should include teacher-support dimensions – autonomy support, structure and involvement – in design thinking, as shown in Figure 3. It is suggested that teachers develop autonomy support in the first two stages – empathize and define – because students should feel they have the choice to identify problems that are relevant and interesting to them. Teachers are advised to pay attention to structure in the last three stages – ideate, prototype and test. Students need feedback to revise their ideas for feasibility because they may be too abstract or challenging. Teachers should be involved in all stages because students' learning is not just their own responsibility but also that of their teachers.

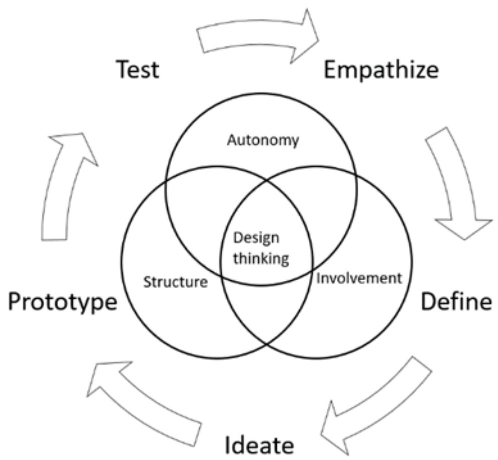

Figure 3. Pedagogical design thinking

7. Conclusion

This study has demonstrated that the integration of SDT elements in STEM education promotes perceived competence and intrinsic motivation towards design thinking. When teachers implement autonomy-supporting strategies, provide enriching structures and relate to students through involvement in group consultations, both students and teachers achieve substantial development. There are two suggested future directions: teacher education and design thinking. First, students' intrinsic motivation over a period of learning time and teaching experience for feedback and reflection should be the focus of teacher PD programmes that aim to change practice (Darling-Hammond et al., 2017). Second, our findings suggest that design thinking, allied with teacher support, could be a viable way to positively foster students' STEM-integrated learning experience.

8. Limitation

Four limitations of this study are noted here. First, while this study appears to support the effects of the teacher-support dimensions on teachers' and students' perceived competence and intrinsic motivation, more studies are needed to validate these findings. The results of the present interventions could be extended by additional studies of other teacher-support strategies (Ryan & Deci, 2017, 2020; Standage et al., 2005). Second, this study did not differentiate between or scrutinise the underlying effect of each stage of the design-thinking process (Stanford d.school, 2009), and future research should be conducted to investigate how teachers support students in each stage. Third, just one cycle of classroom teaching was adopted in this paper, and so the full effects of feedback and reflection may not have been revealed; future studies should adopt iterative cycles. The final limitation is that only intrinsic motivation was used in the interventions, which did not distinguish between different types of motivation. Future studies could adopt questions from the study by Zycinska and Januszek (2019) to measure the self-determination continuum to gain more insights.

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Infusing Computational Thinking into STEM Teaching: From Professional Development to Classroom Practice

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ABSTRACT: Despite increasing attention to the potential benefits of infusing computational thinking into content area classrooms, more research is needed to examine how teachers integrate disciplinary content and CT as part of their pedagogical practices. This study traces how middle and high school teachers (n = 24) drew on their existing knowledge and their experiences in a STEM professional development program to infuse CT into their teaching. Our work is grounded in theories of TPACK and TPACK-CT, which leverage teachers' knowledge of technology for computational thinking (CT), CT as a disciplinary pedagogical practice, and STEM content knowledge. Findings identify three key pedagogical supports that teachers utilized and transformed as they taught CT-infused lessons (articulating a key purpose for CT infusion, scaffolding, and collaborative contexts), as well as barriers that caused teachers to adapt or abandon their lessons. Implications include suggestions for future research on CT infusion into secondary classrooms, as well as broader recommendations to support teachers in applying STEM professional development content to classroom practice.

Keywords: Computational thinking, STEM, TPACK, TPACK-CT, Professional development, Teacher learning, Computer science education

1. Introduction

An emerging body of research (Kafai et al., 2020; Li et al., 2020) has outlined the potential promise--and potential pitfalls--of infusing computational thinking (CT) into disciplinary instruction. Since Jeannette Wing (2006) described computational thinking as a "fundamental skill for everyone, not just for computer scientists" (p. 33), researchers and practitioners alike have sought to identify models, supports, and common pedagogical practices for integrating CT into P-12 educational systems (Barr & Stevenson, 2011; Grover, 2017). Researchers (Yadav et al., 2016) argue that CT, which refers to a set of practices and habits of mind that students can learn with or without the introduction of technology (Papert, 1980; Voogt et al., 2015), can connect to and even enhance numerous disciplinary practices in content area classrooms.

CT provides a quintessential example of real-world problem solving that is integral to STEM education (Israel et al., 2015). Further, infusing CT into disciplinary classrooms can provide opportunities for students and teachers to solve problems while working collaboratively, embedding design methodologies, and using technology appropriately (Shute et al., 2017; Weintrop et al., 2016). However, teachers need explicit support in making these connections between CT and STEM content and understanding the potential benefits for their students (Li et al., 2020).

Although a growing body of literature has demonstrated the critical importance of professional development (PD) in shifting teacher beliefs and self-efficacy for integrated STEM teaching (Nadelson et al., 2013), a crucial and often under-investigated factor is how teachers apply and transform new learning to classroom practice (Goodnough et al., 2014). This is particularly relevant to integrated PD in STEM and CT, which is still in the nascent stages (Hestness et al., 2018). This study draws on theories of TPACK and TPACK-CT to examine data collected from a 3-year, NSF-funded research project to support middle and high school teachers as they infuse CT into their disciplinary teaching. During two week-long PD workshops held in Summer 2018 across two Southeastern states, 116 teachers designed CT-infused lessons using Snap!, a block-based programming tool similar to Scratch (Harvey & Mönig, 2010). In order to trace teachers' experiences with infusing CT, this paper examines data from a purposive sample of 24 teachers who implemented lessons in their classrooms during the 2018-2019 academic year. Data included elements of process and product related to teachers' CT-infused lesson implementation (pre- and post-lesson reflections, classroom video recordings, lesson plans, and interviews). We identify how teachers drew on their developing knowledge of TPACK-CT to transform three key pedagogical supports (articulating a key purpose for CT infusion, scaffolding, and collaborative contexts) for classroom contexts, as well as barriers that caused teachers to adapt or abandon their lessons. We conclude with suggestions for future research on CT infusion, as well as broader implications to support teachers in applying STEM professional development content to classroom practice.

2. Conceptual framework

Technological Pedagogical Content Knowledge (TPACK; Mishra & Koehler, 2006) was used as both a guiding framework for the design of the Infusing Computing professional development and as an analytic lens for examining the supports and barriers that teachers encountered while implementing CT-infused lessons in their classrooms. TPACK focuses on the interactions among three types of knowledge: subject matter or content knowledge (CK), technology knowledge (TK), and pedagogical knowledge (PK) (Angeli et al., 2016a). In the differentiation across these three types of knowledge, the TPACK framework outlines how content is being taught, and pedagogy, or how the teachers instruct that content. This designation is important because the technology being implemented must communicate the content and support the pedagogical opportunities in order to enhance students' learning experiences. Recent critiques (Koh, 2019; Saubern et al., 2020) have called attention to the need to focus not on individual elements of TPACK, but rather to use it to understand and develop the knowledge teachers need to integrate technology into teaching.

While computing is not simply technology integration, Mouza et al. (2017) suggested that an expanded model of TPACK-CT can support pre-service teachers' understanding of CT integration into content learning. When learning about CT concepts, pre-service teachers develop specialized technological knowledge (i.e., TK-CT), which refers to the "computing tools, vocabulary, practices, and dispositions" that interact with CK and PK (p. 63). Rather than focusing on the individual elements and obscuring how teachers use technology to meet teaching and learning goals (Saubern et al., 2020), TPACK-CT is a holistic model that explains how teachers move from fragmented understandings to bring together CT concepts, tools, existing disciplinary practices, and pedagogies (Mouza et al., 2017). This conceptualization presents a shift in CT-infused instruction from a view of CT skills that are generalizable across the curriculum to a disciplinary perspective of practices specific to the specialized language, knowledge, and habits of thinking within particular subject areas.

While initially developed for use with pre-service teachers, we believe that TPACK-CT provides an important lens for supporting and studying in-service teachers' development. Unlike pre-service teachers, in-service teachers have specific student needs and teaching contexts to consider as they integrate CT into their classrooms. They also bring a wealth of expertise and pedagogical content knowledge developed over years of practice. Explicating how TPACK-CT functions in relation to in-service teacher PD offers a potentially valuable way to understand how experienced teachers transform content-driven, pedagogically sound, uses of technology to support students in understanding and using CT to enhance disciplinary learning.

3. Review of the literature

In the following sections, we describe prior research and perspectives emerging from various bodies of literature--CT in educational contexts (Grover & Pea, 2013; Wing, 2006), CT as disciplinary practice (Weintrop et al., 2016), and integrated PD models in STEM and CT (Nadelson et al., 2012; Ring et al., 2017). Given ongoing debates about what CT is and how to best teach it in disciplinary classrooms (Yadav et al., 2017), we draw from multiple perspectives targeting teacher professional learning STEM education in order to highlight the social and cognitive processes needed to embed CT into disciplinary teaching (Kafai et al., 2020; Li et al., 2020).

3.1. Computational thinking in educational contexts

Generally, CT is seen to encompass many of the critical problem-solving practices and concepts that draw on computer science (Wing, 2006), including "problem representation, prediction, and abstraction" (Israel et al., 2015, p. 264). Computer science (CS) in this lens is identified as the study of computers, hardware, software, and the algorithmic processes and applications that impact society (Lye & Koh, 2014). Researchers (Smith, 2016) have argued that students need a deep understanding of CT concepts and practices in order to navigate a workforce that is largely driven by networked communities, data analytics, and algorithmic processes. These intersections require individuals to think algorithmically to solve ill-formed problems with varying levels of ambiguity in facts and abstraction (Yadav et al., 2017). In educational contexts, CT also involves adapting problem-solving approaches from CS in order to enable deeper content area learning (Grover & Pea, 2013).

How computational thinking is defined—and distinguished from other terms such as programming, computing, and coding—has been the subject of much debate in the CS education literature. Yadav et al. (2014) found that classroom teachers initially view CT as the basic use of technology and computers in the classroom, while Cateté et al. (2018) suggest that teachers need clear definitions of CT elements to integrate CT into their teaching. For the purposes of this study and to make CT elements more adaptable to different disciplines, we refined the four elements of Google's (2018) CT definition as follows: (1) Pattern Recognition: observing and identifying patterns; (2) Abstraction: identifying ideas that are important by naming concepts and hiding details; (3) Decomposition: breaking down problems into meaningful smaller parts; and (4) Algorithms: providing instructions for solving a problem and similar problems (Dong et al., 2019). This conceptualization provided a model for teachers' development of specialized technological knowledge for CT instruction (TK-CT) and helped them draw on their pedagogical content knowledge (PCK) to use and adapt CT elements in discipline-specific and interdisciplinary ways.

3.2. Computational thinking as disciplinary practice

There is an urgent need to infuse "algorithmic problem-solving practices and applications of computing across disciplines" (Barr & Stephenson, 2011, p. 112). To address this need, CT can be taught outside of CS classrooms through integrated and interdisciplinary STEM lessons (Yadav et al., 2014). Weintrop et al. (2016) argue that disciplinary classrooms can provide "a meaningful context (and set of problems) within which computational thinking can be applied" (p. 128).

Despite a growing interest in how a reciprocal relationship between content learning and CT can enrich student learning (Hambrusch et al., 2009; Lin et al., 2009; Weintrop et al., 2016), practical models for infusing CT into disciplinary teaching have remained largely unexplored across both research and practice (Grover & Pea, 2013). As Lye and Koh (2014) argue, the teaching and learning of "computational thinking in naturalistic classroom settings are still not well-understood" (p. 57). Much of the existing research on teacher integration of CT has focused on shifts in teacher beliefs and self-efficacy (Chang & Peterson, 2018; Jaipal-Jamani & Angeli, 2017) and the development of teacher knowledge of CT (Angeli et al., 2016b; Yadav et al., 2017). However, while research has demonstrated that successful CT integration requires teachers to believe in its importance, belief alone is insufficient (Rich et al., 2020a).

Conceptualizing CT as a disciplinary practice that can support content area learning represents "a re-direction in CT education to explicitly and substantially link to STEM education, beyond just CS" (Li et al., 2020, p. 152). In an attempt to make explicit the connections between CT and STEM education, this study foregrounds the critical thinking elements of CT and the design thinking process, with a secondary focus on programming. This framing supports teachers in developing TPACK-CT, which connects CT concepts to classroom teaching practices. In response to the need to contribute to the "scarce" literature on teacher implementation of CT-infused disciplinary teaching (Yadav et al., 2020), this study explores how teachers transform professional learning for classroom practice and the barriers they face.

3.3. Integration of STEM and CT into professional development

As is the case with definitions of CT, there are numerous conceptualizations of integrated STEM education, including interdisciplinary approaches that connect two or more STEM disciplines (Sanders, 2009) and transdisciplinary approaches (Vasquez et al., 2013) focused on applications of STEM content to complex problem-solving (Brown, 2012; Rinke et al., 2016).

Previous research (Avery & Reeve, 2013; Nadelson et al., 2013; Norris & Soloway, 2016; Ring et al., 2017) suggests that effective STEM PD models support shifts in teacher self-efficacy about STEM teaching and offer explicit opportunities for teachers to practice integrating appropriate STEM content. As teachers face numerous pressures in terms of covering rigidly structured curricula (Avery & Reeve, 2013), a key element of STEM PD design involves explicitly linking innovative pedagogies to existing standards. Further, as teachers come to any professional learning experience with varied goals and learning trajectories, PD must be explicitly designed to personalize content and outcomes for classroom application (Ring et al., 2017). This is particularly relevant for PD that aims to develop teachers' CT knowledge and pedagogical practices, which are emerging areas for pre-service and in-service teacher education (Angeli & Giannakos, 2020). CT PD also represents unique challenges in that teachers must simultaneously develop CT knowledge and skills for themselves and for the students they teach (Mouza et al., 2017).

Despite inherent connections between CT and STEM, much of the research on STEM education does not consistently connect thinking and computational processes (Li et al., 2020). As Israel et al. (2015) argue, "More research is necessary in order to understand implementation, supports that teachers require, and the types of instructional strategies that could support diverse learners in engaging in computational thinking" (p. 277). There are a number of potential explanations for this gap in the knowledge base--CT infusion requires teachers to bring together complex, and often contradictory, disciplinary norms and practices (Israel et al., 2015); rethink pedagogical approaches (Guzdial, 2008); and reconsider their identities as experts (Israel et al., 2015).

While growing attention has focused on the needs of pre-service teachers (Chang & Peterson, 2018), researchers (Sands et al., 2018) have argued that in-service teachers need ongoing PD to correct misconceptions, learn how to engage their students with CT, and practice and refine new pedagogical practices. A key mechanism for this work is to provide in-service teachers with the training, tools, and resources to understand the benefits of CT infusion, all while they learn how to put concepts into practice. As described in the following sections, this study and the Infusing Computing PD draws on TPACK and TPACK-CT, as well as existing research on effective STEM PD, CT integration into disciplinary content, and CT as a disciplinary practice to investigate how teachers create and transform pedagogical supports for students and the barriers they face as they infuse CT into their pedagogical practice.

4. Methods

This study addresses the following research questions:

- How did pedagogical supports for CT-infused lessons function in classroom settings?
- What barriers did teachers face as they implemented CT-infused lessons into their disciplinary teaching?

Next, we describe the context for the study, the 3C professional development model, teacher perceptions of the PD experience, data sources, and analytic techniques.

4.1. Context for the study

This study emerges from a three-year research project, Infusing Computing, which aims to document how middle and high school teachers create and implement interdisciplinary, CT-infused lessons. The project incorporates multiple supports for teacher learning and lesson implementation: (1) week-long summer PD workshops designed for non-computing teachers; (2) academic year support; and (3) opportunities to return for additional summer PD sessions and/or serving as teacher-leaders.

This paper draws on quantitative and qualitative analyses of data from Year 1 of the project, which included two one-week summer PD sessions held in two Southern states in Summer 2018 and the 2018-2019 academic year implementation. The focus of this study is teachers' implementation of PD content, including their CT-infused lessons, into their classrooms. Of the 116 teachers who attended the Summer 2018 PD sessions, 24 teachers completed lesson implementation and shared the following data sources with the research team: pre-implementation reflections, post-implementation reflections, updated teacher-created lesson plans, end-of-year surveys, and classroom videos. 13 teachers also participated in semi-structured interviews. We chose to focus specifically on the sample of 24 teachers, rather than all teachers who implemented lessons but did not video-record or submit reflections, in order to triangulate findings across data sources.

Of the 24 teachers in this study, 37.5% identified as science teachers, 20.8% identified as math teachers, 16.7% identified as English teachers, 12.5% identified as social studies teachers, and 12.5% identified as other (i.e., business, Spanish, forensic science, instructional coach, and technology). Teachers had an average of 14.0 years of teaching experience; two teachers had fewer than three years and nine teachers had more than 20 years. Most teachers reported a relatively high level of comfort with using technology as a pedagogical tool; on a pre-PD survey item measuring teachers' self-efficacy in using technology, the mean score was 3.81 (n=24). However, only a small percentage of teachers (16.7%) had used programming tools prior to the PD.

4.2. The 3C model

The summer PD workshops were structured according to the 3C (Code, Connect, Create) model (Jocius et al., 2020). During the *Code* sessions, teachers developed their technological content knowledge (TCK) and specialized technological knowledge (TK-CT) by learning how to code in Snap!, a block-based programming environment similar to Scratch that allows users to create animations, games, and other multimodal projects (Maloney et al., 2010). The Code sessions introduced concepts and operations in the Snap! programming environment (e.g., sprites, blocks), control structures (e.g., loops, conditionals, variables), and lists. Facilitators modeled pair programming, which positions one participant as the “driver” using the computer and the other as the “navigator” who provides verbal instructions (Hanks et al., 2011). Then, teachers worked in pairs to use, modify, and create (UMC) programs (Dong et al., 2019; Lee et al., 2011). As teachers used existing Snap! simulations and modified programs, they engaged with CT practices from the perspective of the learner.

Connect sessions were designed to support teachers in identifying authentic opportunities for bridging disciplinary practice and CT, which drew on their content knowledge (CK) and pedagogical knowledge (PK). During Connect sessions, teachers developed understanding of how CT-related concepts, computing tools, and practices (TK-CT) can be infused into disciplinary content (CK) and pedagogies (PCK) to create meaningful outcomes (TPACK-CT). As teachers learned about CT in different disciplinary contexts, they were also tasked with unpacking the practices involved with teaching within their disciplines. The goal was for them to see CT not as a technology-specific practice best left for CS classes, but as a learning process with the potential to create new opportunities for consuming and producing disciplinary content. During Connect sessions, teachers created curriculum maps to identify standards, activities, and supports for disciplinary CT infusion.

Finally, *Create* sessions supported teachers in creating CT-infused lessons, developing their pedagogical content knowledge (PCK) and knowledge of specific strategies to infuse CT (TPACK-CT). Lessons included (1) a Snap! prototype; (2) a detailed lesson plan; and (3) supplemental pedagogical materials. Each Create session included opportunities for reflection on new learning from Code and Connect sessions, structured goal-setting activities, and individualized support from members of the project team.

All elements of the 3C model were explicitly designed to scaffold teachers towards increasingly complex understandings of CT and to help them recognize integration opportunities in both discipline-specific and interdisciplinary ways. Figure 1 provides an overview of the 3C model, facilitator characteristics, and sample activities for each component.

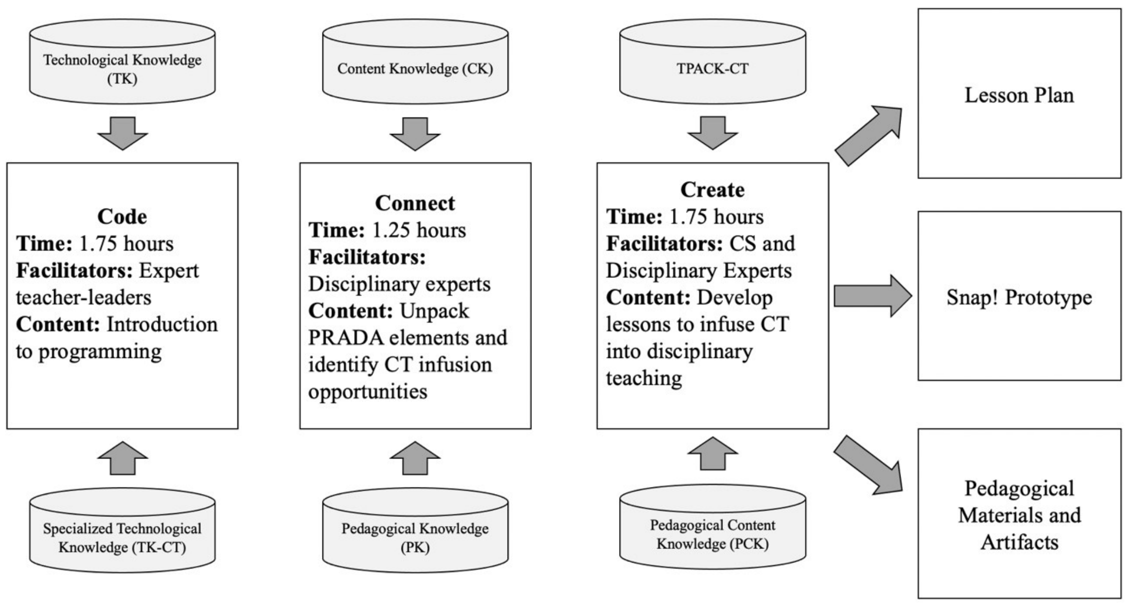

Figure 1. Code, Connect, Create (3C) professional development model

4.3. Teacher evaluation of the 3C model

A post-PD survey including 22 quantitative items and three open-ended items was administered to all participants at the end of the two PD sessions. Items from the validated Standards Assessment Inventory (Vaden-Kiernan et al., 2009) were adapted to understand teachers’ perceptions of the PD in relation to three domains: content, context, and process. Initial analysis of quantitative survey results revealed significant shifts in teacher self-efficacy and beliefs regarding CT infusion into disciplinary teaching (Jocius et al., 2020). 74% of teachers ranked the PD as excellent, with an average rating of 4.71 (5.0 scale). We also performed a paired samples t-test to measure teachers' perceptions of their knowledge and skills before and after the workshop, which demonstrated that there was a statistically significant increase in teachers' perceptions of their skills/knowledge ($p < .001$) (see Table 1). In quantitative and open-ended items, teachers reported overall satisfaction with the PD experience, particularly in relation to their self-efficacy in infusing CT, coding skill development, and experiences collaborating with colleagues.

Table 1. Teachers' perceptions of knowledge and skills before and after the workshop

Before/After the PD, I would rate my knowledge or skills as:							
	Mean	Paired samples *t*-test[1]	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)
State 1 ($n = 55$)							
Before	1.51	$p < .001^{**}$	65%	20%	13%	2%	
After	3.61		7%	9%	49%	29%	5%
State 2 ($n = 66$)							
Before	1.69	$p < .001^{**}$	65%	11%	9%	9%	
After	3.31		4%	11%	31%	31%	9%

Note. [1]Paired samples *t*-tests assess significant changes in percent correct from pre to post; $^{*}p < .05$; $^{**}p < .01$.

4.4. Academic year support and teacher lesson implementation

Drawing on research on active collaboration for teacher learning and PD application (Darling-Hammond, 2005; Borko, 2004), we offered several academic-year supports, including monthly webinars, a Slack channel for online discussion, and technical assistance. Monthly webinar topics included: teacher reflections on lesson implementation, sample lessons, tips and tricks for infusing computing, Snap! functions, unplugged activities, and CT assessment.

4.5. Data analysis

Data analysis proceeded in two phases aligned with the research questions (see Table 2). In Phase 1, we examined teachers' post-lesson implementation reflections and open-ended end-of-year survey responses. Using inductive qualitative coding techniques informed by grounded theory (Charmaz, 2006), we analyzed post-lesson reflections ($n = 24$) using descriptive codes for common topics and in vivo codes to note participants' own words (Saldaña, 2015). During this coding cycle, the area of pedagogical support for CT-infused lesson implementation emerged as a salient theme. A second cycle utilized pattern coding techniques to develop thematic organization (Saldaña, 2015). All responses were double-coded, resulting in 89% inter-rater agreement.

Table 2. Research questions and data sources

Research question	Data sources	Analytic methods
How did pedagogical supports for CT-infused lessons function in classroom settings? (Phase 1)	-Pre-lesson reflection ($n = 24$) -Post-lesson reflections ($n = 24$) -End-of-year surveys ($n = 24$) -Teacher interviews ($n = 13$) -Video recordings of lessons ($n = 24$)	-Descriptive, in vivo, and pattern coding (Saldaña, 2015)
What barriers did teachers face as they implemented CT-infused lessons into their disciplinary teaching? (Phase 2)	-Post-lesson reflection ($n = 24$) -End-of-year surveys ($n = 24$) -Teacher interviews ($n = 13$)	-Idea units (Chafe, 1994) -Pattern coding (Saldaña, 2015)

In Phase 2, we identified two specific survey items: a post-lesson reflection question asking teachers to identify the least successful lesson elements and an end-of-year survey response that targeted teachers' perceived barriers to implementation. We began the analytic process by breaking the comments into idea units, which Chafe (1994) describes as pieces of discourse in which the speaker introduces a singular concept. We then reviewed idea units to eliminate redundancies across data sources, so that each idea unit represented a distinct teacher-identified barrier. Using pattern coding techniques, we engaged in multiple cycles of analysis to organize the barriers into categories and themes. All responses were double-coded, resulting in 83% inter-rater agreement.

Throughout both phases of data analysis, we utilized multiple strategies to ensure trustworthiness. We triangulated interpretations across data sources, including video recordings of lesson implementation and interview responses. We also utilized peer debriefing during weekly research team meetings to discuss interpretations and review emergent codes. Member checks were conducted with nine participants during follow-up interviews. Finally, we kept an audit trail to keep a record of changes throughout the analytic process.

5. Findings

Our analysis identified three primary pedagogical supports that teachers utilized as they infused CT into disciplinary teaching: articulating a key purpose for CT infusion, scaffolding, and student collaboration (see Figure 2). Of the 24 teachers, 79.2% (n = 19) identified scaffolding, 45.8% (n = 11) identified articulating a clear purpose for CT infusion, and 33.3% (n = 8) identified student collaboration as pedagogical supports. In the following sections, we draw on teachers' pre- and post-lesson reflections, revised lesson plans, interview responses, and video recordings of lessons to illustrate how these pedagogical supports for CT infusion functioned in classroom contexts.

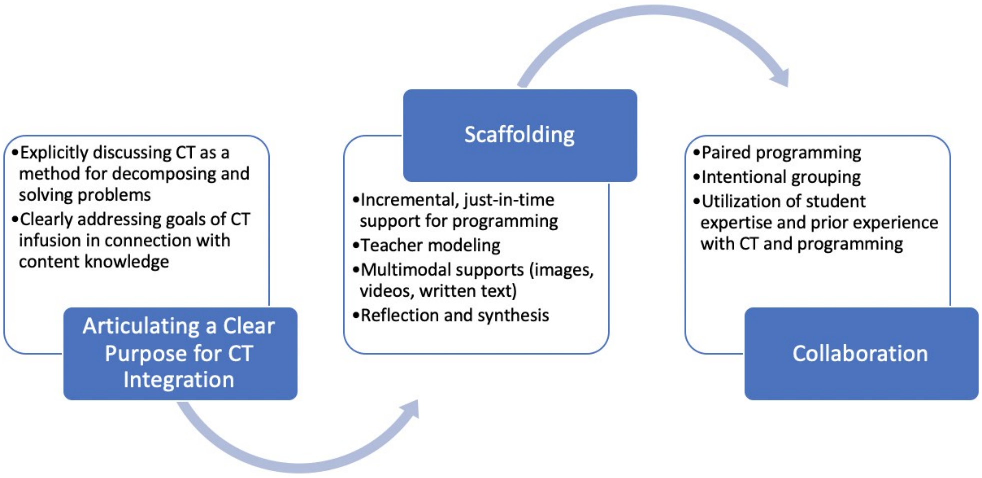

Figure 2. Overview of pedagogical supports for CT infusion

5.1. Articulating a clear purpose for CT infusion

45.8% (n = 11) of teachers described explicit discussion of the goals for CT infusion as a support for lesson implementation. For example, Jessica, a middle school English and speech teacher, drew on specialized technological knowledge (CT-TK) to introduce specific CT elements, such as decomposition, to students: "This is a skill that is essential to problem-solving. The students need to be able to recognize the problem, and then be able to break it down into smaller problems that can be solved." Jessica also said that including "points for reflection," which she adapted from the Connect sessions, supported students' creation of Snap! narratives that recreated Edgar Allen Poe stories.

Other teachers made clear connections between CT elements and disciplinary content to scaffold students' developing knowledge of CT. For example, Jane, a middle school forensics teacher, said: "We went into pattern recognition. Then, you got this big problem of, you know, criminal activity. They've got to learn how to break that down into little bite-sized pieces." Likewise, Alan, a high school math teacher, reported using concept mapping, similar to the work done during Connect sessions, to highlight connections between the CT elements of decomposition and algorithms and math. He recognized the importance of pedagogies utilizing holistic models of TPACK-CT, rather than focusing specifically on technology: "Technology for the sake of technology is not beneficial. I have to be able to use it to teach math. And students need to see that."

Phoebe, a 7th grade science teacher, reported that explicit discussion helped students apply CT concepts, including decomposition and abstraction, to problem-solving processes and disciplinary knowledge. Her lesson tasked students with creating a Snap! flowchart to solve a genetics problem using a Punnett Square. Students completed a storyboard illustrating the passing of genetic information through meiosis, DNA translation, simple dominant, and recessive trait behavior. Then, they used the storyboard to create a Snap! program (see Figure 3).

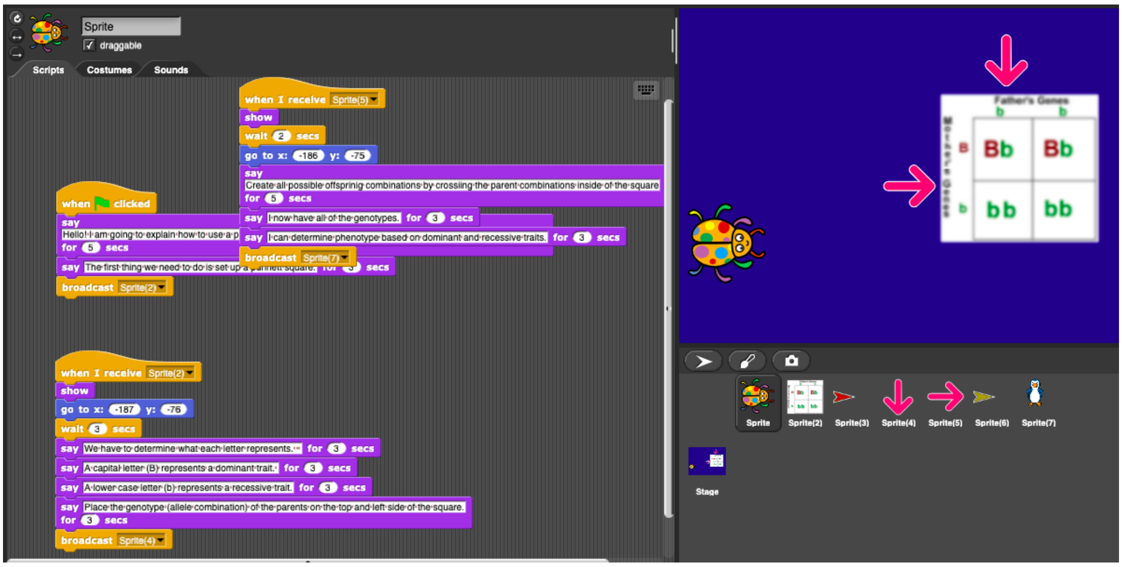

Figure 3. Teacher-created Punnett square Snap! storyboard

Phoebe's pre-lesson implementation reflection noted that she initially planned to share the Punnett square storyboard, introduce Snap! functions, and describe coding procedures. However, lessons she learned from the first day of instruction led her to include an explicit justification for CT infusion:

> I don't feel like I explained the purpose of it. It's really easy to just give a lesson and students just try to complete it to please the teacher but not understanding why this is helpful and how they can take it with them in other lessons. I did go back the 2nd day and stop the students and talk to them about what computational thinking was and how they can use it in other aspects.

Phoebe drew on her pedagogical content knowledge, as well as TK-CT, to utilize the CT definitions from the PD to scaffold both students' CT and content understandings. When asked to describe the most effective elements of the lesson, Phoebe identified students' end products "showing their understanding of the content" and "the 'ah-ha' moments when they really started understanding the coding."

5.2. Scaffolding

79.2% of teachers (n = 19) identified pre-lesson, during-lesson, and post-lesson scaffolds as a for CT-infused lesson implementation. Examples of *pre-lesson scaffolds* included: 10-15 minute Snap! programming lessons, storyboards, review of Snap! commands, and visuals to demonstrate CT concepts. Ellen, a middle school science teacher, repurposed PD Code session materials to introduce Snap! to her students: "We had that material available to us. So those step-by-step directions, that was very supportive because that's one less thing I have to create." Other teachers utilized activities demonstrated during the academic-year webinars, such as unplugged coding, to introduce algorithms and abstractions, using unplugged maze activities and warm-up discussions centered on CT concepts.

During-lesson scaffolds (e.g., graphic organizers, sample code, and guided reflection) offered just-in-time support for students to engage with the disciplinary content and CT concepts. Several teachers utilized TPACK-CT knowledge to scaffold lessons. Lauren, a high school science teacher, adapted the use-modify-create model from the Code sessions: "And you use that use, modify and then create your own--that's what I did. I used all of the things that they gave us. I modified the idea that I was going to do in my own head. And then I created something that also includes a 'complete your own code' and has the kids create their own costumes and sprites." Lauren mentioned that the code completion activity was similar to scientific lab work, indicating that she drew upon existing practices and PCK in transforming scaffolds for CT infusion.

Post-lesson scaffolds, which included presentations of programs, student-led discussions, and exit tickets, enabled student reflection on CT knowledge. Teachers noted that scaffolds that they had experienced as learners served as source material for their own adaptation of classroom supports. For example, Jessica shared that her students presented their coded Poe stories during a "demo fair" much like one held during the final day of the summer PD. Other teachers drew on existing pedagogical content knowledge and structures used frequently in their classrooms, such as book talks and science experiment presentations, as part of their CT lesson implementation.

Teachers also referenced shifts in scaffolds during lesson implementation. Allie's high school English lesson required students to compose an interactive choose-your-own-adventure narrative using CT concepts (decomposition, conditionals, and loops). In her pre-lesson reflection, Allie noted that she planned to model a Goldilocks example but decided to draw on her pedagogical knowledge (PK) and content knowledge (CK), to transform her initial support to instead co-construct a model narrative with students. Allie noted that ultimately, most students were able to successfully reach the objectives related to both content and CT:

> The skill of decomposition was accomplished. They started at the top, recognizing that the story had to have a beginning, middle, and the end. Then, they started designing their game screens on paper, from the beginning story line, developing their story lines as they designed the body of the story, and then resolution/ending screens for each of their stories.

For future iterations of the lesson, Allie said that students will use specific textual evidence to craft their choose-your-own-adventure stories.

5.3. Student collaboration

33.3% of teachers (n = 8) identified student collaboration as a pedagogical support. Teachers noted several types of collaboration, including the intentional use of pair programming (as demonstrated during the PD), informal student collaborations, and leveraging student expertise with programming in other environments. Interestingly, as we detail in the next section on barriers, several teachers also reported that some forms of collaboration instead served to inhibit students from meeting lesson goals.

Teachers found that collaborative structures from the PD designed specifically to build teachers' TK-CT knowledge, such as pair programming, supported student learning during lesson implementation. Ellie, a middle school science teacher, found that using pair programming in her classroom engendered more collaborative interactions, particularly when students' designed algorithms: "The most successful part of the lesson was watching the students turn their written algorithms into a working application and then work to create a practice application. I am very pleased with their growth and engagement during the partner segments (pair programming)." Other teachers echoed the value of collaboration in leading to more complex content understandings of abstraction and algorithms: "Pairs had to rely on each other to 'present' the concepts and to provide correct answers to conversion problems."

Informal student collaborations, which related to teachers' existing pedagogical practices, also served as a support for lesson implementation. Ellie noted that pairs who had successfully translated their algorithms into applications shared tips and tricks with other students. Similarly, Demetria, a middle school Spanish teacher, said that while the Snap! Programming was challenging for her students, students worked together to share developing knowledge: "The other kids were really helpful and willing to show them what they had figured out as well."

Teachers also leveraged students' previous experiences with programming in other environments, such as Scratch, as a pedagogical resource. While Katie, an 8th grade science teacher, noted that all students were successful in programming a water molecule, students with greater expertise in programming utilized their pre-existing knowledge to construct more complex products. As Katie described, "The more complex programs were created by students with Scratch experience or students that received assistance from my student experts." These structures often drew on PD elements designed to support TPACK-CT; for example, Alan stated that student-led demonstrations of specific Snap! functions, like importing content and replicating code, which was similar to the way that teachers interacted during the PD Code sessions.

5.4. Barriers to implementation of CT-infused lessons

In connection with the second research question, a primary goal of this analysis was to explicitly analyze the barriers teachers faced. Across the analysis of post-lesson implementation reflections and end-of-year survey responses, teachers identified barriers (n = 44) in the following areas: time and pacing, scaffolding, infrastructure and technical issues, teacher collaboration, student collaboration, and teacher knowledge.

29.5% of teachers reported a lack of time to implement their CT-infused lessons. As Keith, the high school math teacher, said, "For me, time and flexibility in content was a barrier. It was difficult to free up any time in class to dedicate to Snap! instruction when I struggle as it is to get through the required course content." Katie said that while teaching the lesson was "double the amount of time" she anticipated, "it was well worth it."

15.9% of teachers (n = 7) identified technical issues, such lacking computer access and issues with district website filters, as barriers to lesson implementation. Ellie reported that "the school's email blocked Snap! and the school's server blocked their personal emails." Other teachers said the lack of 1-1 computer ratios and difficulties with Snap! logins caused unanticipated problems during lesson implementation. Throughout implementation, members of the project team helped teachers to create Snap! accounts and to submit requests to district IT departments to allow Snap!, which helped to eliminate these barriers.

18.2% of teachers (n = 8) noted that anticipating student support needs was a barrier to infusing CT. Although several teachers drew on their existing pedagogical content knowledge in designing supports, some teachers expressed that their developing TPACK-CT knowledge limited the types and forms of support they provided. As Katie said, "When I implement Snap next year, I will develop lessons that sequentially build programming skills. For example, lessons will start by building simple skills and culminate by integrating all the skills." She referenced drawing on her experiences with CT infusion, as well as Code session materials, to design future sequential lessons.

Likewise, while student collaboration was identified by several teachers as a pedagogical support, 13.6% (n = 6) and 11.4% (n = 5) of teachers specifically identified teacher and student collaboration (respectively) as barriers to lesson implementation. Teacher-identified collaboration barriers included: difficulties in navigating co-teaching schedules and structures, lack of alignment across course pacing guides, and failed attempts to collaborate with teachers who did not attend the PD. The student collaboration barriers were all specifically connected to issues arising from differences in students' coding skill sets. While several teachers found value in utilizing pair programming (as described in the previous section), others found that it limited students' engagement with the lessons. For instance, as Allie said, "We tried to pair students who struggled with students who were excelling. This ended up leading to less pair programming and more of the driver taking the lead." This problem was echoed by four other teachers, indicating a need to critically examine the role of pair programming in either enabling or supporting CT-infused lesson implementation.

Finally, 11.4% (n = 5) of teachers reported a lack of teacher knowledge served as a barrier for infusing CT. Teachers specifically pointed to gaps in TK-CT in relation to the use of Snap! As a primary barrier. As Jessica said, "I was asked some questions that I didn't remember how to do, or never learned so I was honest with them and we worked together to find out how to do what was being asked." In addition, teachers reported needing to reference Connect and Code session materials when both planning and implementing lessons.

6. Discussion and implications

Infusing computational thinking into disciplinary content is a complex and multi-faceted task that requires teachers to develop deep knowledge of CT concepts and principles (TK-CT) and capitalize on the inherent connections between their content and computational thinking (TPACK-CT). As researchers (Shute et al., 2017; Yadav et al., 2014) have argued, a key challenge for those interested in expanding access to CT across disciplinary boundaries is to design and study how teachers use and transform learning from professional development for classroom practice. Our analysis has identified three pedagogical supports--articulating a key purpose for CT infusion, scaffolding, and student collaboration--that teachers successfully used to integrate CT into their disciplinary teaching, as well as the barriers that they faced.

Israel and colleagues (2015) found that "deliberately embedding" CT into the disciplinary content was key for successful integration. However, our teachers found that their students needed the extra step of clearly articulating the connections between the CT and content and the goals for embedding the CT. This work requires teachers to utilize their content knowledge and pedagogical content knowledge to highlight connections between their disciplines and their developing understandings of TK-CT. In addition to drawing on experiences from Infusing Computing Connect sessions, teachers' prior classroom experiences and knowledge of their students played a key role in how they unpacked the role of CT. For example, teachers reported needed to explicitly explain connections between CT and disciplinary content.

Next, while Mouza et al. (2017) classified TPACK-CT scaffolds used by pre-service teachers as either student-centered or teacher-centered, our study showed that it was easier for in-service teachers to think about scaffolds in relation to their positioning to the lesson components (pre-lesson, during-lesson, and post-lesson). These scaffolds replicate practices that draw on in-service teachers' existing pedagogical content knowledge and represent shifts in how teachers are using TPACK-CT knowledge as a way of making complex content more accessible to students. This suggests that explicitly drawing on teachers' existing pedagogical content knowledge when integrating new STEM pedagogies, particularly in regard to scaffolding classroom instruction for students, could help to address the gaps between teacher learning of new practices in PD settings and classroom implementation (DeJarnette, 2018).

Bower et al. (2017) also classified teaching strategies for CT infusion as student-centered and teacher-centered, finding that "collaboration" was frequently mentioned. Similarly, our teachers stressed that collaboration among students served as a support. Teachers drew on TPACK-CT knowledge to implement collaborative structures implemented during the PD, such as pair programming, as well as existing collaborative structures within their classrooms, to infuse CT into their disciplinary teaching.

Although many teachers were able to successfully implement their CT-infused lessons, our analysis also revealed that they faced a number of barriers, including a lack of time and technological resources, difficulty in anticipating student learning scaffolds, and concerns with both teacher and student collaboration. While some of these barriers, such as the lack of time, are well-aligned with the existing literature (Yadav et al., 2016), others (e.g., the need for specific scaffolds for infusion) suggest potential future directions for research and practice. For example, future research on the ways that teachers in different disciplines and teaching contexts adapt scaffolds (e.g., pair programming, coding mini-lessons, modeling, CT vocabulary support, and unplugged activities) based on their existing pedagogical content knowledge and new understandings of TPACK-CT would make a valuable contribution to the literature.

Finally, the fact student collaboration served as both a support and a barrier suggests that the forms and functions of collaboration play a key role in either supporting or restricting students' engagement and learning (Jocius, 2018; Rodriguez et al., 2017). Providing opportunities for teachers to engage in pedagogies of investigation and enactment (Grossman et al., 2009) to experience and enact different collaborative structures could allow teachers to develop specific instructional routines (TPACK-CT) for CT-infused instruction. Beginning this work in pre-service teacher education courses could also provide an important context for developing skills in infusing CT and designing supports for students with varied learning needs. However, further study is needed to unpack collaborative structures that can enable students of differing levels of expertise to engage fully in CT practices in disciplinary contexts.

7. Conclusion

Given existing gaps in the literature (Rich et al., 2020b), we believe that examining how teachers apply PD content and leverage technological, pedagogical, and content knowledge to transform classroom practice is a critical area for understanding the future of CT infusion. In this study, we identified three key pedagogical supports teachers used to implement CT-infused lessons (articulating a key purpose for CT infusion, scaffolding, and collaborative contexts), as well as barriers that caused them to adapt or abandon their lessons. It is our hope that the pedagogical supports identified in this study, as well as the illustrations of how teachers transformed scaffolds based on their existing pedagogical practices and TPACK-CT knowledge, will assist educators and researchers in developing and transforming supports for classroom use.

As suggested by Li and colleagues (2020), this study positioned CT as a transdisciplinary thinking practice that can support students' development of content knowledge as well as CT skills. We found that as teachers learned about and enacted scaffolds based on their developing knowledge of TPACK-CT in recursive cycles, they came to recognize transdisciplinary opportunities to bridge existing pedagogical practices with the new integrated STEM content. It is our hope that this research can contribute to the design of PD that guides teachers in transforming pedagogical supports based on their existing and developing knowledge, as well as helping them overcome barriers to CT infusion.

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Better Together: Mathematics and Science Pre-Service Teachers' Sensemaking about STEM

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ABSTRACT: While the perspectives and practices of many educational stakeholders in relation to STEM have been documented, research has yet to deeply explore pre-service teachers' (PST) understandings and how to support their sensemaking about STEM during pre-service teacher education. To address this, we used two STEM integration frameworks, focused on discipline-based practices and modeling with data, to inform the design of a STEM unit that brought together thirty secondary mathematics and science PSTs. With an eye on PSTs' development of a situated understanding of STEM, a qualitative analysis of pre/post surveys and STEM lesson sketches revealed that PSTs collectively shifted from initial views of STEM as blurred lines between subjects to a more nuanced understanding of where and how subjects cross and meet. PSTs also described STEM activities through a more plausible understanding of student and teacher actions and viewed data as a bridge to connect disciplines and the real-world. Furthermore, PSTs' descriptions of anticipated challenges to planning for and implementing STEM mirrored those of in-service teachers. We discuss these findings through the lens of sensemaking theory, highlighting shifts in the sum of PSTs' individual understandings to a more collective and situated understanding of STEM. We also discuss implications focused on the role of data in STEM activities and the affordances of secondary mathematics and science PSTs sensemaking together to about STEM.

Keywords: STEM integration, Pre-service teacher education, Mathematics education, Science education, Teacher sensemaking

1. Introduction

The ways in which educational stakeholders understand the meaning of STEM (Science, Technology, Engineering, and Mathematics) is highly varied, causing STEM to be ambiguous in nature and teachers to experience challenges bringing STEM into their classrooms (Akerson et al., 2018; Holmlund et al., 2018; Margot & Kettler, 2019; Mejias et al., 2021). To clarify the ambiguity around STEM, some in the field of education have worked to define STEM through the integration of disciplines that results in a framework for STEM education (e.g., English, 2016; Kelley & Knowles, 2016; Mejias et al., 2021). In these STEM frameworks, content integration is explicit, discipline-based practices work together, activities are ambitiously implemented, and ideas are connected across subjects and embedded in the world around us (NRC, 2014). However, even with these STEM frameworks, the variability in how STEM is understood makes it imperative for "those working in the same system… explore the common elements that are being attributed to STEM education and co-construct a vision that provides opportunities for all their students to attain STEM-related goals" (Holmlund et al., 2018, p. 17). This call for a shared understanding of STEM within local systems is reiterated by Dare and colleagues (2019), indicating a shared understanding (i.e., common language and conceptualization) can help stakeholders better communicate and productively bring STEM into classrooms.

In past research, STEM perspectives and practices of many stakeholders, particularly in-service teachers, have been explored (e.g., Akerson et al., 2018; Allen & Penuel, 2015; Breiner et al., 2012; Herro & Quigley 2016; Ring et al., 2017). However, we know little about how pre-service teachers (PSTs) understand STEM prior to entering the profession and how teacher educators can productively support PSTs' understandings about STEM. Studies that have explored how PSTs understand STEM indicate a similar variation to that of other stakeholders and call for more effective STEM instruction during PST education that helps to "show them the way" (Radloff & Guzey, 2016, p. 771). Furthermore, given the attention to STEM education and recent calls for a greater focus on the integration of STEM subjects (e.g., English, 2017; Mejias et al., 2021; Tytler, 2020), it is important to understand how mathematics and science PSTs' make sense of STEM. It is equally important to understand how teacher education can support the sensemaking process, as sensemaking about STEM has brought coherence and confidence to in-service teacher STEM implementation (e.g., Allen & Penuell, 2016; Davis et al., 2020) and sensemaking has the potential of helping them demystify the meaning of STEM and develop a plausible understanding that informs their future classroom practice. Thus, the purpose of this study is to understand and support secondary mathematics and science PSTs' sensemaking about STEM and STEM integration.

2. Conceptual framework

Often our past and current experiences exist in conflict, causing us to either make sense of current situations through previous experiences or renegotiate our understanding based on the current context and develop greater coherence to a given issue (Ancona, 2011). Teacher education can be viewed as a site for PSTs to build coherence around the ambiguities in teaching and learning, as PSTs often bring experiences that can be leveraged as an opportunity for sensemaking (Davis et al., 2020; Fullan & Quinn, 2015). Therefore, we approach this study with the view that mathematics and science PSTs are sensemakers (Spillane et al., 2002; Weick et al., 2005), constantly creating, interpreting, and negotiating the meaning of mathematics and science teaching and learning.

In general, sensemaking is how we structure ideas and create a "plausible story" to enact (Weick et al., 2005, p.410). This plausible story is further understood through a cognition-oriented perspective that considers individual cognition and situated cognition. Here, individual cognition refers to one's noticing and interpretation of meaning and understanding based on prior knowledge, beliefs, and experiences (Spillane et al., 2002). In contrast, situated cognition refers to the social and contextual aspects that are introduced when individuals work in an organization or community, where context is viewed as a central element in the sensemaking process (Spillane et al., 2002).

With sensemaking being inherently collaborative (Ancona, 2011), the link between an individual negotiating a plausible story and situated cognition is that sensemaking occurs on two interacting levels—the individual and the collective (Spillane et al., 2002). Individual understandings are shaped by one's prior knowledge, context, and activity with the collective. However, the individual's impact on the collective's understanding is not straight forward, as it is further situated by the context (i.e., the learning community and the resources available to them). Additionally, due to the individual and situated notions of cognition, sensemaking can result in a range of meanings and actions (e.g., Allen & Penuel, 2015; Cohen & Hill, 2001). For the purposes of this paper, we focus on the understanding of the collective (i.e., the sum of all individuals' understanding), drawing inferences on how a group of PSTs come to understand in the context of a pre-service teacher education STEM unit.

3. Background

3.1. Models of STEM integration

STEM integration is an effort to combine disciplines in authentic classroom activities (Moore et al., 2014) and a variety of models exist (e.g., Breiner et al., 2012; Brown et al., 2011; English, 2016). Most notably, the NRC (2014) describes how STEM integration occurs in school-wide and after-school initiatives, where teachers either bring together at least two subjects (e.g., mathematics and science), a practice and a content domain (e.g., engineering practices and geometry), or two discipline-based practices (e.g., mathematics and science practices) as a way to achieve STEM integration—underscoring the diversity of STEM conceptualizations and ways in which this integration is carried out in educational contexts.

Narrowing our focus, we use two views of STEM integration that can support mathematics and science PSTs' sensemaking. First, Kelley and Knowles (2016) describe a conceptual framework for STEM education where teachers and students use science inquiry, technological literacy, mathematical thinking, and engineering design to engage in situated STEM learning. They also describe the critical nature of the physical and social context for learning and imagine STEM integration through discipline-based practices and ways of thinking. Second, English (2016) highlights the challenges of attending to multiple disciplines during STEM integration, where often mathematics and engineering take a diminished role in the enactment of STEM learning activities. Her solution is to frame STEM integration through activities where students engage in engineering-based modeling with data—a notion also suggested by Lehrer and Schauble (2020). Further, English frames STEM using four increasing levels of integration—disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary. Briefly, *disciplinary integration* describes how "concepts and skills are learned separately in each discipline," *multidisciplinary integration* describes how "concepts and skills are learned separately but within a common theme," *interdisciplinary* deepens integration through "closely linked concepts and skills learned from two or more disciplines with the aim of deepening knowledge and skills," and *transdisciplinary integration* describes how "knowledge and skills learned from two or more disciplines are applied to real world problems and projects" (English, 2016, p. 2).

With these two framings, PSTs can begin to envision and make sense of STEM integration through familiar concepts like discipline-based practices and data modeling. This also aligns with current mathematics and science content and practice standards (CCSSM, 2010; NGSS, 2013), as both sets of standards center practices and modeling with data.

3.2. Perceptions and challenges of implementing STEM in mathematics and science

To describe how STEM plays out in educational contexts, Akerson and colleagues (2018) determined that there is not an overarching *nature of STEM*, but rather STEM is made up of the individual natures of each discipline. With this in mind, teaching STEM in a single-discipline classroom can be near impossible because teachers lack enough time to teach each integrated subject's content and they have not been trained in the content and pedagogy of disciplines other than their own. The lack of a clear *nature of STEM* furthers the conceptual ambiguity around STEM integration and begins to reveal the practical challenges teachers encounter when trying to implement STEM in their single-discipline classrooms.

The prevalence of disciplinary and multidisciplinary perspectives on STEM integration may be due to the challenge of enacting STEM in an interdisciplinary or transdisciplinary way (Akerson et al., 2018). Furthermore, in-service teachers often view STEM as a fundamental shift in their instructional practice and typical school structures (i.e., single-discipline courses) tend to lack a culture of collaboration across disciplines, creating challenges to successful STEM enactment (Margot & Kettler, 2019). Teachers may also find it difficult to manage different forms of discipline-based reasoning and practices because managing two or more sets of knowledge can exacerbate the challenges that already exist for teachers (Lehrer & Schauble, 2020). Being aware of the challenges around STEM are important to know and will help to overcome these challenges in the future.

Advancing our understanding of how teachers engage in sensemaking about STEM integration, Allen and Penuel (2015) conducted a longitudinal study of science teachers sustained sensemaking about NGSS and STEM in a professional development context. By engaging in discussions and STEM related activities over an extended period, they suggest that sustained sensemaking should help teachers manage the ambiguity, uncertainty, and perceived incoherence of STEM. Cohen and Hill (2001) also speak to these recommendations and argue that when teachers' have opportunities to learn that are grounded in curriculum and instruction over an extended period, policy is more likely to be implemented after sensemaking.

With this study, we aim to address some of the challenges of implementing STEM education by bringing secondary mathematics and science PSTs together over a sustained period. In doing so, they can discuss the ambiguity around STEM integration, engage in activities together, and learn from each other's discipline-specific knowledge and practices. Additionally, we offered the PSTs quality resources and frame STEM pedagogy as something not too different from the ambitious teaching the course was already preparing the PSTs to carry out. By addressing the challenges directly, PSTs will gain a deeper understanding of STEM integration and a more practical vision for STEM integration in their future mathematics and science classrooms.

4. The present study

Given the ambiguity and challenges around STEM, it is imperative for teacher educators to create productive learning environments and activities that help PSTs develop a coherent understanding and vision. Therefore, the purpose of this study is to understand how secondary mathematics and science PSTs make sense of STEM before and after engaging in collective sensemaking during a STEM unit. The following research questions guide this study: (1) How do PSTs make sense of STEM (in education or generally) before and after the STEM unit? (2) How do PSTs make sense of STEM activities in a classroom context before and after the STEM unit? (3) After the integrated STEM unit, what do PSTs continue wanting to know about STEM and foresee as the challenges for implementation?

5. Methods

We used qualitative methods, drawing on inductive coding techniques in the tradition of constant comparative analysis (Corbin & Strauss, 2015), to understand how a group of secondary mathematics and science PSTs collectively make sense of STEM before and after a STEM unit. This approach is appropriate because the ambiguity around STEM makes it difficult to hypothesize how PSTs conceptualize and envision STEM in a classroom context and using inductive techniques allowed for multiple pathways to emerge based solely on the data. In addition, due to our design, we focused on shifts in the collective, situated understanding of PSTs, rather than shifts in individuals' understanding, as the STEM unit was designed around PSTs sensemaking together.

5.1. Participants and context

The participants for this study include a single case of a group of 16 mathematics and 14 science PSTs. Each PST was enrolled in a either a secondary mathematics or science teaching methods course at a large university in the southeastern United States. Each methods class was a semester-long course that met once a week and combined undergraduate and graduate students participating in four- and five-year teacher preparation programs. Throughout the STEM unit, the students from the mathematics and science methods courses, each taught by two of the authors, were combined to make a single class of 30 PSTs.

5.2. STEM unit design

Following recommendations from the literature, we aimed to provide PSTs with opportunities to explore STEM teaching resources, engage in STEM activities, and both reflect on and discuss the meaning of STEM over an extended period. An important aspect of the STEM unit was its focus on framing STEM integration through discipline-based practices, data-use, and modeling, as each is relevant to mathematics and science education and constitute areas of overlap between mathematics and science content and practice standards (e.g., CCSSM, 2010; NGSS, 2013). Additionally, teachers were often challenged to consider plausible implications for how the ideas/activities being discussed would unfold in a classroom. Collectively, these design decisions resulted in a three-lesson STEM unit.

5.2.1. Lesson 1: Thinking about STEM and starting an example task

After discussing PSTs prior knowledge about STEM through small- and whole-group discussions about "What is STEM", we intentionally grouped mathematics and science PSTs together for an engineering design task, *Chutes-R-Us* (Barron, 1997; Figure 1). Groups worked together to collect, analyze, and model data to form conclusions. Central here was our integration of classroom-friendly technologies to display, organize, and work with data in both small and whole-group discussion—specifically we used Desmos (see https://www.desmos.com/calculator), an online graphing calculator, and CODAP (see https://codap.concord.org/for-educators/), an online data analysis platform. PSTs created visualizations using self-collected data and engaged in conversations about the strengths and challenges of using these technologies with students, further sensemaking about how technology is integrated as both a teacher and student tool in STEM activities.

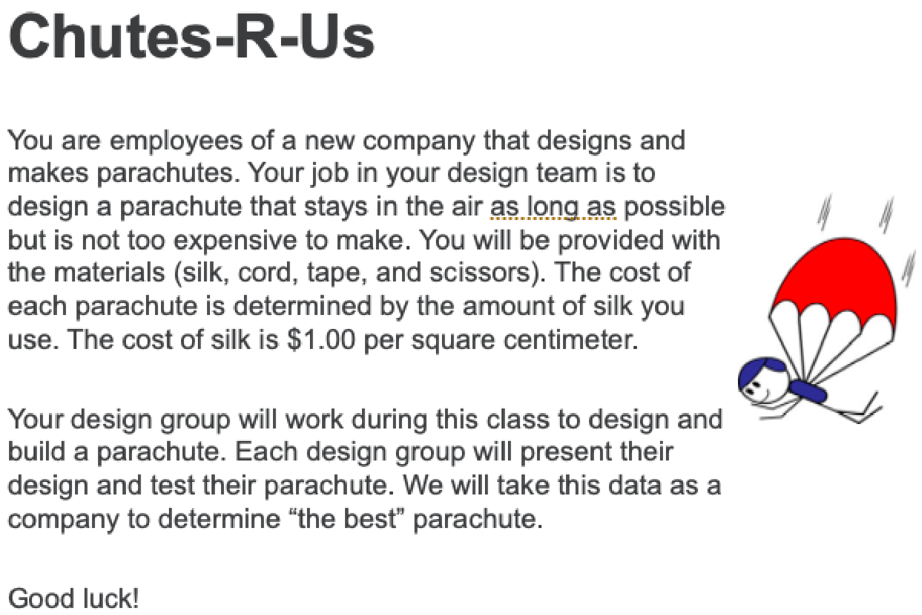

Figure 1. Chutes-R-Us (Barron, 1997)

5.2.2. Lesson 2: Inviting a Geographic Information Systems (GIS) expert

In the second lesson, PSTs learned from a geographic information systems (GIS) expert who exposed them to sample lessons using local data to teach different mathematics and science content standards. PSTs also had time to explore how to navigate and use ArcGIS (see https://www.arcgis.com), an online GIS platform, in their instruction. By introducing PSTs to these GIS resources, they had to make sense of how this technology would be used to facilitate learning in their classrooms, where local data can serve as the catalyst to understand and explore local issues through mathematics and science concepts.

5.2.3. Lesson 3: Wrapping up and cross-over lesson sketches

Prior to class, PSTs completed an assignment where they used Desmos or CODAP to analyze the class dataset (developed in Lesson 1) and form conclusions about what would constitute *the best* parachute for the company. In class, we modeled the process of facilitating a class discussion and using data to form conclusions, focusing conversations around effective use of data visualizations using technologies previously introduced. The class then recapped the *Chutes-R-Us* activity and situated our understanding by thinking about potential benefits and challenges around for implementation in a classroom context.

After closing the activity, we placed PSTs in groups (at least one mathematics and science PST per group) to create a STEM Lesson Sketch (Figure 2). In these sketches, PSTs were prompted to consider topic, objective, and cross-over, in addition to describing how the lesson would be enacted, what challenges they would anticipate, and any external sources or materials they needed. Overall, the lesson sketches provided an opportunity for PSTs to apply their sensemaking about STEM and think through how this new plausible understanding would playout in a classroom context.

Cross-Over Partner STEM Lesson Sketch

Names:

Subjects taught:

Topic and Cross-over:

Objective/Outcome:

Please describe the following:

1. Links to any sources (particularly GIS maps or data used):
2. Materials needed:
3. Steps to the lesson implementation and overarching question:
4. Challenges you anticipate during this activity. How might you address them?

Figure 2. Cross-over STEM Lesson Sketch template

5.3. Data sources and procedure

Data were collected using an open-ended survey with three items and lesson sketches. The survey questions were specifically designed to capture data that would inform the three research questions (Table 1) and PSTs completed the survey at two time points—once before starting the STEM unit, indicating PSTs' prior knowledge, and then again after its conclusion, indicating PSTs' situated understanding. The lesson sketches captured the plausible stories of PST for STEM integration and the challenges they anticipated as they planned for and implemented an integrated STEM lesson.

Table 1. Survey questions' alignment with research questions

Pre/Post-survey questions	RQ alignment
What do you know about STEM? *Your answer can include anything at all— related to teaching and learning or related to general knowledge about it.*	RQ1: How do PSTs make sense of STEM (in education or generally) before and after the STEM unit?
What does a STEM activity look like in the classroom? *Consider what the students and teaching are (or should be!) doing.*	RQ2: How do PSTs make sense of STEM activities in a classroom context before and after the STEM unit?
What do you want to know more about regarding STEM?	RQ3: After the STEM unit, what do PSTs continue wanting to know about STEM and foresee as the challenges for implementation?

5.4. Data analysis

All data were collected without individually identifiable information, meaning the following description of our analyses takes place at the whole-group level, rather than the individual. Overall, the analysis process took place in three phases that assisted in developing themes from the pre- and post-survey data, understanding shifts in PSTs' sensemaking from pre-to-post, and understanding their plausible stories for STEM integration from the lesson sketches. To provide evidence of validity and trustworthiness, all data were analyzed by the authors individually before meeting to discuss discrepancies and agree on all codes and themes at each step in the data analysis. During this process we also developed analytic memos (Saldaña, 2013) to narrate the analysis process and record our decision-making.

In Phase 1, we employed open and *in vivo* coding techniques (Saldaña, 2013; Strauss & Corbin, 1990) allowing us to be descriptive while also staying true to PSTs' voice during the initial coding phase. For example, when a PST said, "A STEM activity in the classroom would involve aspects from multiple STEM areas (so incorporating mathematics into biology). The teacher would be teaching how interconnected the subjects are," we wrote an *in vivo* code of, "teaching how interconnected the subjects are," and an open code of, "blurring the lines between subjects." In Phase 2, we employed axial and selective coding (Saldaña, 2013; Strauss & Corbin, 1990) to put the data back together and make connections between the codes using descriptive categories. The outcome of axial and selective coding produced analytic themes that were then used to answer each research question. During Phase 1 and 2, we also wrote analytic memos after each meeting. In Phase 3, we explored key shifts from pre-to-post, grounded in our discussions of the overall dataset, themes, and analytic memos. Phase 3 also included analyzing the lesson sketches, a proxy for understanding how PSTs understand STEM integration in their practice, using English's (2016) *levels of STEM integration*. Here, we classified the ways teachers were making sense of STEM integration after the STEM unit and applied the previously described coding phases to the lesson sketches to assist in triangulating the findings.

6. Findings

The following sections link findings from the analysis to each of the three research questions. Themes from the pre- and post-data and lesson sketches are first discussed individually before looking at shifts from pre-to-post in the discussion. An overview of themes, organized by research question and pre/post, can be found in Table 2.

Table 2. Descriptions of themes identified before and after the STEM unit

Pre-STEM Unit			Post-STEM Unit		
Theme	*n*	Description	Theme	*n*	Description
RQ1: How do PSTs make sense of STEM (in education or generally) before and after an integrated STEM unit?					
Blurring the lines between subjects	22	STEM is seen as something within and across STEM disciplines included in the acronym.	Where subjects cross and meet	36	STEM is where subjects cross and meet through authentic activities that are grounded in real-world issues and data.
STEM as economic capital	9	STEM is important because it prepares students to become a part of the future workforce that is increasingly STEM-related.			

Stereotypes of STEM	4	STEM comes with labels or stereotypes, such as being hard and male dominated.			
RQ2: How do PSTs make sense of STEM activities in a classroom context before and after an integrated STEM unit?					
Expectations of STEM activities	26	STEM activities are seen as student-centered, inquiry-driven, hands-on, and contextually relevant ways to promote critical thinking and knowledge transfer across the subject domains. These activities have specific roles for teachers (e.g., asking questions/facilitating) and students (e.g., analyzing data).	We DO STEM activities together	47	STEM is not specific content subject-related knowledge but rather something that students' do. It is a set of collaborative practices between students and between teachers and students. These practices have required roles for teachers (e.g., circulating and probing student thinking with questions) and students (e.g., producing/gathering data).
			Data as the bridge	10	Data is the site where discipline-based content and practices can cross and meet.
RQ3: After the STEM unit, what do PSTs continue wanting to know about STEM and foresee as the challenges for implementation?					
			Planning for STEM requires the other disciplines	16	PST's identify time planning with teachers from other disciplines as a challenge to have but necessary for effective STEM implementation.
			In-the-moment challenges	24	PST's describe challenges related to pedagogy (e.g., scaffolding, facilitating classroom discussion) and content (e.g., having a deep knowledge of multiple disciplines) that can arise when planning and implementing STEM activities.

6.1. RQ1: How do PSTs make sense of STEM (in education or generally) before and after the STEM unit?

Three themes describe PSTs' prior knowledge about STEM before the STEM unit: *blurring the lines between subjects*, *STEM as economic capital*, and *stereotypes of STEM*.

In describing STEM as *blurring the lines between subjects*, PSTs demonstrated an uncertain understanding of STEM largely through a disciplinary and multidisciplinary lens. "I know that STEM stands for Science, Technology, Engineering and Mathematics. Thus, anything that has to do with STEM must fall into one of those categories," one PST explained. Another indicated, "STEM is a way of combining science, technology, engineering and math." Through statements like this, PSTs' prior knowledge of STEM showed they understood STEM as a blurring of subjects but struggled to describe the blur. However, some PSTs did move past a multidisciplinary understanding of STEM and attempted to describe the blur across subjects, "STEM is integrating science, math, technology, and engineering to teach concepts with real-world application. To me science and mathematics provide more of the conceptual aspect and engineering and technology provide the basis to complete these studies." While this and other similar responses broadened STEM past a disciplinary lens, there was ambiguity in their understanding of STEM.

Beyond levels of integration, PSTs' prior knowledge indicated *STEM as a type of economic capital* students accrue to prepare for future careers. "STEM becomes very important potentially nowadays because many occupations are related to STEM. Moreover, since the 21 century is the Era of Technology, STEM becomes big deal," one PST asserted. PSTs also considered the various stigmatizations of STEM, culminating in the theme, *stereotypes of STEM*. Here, PSTs described STEM as "being hard and not fun" or found the field of STEM as gendered because there are "a lot of men." These themes, along with *blurring the lines between subjects*, describe PSTs' initial understandings prior to the STEM unit, where they had individually made sense of STEM as an important set of skills for students to learn, but were unclear what those skills might be and how students can learn them.

After making sense of STEM together during the STEM unit, only one theme emerged to describe PSTs' situated understanding of STEM: *where subjects cross and meet*. In describing this theme, PSTs demonstrated a more nuanced and deeper understanding of STEM, indicating increased levels of STEM integration (i.e., multidisciplinary, interdisciplinary, and transdisciplinary). For instance, one PST explains the *cross* as a place situated in authentic problems and reliant on the application of discipline-based practices: "STEM includes the application of science, technology, engineering, and mathematics to solve problems or make sense of natural phenomena. It includes inquiry, evidence, argumentation, and reasoning." Another PST describes the *meet* as a place where mathematics and science practices create a STEM practice: "STEM is a practice that allows you to incorporate the different types of science and mathematics into solving problems. It's a way to apply them all together and use the skills from different parts." Together, these two responses are examples of how the group of PSTs no longer described STEM as disciplinary and began showing a more situated understanding of STEM that included higher levels of integration.

PSTs' new situated understanding of STEM was further shown in the plausible stories they told in their STEM lesson sketches. Of the twelve lesson sketches generated by the PSTs, all included some use of technology for analyzing and visualizing data (e.g., GIS, Desmos, CODAP) and five lessons were identified as multidisciplinary, four interdisciplinary, and three transdisciplinary, with zero disciplinary. Multidisciplinary lesson sketches included both science and mathematics content centered around a common theme but separated the content when describing the lesson. For example, in a lesson on modeling evolutionary change of peppered moths over time, PSTs wrote "for the science side" and "for the mathematics side" to discuss lesson objectives, processes, and outcomes, and this delineation of subjects was furthered in their description of the lesson steps. Interdisciplinary lesson sketches showed PSTs using complementary concepts and skills from mathematics and science to elaborate and explain the other, deepening the knowledge and skills being learned. For example, in a lesson about environmental impacts of landslides, PSTs described how students would "gather and interpret data in order to create graphs that show the impacts of landslides and explain those impacts on the environment." Transdisciplinary lesson sketches posed authentic problems that situated student learning through the use of knowledge and skills in math, science, and beyond. For example, in a lesson on sustainability and minimizing human impact on the environment, PSTs described how students would "create a device that will filter water the most efficiently with the least cost for filtration material," learning and applying skills across the STEM disciplines. Together, the survey and lesson sketch data indicate that, after the STEM unit, PSTs were able to develop more transformational ways of understanding STEM that more clearly defined the blur through multidisciplinary, interdisciplinary, and transdisciplinary ways.

6.2. RQ2: How do PSTs make sense of STEM activities in a classroom context before and after the STEM unit?

Only one theme emerged to describe PSTs' prior knowledge of STEM activities in the classroom before the STEM unit: *expectations of STEM activities*. Here, many of the expectations PSTs' described were broad and vague. For example, one PST said STEM activities should include, "engaging with the STEM content in a way that builds understanding." However, some PSTs described more specific roles for teachers and students in STEM activities, such as a PST who indicated that, "the teacher should be facilitating and leading the discussion while the student should be asking questions." Overall, *expectations of STEM activities* illuminated how PSTs' prior knowledge of STEM activities initially involved many buzzwords (e.g., hands-on, engaging) but they failed to unpack them in meaningful ways, demonstrating the difference between knowing about something versus knowing how to *do* something.

After the STEM unit, two themes emerged to describe PSTs' situated understanding of STEM activities: *we DO STEM activities together* and *data as the bridge*. Under *we DO STEM together*, we see PSTs beginning to describe a clearer and connected vision for STEM activities, where teachers and students engage in a set of collaborative practices with specific roles, similar to the situated and practice-oriented STEM framework of Kelley and Knowles (2016). For example, PSTs described STEM activities as where students use skills from multiple subjects to explore an authentic problem and are "communicating and collaborating in groups," linking to both the discipline-based practices and situated nature of the Kelley and Knowles' (2016) framework. Regarding the role of the teacher, PSTs described a more student-centered approach, where the teacher is a facilitator who acts as a collaborator with students and other teachers when designing and implementing STEM activities. From this theme, we see how the STEM unit pushed PSTs to develop clearer visions of STEM enactment.

The STEM unit also pushed PSTs towards a situated understanding of data's role in connecting STEM disciplines. Here, the PSTs describe *data as a bridge* between STEM disciplines STEM and to the real-world. For example, one PST described how "data should look like things that could connect to more than one content." PSTs further tease out this bridge as being rooted in the real world because the data they describe using authentic data either from the real-world or able to be collected or produced by students. The clarity of *data as a bridge* is so salient for some PSTs that they began to provide examples of real-world data students could use to create that bridge, such as, "the number of bacteria (that replicate) in a cup each minute could be used to also calculate for rate of change." Additionally, in the lesson sketches, PSTs largely used data as the catalyst to situate student learning around authentic data. For instance, one lesson involved students exploring GIS data and making recommendations regarding rising sea levels in Miami-Dade County. These PSTs showed how data served as the site for exploring a scientific phenomenon using technology literacy, mathematical thinking, and scientific inquiry, all of which are situated in the authentic practice of STEM professionals (Kelley & Knowles, 2016). Across the lessons, others also used data as the bridge to connect regression analyses with understanding scientific concepts and engineering-design (e.g., developing a water filtration system and exploring issues with coastal erosion, landslides, and population growth), further showing how their newfound situated understanding of STEM could be plausibly enacted in their future classrooms.

6.3. RQ3: After the STEM unit, what do PSTs continue wanting to know about STEM and foresee as the challenges for implementation?

After the STEM unit, two themes emerged regarding challenges and gaps in learning PSTs foresee in relation to STEM: *planning STEM requires other disciplines* and *in-the-moment challenges.* Regarding *planning STEM requires other disciplines,* PSTs discussed how communication and collaboration with teachers in other disciplines would help share the intellectual load of combining disciplines in one lesson and help navigate the challenge around STEM activities having multiple "correct answers." PSTs saw other teachers as the most fundamental resource for helping create successful STEM experiences in their classrooms, as others can provide insights and knowledge that would otherwise be lacking. However, many also expressed concerns about the time and space they would have to engage in such collaborations. While the PSTs appreciated the lesson plans given to them during the unit and the cross-over lesson sketch activity, they wondered when they might have the experience of developing STEM lesson with other teachers in the future.

Under *in-the-moment challenges*, PSTs described challenges they would anticipate when implementing a STEM activity. For instance, PSTs discussed how students may not arrive at or understand the answer the teachers intended or predicted that some students may not understand why certain functions/equations make sense for modeling natural phenomena. PSTs also described how students may or may not be familiar with the real-world context of an activity, anticipating this might hinder students' ability to make sense of the STEM activities and consider other factors that would interact with the real-world phenomena under consideration. In addition, PSTs described challenges to scaffolding STEM lessons to alleviate the burden on students' learning to use technology and worried about being able to facilitate classroom discussions about content from STEM activities that they may not be as knowledgeable about (i.e., mathematics teachers worried about facilitating discussions about and explaining science phenomena, or science teachers being worried about facilitating discussions about and explaining mathematics content) while also keeping students in on-task discussions. This theme of *in-the-moment challenges* is indicative of PSTs' careful considerations about how a STEM activity would be enacted in their future classrooms while attending to issues of both pedagogy and content.

7. Discussion

7.1. Key findings

The preceding findings highlight the shift to a collective, situated, and deeper understanding of STEM that PSTs developed after engaging in a STEM unit designed around sensemaking. Similar to the ways stakeholders and PSTs hold varying practices and views of STEM (e.g., Radloff & Guzey, 2016), we also found PSTs hold varying views. Specifically, PSTs' prior knowledge and experiences resulted in them beginning the STEM unit with individual sensemaking about STEM that indicated an understanding of STEM through stereotypes, economic capital, and as a blur between disciplines. After further making sense of STEM with other PSTs during the STEM unit, they were able to reconcile their varied views to a more nuanced and situated understanding of STEM, bringing clarity to the blur. The context and design of the STEM unit—bringing together mathematics and science PSTs, along with the activities and materials PSTs engaged with and discussed—pushed PSTs to develop a collective, situated understanding of STEM as a place where subjects cross and meet (Spillane et al., 2002). This shift in understanding allowed PST to describe a more plausible story of STEM integration at higher levels, as indicated by the largely interdisciplinary and transdisciplinary lesson sketches PSTs developed (English, 2016). Teachers' self-report data, like the survey and lesson plans collected in this study, have been shown to be a valid proxy for the actions teachers take up in the classroom (Copur-Gencturk & Thacker, 2021). Thus, we view the finding of PSTs increased levels of STEM integration in their lesson sketches as indicative of how they plan to take up higher levels of STEM integration in their future classrooms and provide their students with better opportunities to engage in authentic and high-quality STEM activities.

PSTs also showed evidence that their understanding of STEM activities shifted to a more targeted, situated vision for STEM enactment that links to the STEM discipline-based practices and data modeling framework proposed by Kelley and Knowles (2016). No longer were PSTs vaguely describing STEM activities with generic buzzwords, instead they were using very intentional and descriptive language about how teachers and students *do STEM activities together* and how these activities use *data as the bridge* between disciplines and to the real-world. The type of data PSTs discussed using was either student-collected or from the real-world and served as the catalyst for teachers and students to engage in a variety of discipline-based practices and authentic problems using student-friendly technologies. These descriptions mimicked the data collection processes and conversations around the *Chutes-R-Us* and GIS activities and lessons from the STEM unit. Though predictable, due to the STEM unit design, this shift is important because PSTs were able to select these specific elements as plausible to their future practice and develop an emerging picture of STEM that brought coherence to its ambiguity (Ancona, 2011). Furthermore, developing an understanding of STEM through discipline-based practices and data modeling aligns with current reform efforts in mathematics and science education (CCSSM, 2010; NGSS, 2013) and doing so helps PSTs make sense of STEM teaching as more practical and not much different from what they are already learning in individual mathematics and science teaching methods courses. All of which better prepares PSTs to engage in continued sensemaking around the calls for more STEM in single-discipline classrooms.

Though PSTs described STEM in more plausible and concrete ways after the STEM unit, they also anticipated many of the challenges that in-service teachers describe in relation to STEM (Margot & Kettler, 2019). For instance, we found PSTs described challenges related to planning and implementing STEM activities, where they anticipated challenges around their own knowledge about concepts and finding time to plan with teachers in relation to other disciplines. The PSTs also forecasted challenges with students' ability to effectively navigate available technologies and make connections between scientific phenomena and mathematics. These concerns are common among in-service teachers but demonstrated how PSTs were thinking critically and transferring their learning about STEM to their future teaching contexts. Moreover, this anticipation of STEM-related challenges lays the groundwork for continued sense-making around the varied requirements and expectations of their future careers (Weick et al., 2005).

Overall, we saw how mathematics and science PSTs engaged in sensemaking together, during a STEM unit, situated their understanding of STEM and further clarified their vision for specific actions they would need to take to make STEM a reality. We credit this shift in understanding to the STEM unit design where they engaged in an engineering design task, explored student- and discipline-friendly technologies, and developed lesson sketches, while engaging in discourse around implications for content and practice (Cohen & Hill, 2001; Allen & Penuel, 2015). We also believe this study serves as an important model for teacher education programs to consider using when preparing single-discipline teachers to meet the call for STEM. Considering many mathematics and science PSTs are not exposed to specific STEM teaching methods in single-discipline methods courses, this study highlights the need for teacher education programs to manage the dilemma around what type of exposure to STEM teaching benefits PSTs while also considering the discipline-specific goals of the course. We argue that STEM is better navigated mathematics and science PSTs together, because together they can help each other make sense of and identify specific plausible elements of STEM which serve as bridges for their continued sense-making and future enactment in classrooms.

7.2. Implications

Stepping back, we discuss three implications for mathematics and science teacher education that align with our purpose of exploring PSTs' understanding of STEM and supporting teacher sensemaking about STEM.

Provide opportunities for PSTs to plan together. One of the most concrete barriers facing in-service teachers regarding STEM is their own content knowledge and capacity to plan STEM activities (Margot & Kettler, 2019). We recommend that teacher educators provide opportunities for PSTs from different disciplines to plan for STEM together. As seen in this study, even planning one lesson together provided PSTs with a model of how this type of collaboration should work and exposed them to different teaching-related concepts, technologies, and practices which deepened their understanding of STEM enactment.

Use authentic data as the site for connecting STEM disciplines. Collecting, modeling, and analyzing data is a core feature of both mathematics and science standards (CCSSM, 2010; NGSS, 2013), which makes it vitally important for PSTs to make sense of this practice prior to entering the field. Data is also a rich context for STEM learning (Lehrer & Schauble, 2020) and flexible enough to engage students in cross-disciplinary practices that help students make sense of the real-world. We recommend, as seen in this study, STEM activities that center real-world data and use student-friendly data analysis technologies as a means to support teacher sensemaking about STEM integration.

Focus PSTs' STEM learning through sensemaking. Similar to others (Allen & Penuel, 2016; Cohen & Hill, 2001; Davis et al., 2020), we also recommend teachers engage in recurrent professional learning, that focuses on content and different dimensions of practice, as an effective framework to support sensemaking. This can be done with PSTs by engaging in more open-ended and cognitively demanding tasks that link these experiences to their future jobs as teachers. Key here is understanding teaching methods and assistive technologies that support and facilitate the enactment of STEM activities, and modeling and engaging PSTs in these ideas will go a long way in supporting their future implementation.

7.3. Limitations and recommendations for future research

We used two STEM frameworks to design our STEM units, and although we emphasized discipline-based practices, data modeling, and student-friendly technologies as a context for PST learning about STEM, one can easily imagine other contexts for STEM learning. For instance, learning events designed around computational thinking (e.g., Weintrop et al., 2016), robotics (e.g., Kim et al., 2015), or even STEAM (STEM with Arts) practices that go beyond disciplinary boundaries and begins to take a more transdisciplinary approach to STEAM teaching and learning (Mejias et al., 2021). While we take the view that our approach is both a core and accessible focus for STEM learning, we also recognize that other approaches may have different outcomes for PSTs and believe the topic of what knowledge and practices single-discipline PST learning about STEM should focus on is generative for future research.

We also worked with a small number of PSTs at a single university and used surveys without individually identifiable information, focusing our analysis on the collective. Though we saw sufficient variability among the PSTs, this small and situated sample means that some of our findings may be highly particular to our own teacher preparation context. Future work may explore similar STEM activities in different contexts to better understand which parts may generally support PSTs developing productive views of STEM and which were due to the particularities of our setting. Additionally, future studies may narrow the unit of analysis to the individual PST to gain more nuanced insights about teacher change at the individual level, as this study did not link pre-to-post surveys and focused more on the collective shift in PSTs' understanding of STEM.

8. Conclusion

Sensemaking is inherently collaborative and serves as an opportunity for learners to develop coherence about a topic and actionable steps. While STEM can be challenging for teachers and PSTs working in individual disciplines, this study is an example of how teachers can learn better together, drawing on each other's discipline-based knowledge and practices. Further, focusing STEM learning through discipline-based practices, data, and appropriate technologies served as a fruitful approach for deepening PSTs' understanding of STEM. Doing these can help make STEM a more practical reality in mathematics, science, and perhaps STEM classrooms.

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Using an Enhanced Video-engagement Innovation to Support STEM Teachers' Professional Development in Technology-Based Instruction

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ABSTRACT: This paper reports on the design, implementation, and results of a video-based study that focused on supporting an individualized viewing experience, keeping a record of what was noticed, providing a degree of guiding framework, and facilitating a combination of individual and collaborative reflections in noticing activities for STEM professional development. A cohort of 20 prospective mathematics teachers at a public university in Hong Kong participated in the study. The participants engaged in a series of blended learning activities with a feature that allowed them to leave comments while viewing of a lesson video, which focused on technology integration in mathematics classrooms. The designed activities were helpful for the participants to document and reflect on their observations, while viewing videos outside the classroom allowed them to meaningfully engage with the course materials. Moreover, the use of videos supported the participants' broad but crucial STEM classroom practices that would help them prepare for future lessons.

Keywords: Professional development, Teacher noticing, Videos, STEM education, Preservice teachers

1. Introduction

STEM education covers science, technology, engineering, and mathematics disciplines across all grade levels in both formal (e.g., classrooms) and informal (e.g., afterschool programs) settings. STEM education plays an increasingly pivotal role in all aspects of human behavior, and there is a need to improve K-12 STEM education and to support professional development for teachers in effectively delivering STEM concepts and practices in their classrooms (Chai, 2019; Lynch et al., 2019). For example, the emergence of various forms of technology enables the use of new technology in STEM education to transform the way we teach and learn. However, the mere presence of technology will not ensure the quality of education; it is imperative to support teachers with STEM education models and technology-enhanced pedagogies in order to take full advantage of technology in STEM instruction.

Teacher professional development (TPD) is crucial in all kinds of educational reform, including STEM (e.g., Desimone, 2009; Fore et al., 2015; Guskey, 2002). Parker et al. (2015) argue that STEM teachers have greater needs to develop their technological, pedagogical, and content knowledge (TPACK) than other forms of knowledge (Koehler & Mishra, 2009) and understand how different disciplines can be integrated in classrooms. In recent years, the use of video as a technological tool for developing teachers' technological and pedagogical expertise in the STEM disciplines has been on the rise (Chai, 2019). Particularly, video-based reflections have been widely adopted to facilitate productive noticing for science and mathematics teachers: the kinds of classroom events that teachers attend to, how they interpret the events they observe, and how they act on them (Chan et al., 2021; Schack et al., 2017). The construct of teacher noticing has been empirically investigated to shed light on the dynamic and situational aspects of teaching expertise that underlies teaching decisions and actions that occur in the moment (Chan et al., 2020). Coupled with video-based noticing, this approach could help pre- and in-service teachers visualize and interpret complex classroom situations and student learning in STEM classrooms. Despite positive results regarding video-based teacher reflections in professional development programs, a meta-analysis by Tripp and Rich (2012) revealed that a consensus has not been reached as to how to effectively engage teachers in video-aided reflections, particularly on the kinds of noticing tasks or reflections to be used in video-based professional development.

This paper focuses on the video-based professional development experience of preservice teachers (PSTs) in the context of integrating instructional technology in mathematics teaching. In response to the meta-analysis study by Tripp and Rich (2012), which identified a research gap in the kinds of video-aided reflections used to effectively support TPD, this paper reports a set of design-based professional development activities for PSTs that: (1) promote individualized, out-of-class video watching, (2) provide a framework that guides PSTs to notice various aspects of classroom interactions and events, and (3) facilitate a combination of individual and collaborative reflections. This design-based study aimed to evaluate a video-based technological innovation and the accompanying series of blended learning activities to facilitate productive noticing in PSTs about various aspects of technology integration during a teacher education course. With regards to STEM integration in the TPD, closely linked mathematical concepts and technological skills were taught in authentic classrooms to expand knowledge and skills, i.e. constituting an interdisciplinary STEM education (English, 2016). First, we describe the design and implementation of activities to promote video-based noticing in mathematics teacher education. We then present the results of these video-based noticing activities, detailing how the activities helped PSTs to meaningfully engage in noticing, make connections with course material, and express pedagogical considerations for future teaching. Finally, we discuss limitations of the designed activities and the potential for asynchronous video noticing to direct future research on teacher noticing.

2. Literature review

2.1. STEM teacher professional development

In a review of the notable trends of TPD for STEM, Chai (2019) noted that one of the most common pedagogical approaches for STEM TPD studies is the use of workshops. This approach varied in complexity; studies employed workshops only, workshops with lesson design, and workshops with lesson design/refinement and professional learning communities. The approach of mentoring was highlighted by Ufnar and Shepherd (2019), who posited that an effective TPD model should contain feature discipline content knowledge, pedagogical content knowledge, inquiry strategies, collaboration, and teacher renewal. In terms of structural features, TPD should be focused on specific grade levels and provide a variety of activity types. Parker et al. (2015) proposed five critical features of professional development for large-scale STEM urban elementary school reform: coherence, content focus, active learning, collective participation, and duration. Overall, scholars agree that STEM TPD should help teachers learn to use technology-enhanced curriculum materials and improve teachers' content knowledge, pedagogical content knowledge, and/or understanding of how students learn in technology-enhanced contexts. In particular, the design of the technology and, more importantly, the teachers' levels of adaptive expertise in helping their students learn with technological tools are important for integrating technology into STEM education (Roschelle, 2006). As such, more research is needed to help teachers to incorporate novel technologies and transform their pedagogies accordingly. This study draws on the effective TPD model of Ufnar and Shepherd (2019) and Parker et al. (2015) in supporting development of different types of knowledge through inquiry, as well as focusing on content and providing active learning opportunities (see Section 3.2). Despite the fact that extant research has examined the development of technological and pedagogical expertise in subject teaching by in-service teachers (e.g., Ng & Chan, 2021; Pilgrim & Martinez, 2015), relatively few studies focus on how PSTs develop their competence in implementing technologies that are novel to them.

Without the identification of noteworthy and important objectives in STEM lessons, PSTs cannot make relevant connections between educational theory and professional practice nor can they use these connections to make decisions (Floro & Bostic, 2017). Lee (2019) examined the lesson study approach as an effective means of TPD in initial teacher education. The lesson study involved four main stages: the investigation of students' thinking, initial lesson revision before teaching, teaching, and lesson study discussion. The lesson study method improved PSTs' ability to practice noticing when reviewing and planning lessons. The lesson study method can be coupled with videos to provide more intensive support for learning in PSTs. According to Chai (2019), video recordings were frequently used as learning tools for PSTs who otherwise lacked access to STEM classrooms; by watching videos of activities in an authentic classroom, teachers could relate the videos to their future teaching practices and thus, grow professionally. Video-based reflections have been used to complement the pedagogical strategy of teacher noticing (Radloff & Guzey, 2017) because videos can capture the complexity of classroom events that could otherwise be easily overlooked, such as critical moments during teaching and learning (Stockero & Van Zoest, 2013). For example, a study conducted by Gröschner et al. (2015) examined the effect of the "dialogic video cycle" by videotaping the participants' own teaching courses during a workshop and then discussing and reflecting in groups. They found that two independent raters strongly agreed on the implementation of effective components in the workshop. In a similar study (Radloff & Guzey, 2017), the use of videos was found to help PSTs to identify significant events in STEM classrooms, make sense of the events, and connect them to pedagogical knowledge.

2.2. Noticing in mathematics teachers

Due to their lack of classroom experience, PSTs often face challenges in planning effective lessons and interpreting students' actions and difficulties, especially when facing unfamiliar classroom contexts such as implementing technology-enhanced pedagogies during the lessons. In this regard, mathematics teacher noticing has been highlighted in practice and research for developing teachers' abilities to comprehend teaching and learning scenarios and to interpret classroom events (Choy, 2016; Jacob et al., 2010; Star & Strickland, 2008). The term "teacher noticing" comprises a set of inter-related processes, such as attending, interpreting, and deciding (Jacobs et al., 2010 Mason, 2002; Star & Strickland, 2008). For instance, the use of videos provides an effective means to foster observations, discussions, and reflections (Bencze et al., 2009). Although in-service teachers may realize that they have experienced most of what happens in the videos (Borko et al., 2008), the use of videos may help PSTs to anticipate what they might experience in unfamiliar situations, such as teaching in technology-rich classrooms. As Standen (2021) argued, one of the main critiques in educational research is the lack of connection between the knowledge production of teachers in academic settings and teachers' work practices. This is especially pertinent for initial teacher education, which is often considered to be decontextualized and far removed from teachers' every day practices. Thus, it is important to examine the relationship between PSTs' abilities to attend, analyze, and respond to their noticing in order to address the complexity of everyday STEM teaching as well as the effectiveness of video-based methods used to provide detailed descriptions of the teaching context (Barnhart & van Es, 2015; Kilic, 2018).

In the current study, we used video-aided reflection to facilitate a productive noticing experience regarding effective technology integration in classroom teaching for mathematics PSTs. The specific technology used was the 3D printing pen (hereafter, the 3D pen; Figure 1), a tool that enables one to construct artefacts in three dimensions, thereby enhancing the teaching and learning of topics in geometry, such as the volume of prisms and pyramids and cross sections of solids (Ng & Ferrara, 2020; Ng et al., 2020). The choice of 3D pens is suitable for our investigation as it is a novel technology not only for the participating PSTs but also in STEM education in general. Therefore, we were interested in how the PSTs interpreted what they noticed while watching the videos of a mathematics lesson involving the use of 3D pens as an integrated STEM pedagogy (English, 2016). Previous research has shown that video-aided teacher reflection promotes genuine engagement with student thinking and learning, thus enriching teachers' pedagogical knowledge (Jacobs et al., 2010). In this study, our first objective was to extend video-aided reflections to the context of technology-rich classrooms, considering videos of authentic 3D pen–enabled classroom episodes to have the potential to enrich PSTs' reflections. The second objective of this study was to examine the designed video-based reflection activities and lesson-refining tasks used to facilitate PSTs' TPD in a blended learning setting. We describe our design principles in the following section.

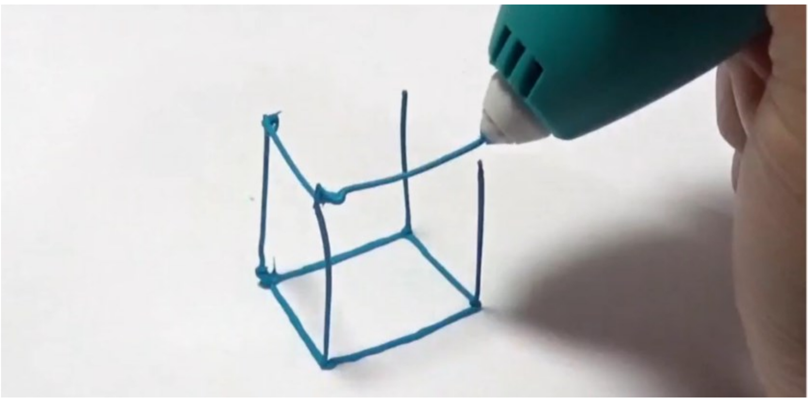

Figure 1. Drawing a cube in three dimensions with a 3D pen (see also, Ng, 2021)

3. Methodology

3.1. Participants and context

The current design-based study took place during a mathematics education course taken by 20 prospective teachers who specialize in mathematics education at a public university in Hong Kong. In the course, Mathematics Curriculum and Teaching: Instructional Technology and Design of STEM Learning Activities, an emphasis was placed on designing technology-rich learning tasks in mathematics and anticipating their use in the classroom. For example, the introduction to the use of instructional technologies, such as dynamic geometry software, 3D printing, and coding, for designing STEM learning tasks and projects was one of the major objectives of this course. To facilitate mathematics PSTs' noticing in and out of the classroom during the course of their studies, blended learning was utilized to combine classroom learning with asynchronous online learning, hence, students could, in part, control the time, pace, and location of their learning (Tucker, 2013).

3.2. Designed modules with technological innovation to support video-based noticing

With technical support from the authors' institution, the first author developed four online video modules to be hosted in the course management system, Blackboard, for the said required mathematics pedagogy course taken by fourth-year mathematics teacher education undergraduates (Table 1). Each module required about half an hour of viewing time and formed the core of class discussion for one day in class.

Table 1. Learning content of four modules designed prior to the noticing activity

Module	Objective	References
1. The discipline of noticing	To provide fundamental concepts about teachers' professional noticing and its importance for their professional growth.	Mason (2002)
2. Learning to notice for professional growth	To explain that noticing skills can be trained and differ by level of experience; to improve noticing skills by applying the observational strategies learned.	Star and Strickland (2008)
3. Professional noticing of children's mathematical thinking	To learn and practice the skills necessary for attending to, interpreting, and deciding what to do with students' mathematical thinking.	Jacob et al. (2010)
4. Mathematics teacher noticing during the task design	To introduce and apply a model for productive noticing before, during, and after lessons.	Choy (2016)

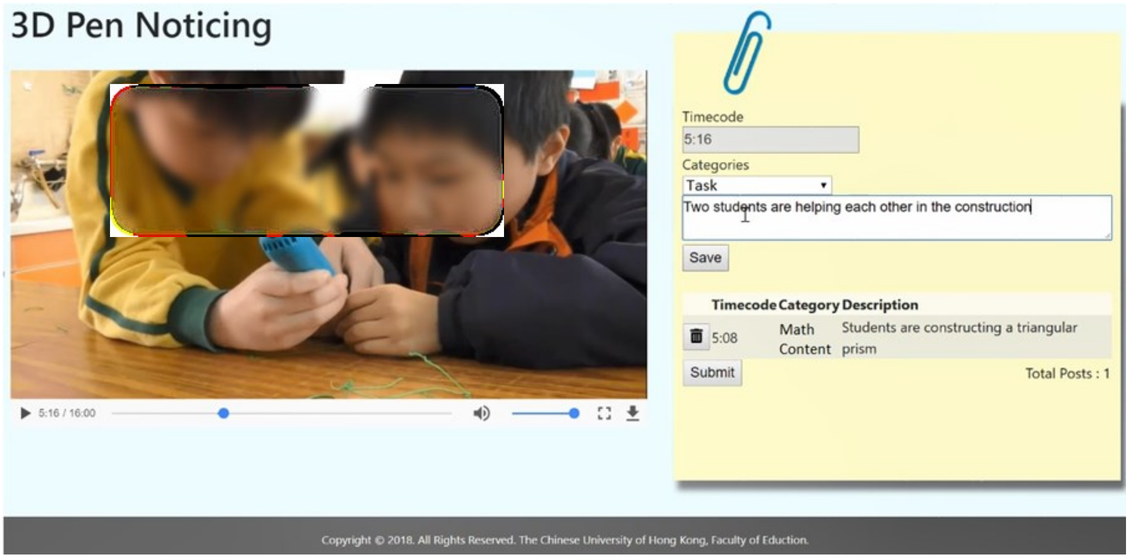

Figure 2. Screenshot of the video module with the commenting feature

The design of the modules was informed by research on elements that characterize effective TPD, such as the development of different types of content and pedagogical knowledge through inquiry, the focus on content, and the provision of active learning opportunities (Parker et al., 2015; Ufnar & Shepherd, 2019). Specifically, the design aims to promote active learning and metacognitive strategies through interactions with the video-based noticing interface, which enabled PSTs to pause the video anytime, comment on what they noticed, and save the time-stamped comments instantly and conveniently. For instance, as seen in Figure 2, the video captured two students working in pairs while using a handheld 3D pen to investigate three-dimensional geometry (Ng & Ferrara, 2020; Ng et al., 2020). The rest of the video captured both the classroom teachers' and students' actions during lessons, which adopted an inquiry-based and student-centered approach to mathematics instruction. Along with describing what they noticed, the PSTs submitted their reflections via Blackboard to be stored and retrieved by the instructor for grading and for preparing class discussions in the next class session. According to the framework of Chi and Wylie (2014), the designed activities linked cognitive engagement to everyday STEM classroom practice through constructive (making notes of noticing) and interactive (discussing interpretations and opinions) modes of active learning. Moreover, this unique blended learning environment with an instant commenting feature was designed to improve PSTs' noticing in the following ways that are not afforded by watching the videos in a face-to-face class setting:

- all PSTs will participate in video commenting and reflecting;

- they will do so at their own pace;
- the instructor can assess PSTs' skills of noticing certain aspects of the video;
- the instructor can organize PSTs' comments to facilitate meaningful discussions accordingly and to plan pedagogical activities for the subsequent lesson.

The design of the interface made it possible for the instructor to customize the choice of video and categories of noticing, and this helped viewers attend to certain prescribed categories. For instance, in one of the modules, the PSTs learned about five observation categories developed by Star and Strickland (2008) as well as details of the study's findings. Then, they practiced noticing by watching an authentic lesson video while choosing one of five observation categories from a drop-down menu: classroom environment, classroom management, mathematical content, tasks, and communication. As Star and Strickland (2008) pointed out, these categories were chosen to improve teachers' video-based noticing in classroom situations, interactions, and events. Thus, PSTs could use the prescribed categories to organize what they considered meaningful in order to be more aware of different aspects of teaching and learning mathematics. Organizing their attention in certain broad categories can foster PSTs' metacognition in terms of increasing awareness and making sense of their viewing (Topcu & Ubuz, 2008). According to Tripp and Rich (2012), the predetermined observation categories could allow the students to freely identify what was personally meaningful to them. At the same time, these categories also helped students relate their noticing to specific aspects of teaching and learning mathematics in technology-rich environments. In addition, the timecode of comments allowed the course instructor and the PSTs to locate the identified episodes during the ensuing class discussions.

3.3. Blended learning activities with video-based noticing

The first author designed and implemented the following blended learning activities to accompany the four modules of the teacher education course. Before coming to class, PSTs were to watch a video consisting of two parts (10–15 min each). The first part was a lecture with a voice-over PowerPoint presentation on learning to notice and on applying noticing in mathematics teaching (Table 2). The second part featured children learning mathematics in a technology-enhanced lesson. For example, Module 2, Part 1 of the video presented conceptual ideas and empirical findings for directing PSTs' attention to productive noticing, so they could practice their noticing while watching students' activities in Part 2 of the video, which captured the beginning and end of the lesson, including episodes of the teacher leading whole-class discussions to convey instructions, introduce relevant mathematics concepts, and present the activity. Therefore, the video summarized key aspects of the lesson and aspects consistent with the observation categories developed by Star and Strickland (2008).

While watching Part 2, PSTs commented using the eLearning system, Blackboard, on what they noticed. In addition, they were asked to engage in a lesson reflecting activity after completing each module. The lesson reflecting activity prompted them to reflect on various aspects of the lesson. The prompts used in this activity were drawn from the work of Mason (2002), who argued that there are two requirements for professional noticing. The first requirement is to make "account of" (i.e., reconstruct observations step by step and describe some incidents from the video briefly but vividly), and the second requirement is to "account for" (i.e., offer interpretation, explanation, value, judgement, justification, or criticism on the accounts). This two-part noticing task was intended to help PSTs make the distinction between the two constructs by interpreting the accounts and then asking "why" (Mason, 2002).

At the end of all four modules, the students completed a final assignment to cohesively apply their learning from the modules. In this lesson planning activity, they planned a technology-enhanced mathematics lesson of their choice. In particular, the lesson plan was to contain details of materials (including the target technology) used and how it would be used, the target concepts to be learned and how they would be developed during the lesson, anticipation of students' and teacher's actions, and justifications of the lesson design. The assignment design was aligned with research-based principles of developing metacognition through a cycle of reflecting, assessing, evaluating, planning, and applying (Ambrose et al., 2010).

3.4. Data collection and analysis

The data collection and analysis methods were consistent with design-based research (DBR), having "the intent of producing new theories, artefacts and practices that account for and potentially impact learning and teaching in naturalistic settings" (Barab & Squire, 2004, p. 2). The design aspect of this DBR study was a series of video-based blended learning activities used during the course for the PSTs. An important goal of DBR is to impact practice directly through iterative cycles of lesson design, enactment, analysis, and redesign. The data reported in this study was collected from the second cycle of lesson design and enactment, after an analysis of the lesson enactment in the first cycle during the previous year. With respect to developing empirically grounded theories, this study intends to advance the concept of teacher noticing in technology-enhanced classroom contexts through qualitative investigations of PSTs' development in various types of knowledge: technological, pedagogical, and content.

Before the first lesson, the first author obtained informed consent from the PSTs enrolled in the aforementioned course. The data obtained in this study included records of the PSTs' participation in the blended learning activities (time-stamped noticing comments and reflective writing) as well as field notes gathered during whole-class discussions on video-based noticing. The data were collected based on the principle that this study is beneficial to the participants' learning experiences and poses no known conflict of interests to them.

The large amount of textual data obtained from the blended learning activities was organized and then analyzed using thematic analysis (Hatch, 2002) in order to "generate plausible themes based on a plethora of evidence and paucity of counter examples" (Floro & Bostic, 2017, p. 79). A thematic analysis coupled with the use of constant comparative strategies (Strauss & Corbin, 1990) is appropriate in qualitative studies because it facilitates data analysis according to commonalities, relationships, and differences (Gibson & Brown, 2009). The authors reviewed the data in its entirety. Then, common patterns were organized into initial, tentative themes, namely: (1) guided noticing of STEM teaching and learning, (2) individualized noticing and in-depth reflection of STEM lessons, and (3) noticing structuring features of STEM classroom practice. At this stage, triangulation of data was performed by seeking supporting (or non-supporting) evidence within individual responses written by PSTs from different data sources (i.e., time-stamped noticing comments, reflective writing, and whole-class discussions). The authors went over the data a second time to explore the degree to which general patterns matched the data. Based on these patterns, themes were generated to describe the PSTs' professional growth stimulated by the designed video-based noticing activities.

4. Results

We report the DBR results based on the PSTs' engagement of Modules 2 and 3, Learning to Notice for Professional Growth and Professional Noticing of Children's Mathematical Thinking. In these two modules, the number of noticing comments for each PST ranged from 12 to 38, with interaction time ranging from 45 min to 1 h 42 min. Considering that modules were roughly 20 min long, the PSTs had varied levels of engagement with the video. For instance, some PSTs watched the video in one sitting while others rewatched the video multiple times in order to write detailed comments on their observations. In the following section, we report on our second DBR implementation cycle of facilitating video-aided professional development in STEM education.

4.1. Guided noticing of STEM teaching and learning

During Module 2, PSTs were tasked with choosing from five observation categories as prescribed by the noticing task. Table 2 illustrates their observations on a lesson video during which 3D pens were used. Based on the total number of comments made under each category, PSTs generally paid more attention to tasks (91 times) and mathematical content (79 times), followed by classroom management (61 times) and communication (60 times). They paid the least attention to classroom environment (30 times), and this was consistent with the results of Star and Strickland (2008) who also found that PSTs are less competent in attending to the classroom environment.

As shown in the noticing comments presented in Table 2, some PSTs' noticing converged when guided by the noticing task. For example, PSTs 3 and 4 noticed the same classroom routine (i.e., clapping hands) used by the teacher in the video around the 12:40 mark to draw students' attention and maintain control of the classroom. Similarly, PSTs 5 and 6 commented on the same mathematical content in which the teacher was helping his students make "generalizations" about the number of vertices, edges, and faces "in any prism". Although both PSTs 5 and 6 commented on the same part of the video, PST 6's noticing was more detailed than that of PST 5. The video noticing interface with predetermined observation categories were helpful for the PSTs to focus on various classroom events, thereby broadening their considerations for different aspects of teaching and learning mathematics. At the same time, it afforded high video engagement and helped PSTs describe details of the viewed content.

Table 2. Examples of PSTs' time-stamped comments with chosen categories of noticing

Categories	Comments
Classroom environment	• "Keywords going to be taught are already written on the blackboard" (PST 1, 3:19). • "The teacher sets a timer (8 min), and students are allowed to focus on their task to draw the prism. Some students get involved quickly in the activity" (PST 2, 3:43).
Classroom management	• "The teacher uses some classroom routines (clapping three times) to attract the attention of students; students respond accordingly" (PST 3, 12:45). • "The teacher used a ring to call students back from group work and attracted students' attention by clapping" (PST 4, 12:40).
Mathematical content	• "The teacher generalized the pattern of how many Vs, Es, and Fs there are in any prism" (PST 5, 15:28). • "After generalizing results, the teacher asked students about hexagonal prisms. Students answered quickly and could make good reference with the previous results, concluding that any prism has the same number of lateral faces as the number of sides of the base" (PST 6, 15:44).
Task	• "The teacher kept checking on the progress of students and checking the students' work" (PST 7, 10:02). • "Students were encouraged to think about the teacher's question based on how they drew with the 3D pens" (PST 13, 14:11)
Communication	• "A student was trying to help the student who was holding the pen to fix the object, but she refused" (PST 10, 5:19). • "The teacher asked each group of students to take one prism and told students to turn off the 3D pen" (PST 14, 14:59).

We were also interested in the extent to which the PSTs noticed the connection between pedagogy and content when 3D pens were used in the video. To this end, we located 28 comments that included the words "3D pens" or "3D Printing"; 11 of them were attributed to the category of tasks, six to mathematical content, six to communication, four to classroom management, and one to classroom environment. Based on these comments, we characterized the knowledge demonstrated by the PSTs into technological knowledge (TK), technological content knowledge (TCK), and TPACK based on the framework by Koehler and Mishra (2009; Table 3).

Table 3. Examples of PSTs' time-stamped comments about 3D pens and the types of knowledge demonstrated

Types of knowledge	Comments about 3D pens/printing
Technological knowledge (TK)	• PST 2: "The teacher asked each group of students to turn off the 3D pens" • PST 9: "They used scissors to cut unnecessary 3D printing"
Technological content knowledge (TCK)	• PST 7: "Students used the 3D pen to draw the base of the prism first while some drew the lateral face first" • PST 12: "The use of 3D printing allowed students to investigate some properties of triangular prisms on their own (e.g., the number of edges)"
Technological pedagogical content knowledge (TPACK)	• PST 5: "Students tried to complete the table on the blackboard with the use of the prism they made with the 3D pen; this enabled them to visualize the prism" • PST 6: "The teacher linked the imagination of a pentagon cylinder with the experience of the 3D pen activity" • PST 8: "The teacher tried to encourage students to think of alternative methods to create a prettier 3D figure while students were trying to make an appropriate figure"
Other knowledge pertaining to aspects (characteristics) of the learner; learning environment	• PST 8: "A group of two students got only one 3D pen, and some of them cooperated with each other while some were just looking at their partner" • PST 3: "The girl grabbed the 3D pen from the boy"

4.2. Individualized noticing and in-depth reflection on STEM lessons

When given more time for noticing, the PSTs generally recorded more precise and frequent "accounts of" noticing before moving onto the reflection task ("accounting for"; Mason, 2002). This stood in contrast to watching the videos in class, where the PSTs were quick to share their interpretations and judgements (e.g., "I feel that . . .") before sharing their observations, and this could hinder the development of noticing skills.

Moreover, out-of-class viewing allowed for extra time to reflect on the video or even to revisit the course material before "accounting for" what was watched. During the reflection task, they demonstrated fluency in making connections between the video and course content by analyzing crucial aspects of classroom practices for mathematics teaching and learning. A PST's reflection exemplifies this observation:

The student [in the video] seemed to have wrongly recognized a pyramid as a prism. It is a common mistake made by students when a prism is placed in a different way as they would wrongly recognize a side of a triangle as the apex of a triangular pyramid. [I suggest] asking students to recall the characteristics of prisms and pyramids. Then I'd ask students to have a quick check to see if the object fulfills all the conditions.

The above quote illustrates that, upon watching the video, the PST had diagnosed a "mistake" made by a student in the video ("attending to children's strategies" [Jacob et al., 2010]), made sense of why it might have happened ("interpreting children's understanding"), and made decisions about teaching this topic in the future ("deciding how to respond on the basis of children's understandings"). Therefore, she had anticipated the content in Module 3 (i.e., the definition of "professional noticing of children's mathematical thinking" by Jacob et al., 2010) to reflect on her noticing. This shows how PSTs, when given the prompt and time to engage in individualized noticing, can make meaningful connections with the course material. In addition, the PST linked her noticing to other course content, namely, "structuring features of classroom practices" (Ruthven, 2009). According to Ruthven (2009), she paid attention to the "curriculum script" as a sequence of goals, actions, and expectancies (including the expected difficulties and alternative paths) for teaching a curricular topic. Moreover, she "developed ways of staging [. . .] and managing patterns of student responses" (p. 387) to support mathematics learning through this noticing activity. As shown in these observations, the blended learning environment enabled PSTs to participate in noticing at their own pace, and this helped them thoroughly reflect on their learning as opposed to spontaneously reflecting on the video as a group.

4.3. Noticing structuring features of STEM classroom practice

Complementary to the course aims, the students applied pedagogical frameworks learned during the course to make sense of elements that underpin the successful integration of technology in mathematics classrooms. In their reflections, for example, they referred to the "working environment," "resources systems," and "activity structure," as proposed by Ruthven (2009), as structuring features in which teachers integrate (or fall short of integrating) new technologies into classroom practice. By analyzing these crucial aspects of classroom practices, they improved their knowledge on incorporating technology into mathematics lessons, as illustrated in the following reflection by PST 3 (see Table 4).

Table 4. PST 3's reflections about STEM classroom practice

Structuring feature of classroom practice	PSTs' making account of their noticing	PSTs' accounting for their noticing
Resource System	1. A real-life object (a rectangular prism [i.e., food packaging]), 2. A set of 3D pens for the student activity (constructing triangular prisms), 3. A set of premade pentagonal prisms made by the teacher using a 3D pen	1. Provided real-life situations for students to observe the number of faces of a prism 2. Enabled students to have hands-on experience with prism construction 3. Provided another example for further observation on the relationship between the number of faces and lateral faces of a prism

As seen in the above reflection, PST 3 paid attention to "resource systems" (Ruthven, 2009), a collection of didactical tools and materials used by the teacher. Accounting for the "resource systems" used, PST 3 reflected on the coordination of use towards achieving curricular goals. Importantly, PST 3 not only commented on the impact of using 3D pens but also on more traditional teaching aids such as real-life objects and premade prisms used to enhance student learning. Hence, PST 3 reflected on each resource in detail and on their use as a system for learning the properties of prisms. In the terms of Ruthven (2009), through this noticing activity, PST 3 made sense of "appropriate techniques and norms for use of new tools to support subject activity," and "the double instrumentation in which old technologies remain in use alongside new" (p. 387).

Importantly, PSTs' decision-making regarding their future teaching practices was justified by what they observed and learnt from the video modules. In general, after observing students' mathematical thinking in a technology-based task in Module 3, the PSTs positively evaluated the effectiveness of technology-enhanced learning: “It is easier to find the relationship of the cross-sections along similar cuts using 3D pens” (PST 7). On the other hand, in their decision-making, students reflected on learning difficulties and “hiccups” (Clark-Wilson & Noss, 2015) that arose in tool-based learning situations. For example, one student commented that there was room to “develop an extension question to test whether the student can understand and think correctly” (PST 7). It is expected that these observations will be considered in the PSTs’ future lesson plans, promoting quality implementations of technology-enhanced lessons.

5. Discussion

As shown in the results, the PSTs applied course content to consider and reflect on technology integration in mathematics teaching. For example, they critiqued the lesson video with respect to: the lesson and task design, technology use, how mathematical concepts unfolded, and student engagement and communication during the lesson. Their noticing was generally rich in terms of variety, as shown by the observation categories analyzed, as well as personal and meaningful in terms of making connections to technology-enhanced pedagogy. This can be traced to the method of individualized video-based noticing to enable PSTs to visualize themselves as the teacher in the lesson while they were guided by reflection prompts, which facilitated discussions on how the lesson could be improved.

In turn, the PSTs were able to formulate an effective lesson and to pinpoint the enhancements made in the lesson afforded by the 3D pens. This demonstrated their growth of TPACK (Koehler & Mishra, 2009), in the sense of both gaining an understanding of how 3D pens are used to create 3D solids (i.e., TCK) and can be used for teaching and learning (i.e., TPK). They also realized how certain learning activities with 3D pens could support student learning of geometrical concepts (i.e., TPACK). The use of videos seems to be instrumental for PSTs’ professional growth as it provided extensive imagery of technology-rich classroom contexts and classroom activities through episodes of teaching and learning and key moments of the technology-aided lesson. In relation to the key dimensions of video-aided teacher reflection proposed by Tripp and Rich (2012), the designed activities achieved individualized, out-of-class video watching and guided noticing in PSTs about various aspects of technology-enhanced mathematics learning. Scholars (e.g., Knolton, 2014; Pilgrim, 2015) have argued that various learner aspects and contextual features are not addressed in the TPACK framework despite their significance in teaching and learning. The PSTs’ comments in this study reiterated the importance of teacher knowledge or understanding of their target learners and learning environment. PSTs’ comments beyond the conventional TPACK framework should be further analyzed and categorized to better understand PSTs’ various types of knowledge involved in the design and implementation of the target lesson.

Besides the benefit of individualized viewing, the ability to store PSTs’ noticing comments on Blackboard allowed us to assess and differentiate noticing in PSTs and to facilitate class discussions based on commonalities and differences. For example, some PSTs noticed more subtleties in one category than other categories while completing Module 2, and so we facilitated group discussions in the ensuing class focusing on the commonality or lack thereof of PSTs’ noticing. As a result of the discussions, they realized that they were most concerned with classroom management issues related to implementing technology- and inquiry-based learning activities. Hence, they further discussed different classroom management strategies that could be implemented to enhance the lesson watched. Another discussion unfolded, in which some PSTs acknowledged that their previous schooling experience might have influenced their “viewing lens”. They also reflected on their strengths and weaknesses regarding noticing as well as their plans to improve their future teaching practices. Lastly, the categories of noticing facilitated a meaningful class discussion about what should be considered communication, classroom management, and tasks, and the possible overlap of two or more categories in a single noticing act. This was interesting because these had not been brought up in face-to-face video sessions in our prior experience of teaching in a fully face-to-face format. Overall, we were satisfied with the participation level of these discussions, as it seemed that PSTs were prepared to engage in group discussions and class time was consequently optimized.

In relation to advancing teacher knowledge and the concept of teacher noticing, we highlighted two methodological choices that helped to explain the results: (1) two requirements of noticing proposed by Mason (2002), which prompted the teachers’ interpretation (“accounting for”) upon recollecting (“made accounts of”) what they saw in the video; and (2) conducting class discussion after individual viewing. The first choice allowed the PSTs to become conscious of the connections they were drawing between specific classroom episodes and principles of teaching and learning and to reason about classroom events (Star & Strickland, 2008). The second enabled the researchers to observe changes in the teachers’ expertise as a collaborative and social process. During the classroom discussions, the PSTs guided each other’s attention, interpretation, and decisions regarding STEM teaching and learning. These empirically grounded results inform future STEM professional development programs on two effective methodologies for developing teacher expertise in STEM and technology-enhanced pedagogies.

Although the design-based implementations yielded some satisfactory results, they had some trade-offs. While individualized, out-of-class video watching could potentially facilitate a more prolonged engagement with the video content and reflection, not all PSTs took advantage of it. Some commented as little as 12 times in one video module. Similar to the findings of Krammer et al. (2006), our findings showed that some PSTs commented that typing comments and reflections took up too much time. In contrast, in-class noticing activities are more effortless since they are completed verbally, though participation and engagement levels will vary amongst PSTs. Finally, it seems that the various activities favored different kinds of class discussions; in-class noticing promoted more spontaneous, personal discussions and blended learning prompted more planned, theoretical discussions.

6. Conclusion

In this paper, we discussed the design, implementation, and results of a video-based STEM professional development intervention that focused on supporting an individualized viewing experience, keeping a record of what was noticed, providing a guiding framework, and facilitating a combination of individual and collaborative reflections. The use of the designed blended learning activities with a feature that supports instant commenting enabled mathematics PSTs to document and reflect on their noticing, and out-of-class video watching allowed them to engage and make connections with the course materials meaningfully. In addition, the prescribed observation categories of video-based noticing addressed various broad but crucial aspects of STEM classroom practices that aimed to help PSTs prepare for their future teaching careers. Aligned with previous research on video-based noticing (Jacob et al., 2010; Ng & Chan, 2021), the videos captured the dynamic processes of students' actions rather than just their final "answer," and this facilitated the participants' reflections about the evolution of students' mathematical thinking.

The designed innovation with blended learning activities effectively drew the attention of PSTs to different aspects of technology-enhanced mathematics instructions, but the innovation was not limited to addressing such contexts. Future TPD programs and research can use video-based noticing to develop teachers' expertise in other STEM areas, particularly those that are unfamiliar and not easily accessible by teachers in their everyday teaching. Researchers can also investigate whether the use of videos can influence teachers' perceived efficacy of teaching STEM after the blended learning activities.

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Integrated STEAM Approach in Outdoor Trails with Elementary School Pre-service Teachers

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ABSTRACT: Due to the COVID-19 pandemic it was impossible to carry out on-campus teaching and examinations as planned for the first-year elementary school Bachelor's degree teacher training courses during the summer term of 2019/2020. Therefore, we moved our on-campus STEAM (Science, Technology, Engineering, Arts and Mathematics) related courses to schooling at home. For their course examination, students designed outdoor trails in groups with the educational technology MathCityMap based on an integrated STEAM approach. Hence, they combined STEAM with real-world situations (e.g., monuments, marketplaces, playgrounds). The tasks within the trails required the use of technologies such as augmented reality (AR), digital modelling (e.g., GeoGebra 3D Graphing Calculator), and GPS. Analogue measuring tools (e.g., triangle ruler) were also used in the task designs. We collected data from 21 trails with 259 tasks from 49 pre-service teachers to analyse the effects on professional growth in STEAM education. Through hierarchical cluster analysis we identified three different clusters with patterns regarding STEAM in outdoor trails. This paper will describe a pedagogical framework for the integrated STEAM approach to designing and evaluating outdoor trails. Furthermore, we will explain patterns pre-service teachers developed during this professional development.

Keywords: STEAM, Outdoor trails, Professional development, Pre-service teachers, Higher education

1. Introduction

Digital technology (e.g., smartphones) and the digitalisation of processes (e.g., online purchases) are an important element of student lives. As a result, policymakers aim to develop skills in STEAM (Science, Technologies, Engineering, Arts and Mathematics) early, even in elementary schools, so students can understand and engage actively with their environments. A particular focus is on fostering STEAM-related process skills (NCTM, 1999; Selter & Zannetin, 2019). Therefore, teaching in elementary school needs to develop hands-on activities related to real-world problems (Blum & Leiß, 2007) in students' living environments (Lavicza, Haas, & Kreis, 2020). However, this teaching represents significant challenges for school communities. The integration of STEAM skills, where arts (e.g., architecture, monuments, paintings) extends STEM, is relatively new to teachers. Teachers tend to teach content skills in an isolated manner. According to Radloff and Guzey (2016), teachers understand only basic concepts in STEAM and thus feel uncomfortable teaching it. This led us to reconsider our higher education teaching in the first year's elementary school teacher training.

Our courses are built on hands-on activities, related to technology (e.g., dynamic mathematics software) and to the environment of elementary school students. During the last on-campus courses, we thought about teaching approaches to connect mathematics to architecture, cultural constructions or paintings and how mathematics within STEAM could be connected to real-world examples. However, we observed, that our pre-service teachers tended, based on their internship experience, to teach mainly on written tasks in-class and integrated only few tasks outside students' school environment. Moreover, we observed, most pre-service teachers, conceived their lesson plans in an isolated skills approach (e.g., teaching geometry, without technology and without connection to real-world), rather than using an integrated STEAM approach. Thus, in an integrated STEAM approach (Psycharis, 2018), methods and contents from the different STEAM domains are connected through transdisciplinarity (Kim & Bastani, 2017), similar to real-world situations, objects or problems (e.g., architecture needs mathematics, engineering, art, science and technology). It seemed more meaningful to teach through an integrated STEAM approach instead of creating learning and teaching settings for each domain separately.

As did Cooke and Walker (2015), we concluded that pre-service teachers should experience real-world problems within an integrated STEAM approach to improve STEAM teaching. According to Singer, Ellerton, and Cai (2013), connecting process skills to real-life situations could create new understandings of education, particularly the integrated STEAM approach. Therefore, we aimed to make this next step and work with pre-service teachers on outdoor STEAM trails related to places or objects within the real-world (Cahyono & Ludwig, 2019). With MathCityMap (Ludwig & Jesberg, 2015) pre-service teachers created in a collaborative approach, outdoor trails using GPS technology outside the classroom, with guidance and scaffoldings.

The designed tasks and trails relied on the integrated STEAM teaching approach, mathematical processes and content skills (e.g., areas, volumes, number theory) of the national curriculum (MENFP, 2011). During the trail creations, we performed a close monitoring through a series of tutorials. Finally, students performed a self-evaluation and three peer-reviews of the submitted outdoor trails.

Considering that we undertook an experimental investigation on teachings, we focused on identifying teaching patterns with this new approach, among pre-service teachers. Furthermore, we wanted to understand which possible support or scaffoldings would be needed in their future professional developments.

We carried out a quantitative investigation by addressing the following two research questions:
- Which integrated STEAM teaching patterns are pre-service teachers likely to develop during the creation of outdoor trails?
- What can we learn of this first integrated STEAM approach through outdoor trails for future professional developments in pre-service teacher courses?

Due to the complexity of measuring teaching patterns, we used a mixed-methods triangulation design by combining quantitative and qualitative instruments (Creswell & Clark, 2011). Thus, we collected data for 21 trails with 259 tasks from 49 students. Based on hierarchical cluster analysis (Antonenko, Toy, & Niederhauser, 2012), we identified the task design patterns. Besides, we analysed field observations from tutorials (e.g., questions and remarks during online meetings) and students' interactions during our courses (e.g., interactions or requests on Moodle™). This qualitative data was coded in a similar approach as grounded theory (Corbin & Strauss, 2014) and used further to describe upcoming needs in the elaborated learning settings. We will present in this paper a pedagogical framework, our findings on patterns in task design in outdoor trails and describe future improvements we learned through our initial experiences.

Amidst the COVID-19 pandemic in 2020, on-campus learning and teaching at the university was suspended and changed to schooling at home (Kreis, Haas, Reuter, Meyers, & Busana, 2020). Therefore, the professional development we present in this article was done exclusively in remote teaching.

2. Literature review

To prepare a STEAM integrated approach in outdoor trails, we performed a literature review of topics related to the professional development we wanted to experiment. Thus, we investigated frameworks and experiences with STEM integrated approach (Breiner, Harkness, Johnson, & Koehler, 2012; Kelley & Knowles, 2016; Lavicza et al., 2018; Madden et al., 2013). The frameworks described strong interactions between STEM disciplines (e.g., didactical approaches, problem solving, contents) and how important the transdisciplinary approach is. Findings from the studies indicated the need to connect STEM to real-world or as we wrote earlier, to students' living environments. However, there are various recommended teaching approaches and experiences for implementing STEM integrated teachings.

We consulted the literature on STEM in- and pre-service teachers training (Brown & Bogiages, 2019; Cooke & Walker, 2015; Madden, Beyers, & O'Brien, 2016; Michaluk, Stoiko, Stewart, & Stewart, 2018). Pre-service teacher training in STEM from the consulted literature highlighted the importance of hands-on activities and practical approaches in STEM teachings. Throughout the first reviews, we identified possible added values (e.g., creativity, presence of arts in myriad outdoor objects) to add Arts in the STEM. Hence, in completion, we investigated the extension to STEAM (Conradty & Bogner, 2018; Kim & Bastani, 2017; Land, 2013). Furthermore, students learn their first skills in the design process in arts, similar to engineering through problem-based learning with real design projects (Cook et al., 2017). According to Quigley, Herro, and Jamil (2017), arts support students to connect the other STEM disciplines to real-world problems. We decided therefore to work on a STEAM rather than a STEM integrated approach for our initial experience.

The connection to real-world in outdoor trails, led us to identify possible models used within literature and documented teachings. Out of the reviews on STEAM integrated approach, we identified the importance of mathematics in connection to the different domains of STEAM and referred to frameworks, which are usually used in mathematics education in our elementary schools to connect to real-world. Different mathematical modelling process approaches with real-world information (Blum, 2013; Blum & Leiß, 2007; Cahyono et al., 2020; Schukajlow et al., 2012; Selter & Zannetin, 2019) described how to apply mathematics and/or scientific solving approaches during task solving processes. These approaches allowed to structure the outdoor tasks by indicating important steps in solving (e.g., creating a situation model, modelling a situation model, modelling mathematical concepts, and interacting with real-world situations).

We used educational technology to apply an integrated STEAM approach through outdoor trails; thus, we consulted several research approaches on technology (e.g., MathCityMap) and outdoor trails involving real-world data (Cahyono & Ludwig, 2019). In these studies, most tasks focused on mathematics alone, however they described numerous interactions with real-word objects or places. Due to the technology, students used digital instruments, in addition to more traditional analogue measuring instruments. To understand how users get involved with educational technology, we referred to the theory of instrumental genesis (Lieban & Lavicza, 2019; Trouche, 2004) and the TPACK (Technological Pedagogical Content Knowledge) framework (Tondeur, Scherer, Siddiq, & Baran, 2020), which focus on the interconnections in teaching between pedagogy, content and technology knowledge. Teachers use educational technologies differently and show different manipulations of the same technology in their teachings. However, considering the different appropriations of technology by pre-service teachers, scaffoldings could help them develop skills to advance their use of technology (Tondeur et al., 2020). Based on the reviewed literature, we were able to identify, how pre-service teachers could use different technologies in the task design (e.g., augmented reality or GPS based measuring).

Pre-service teachers gained experience through working with frameworks for task designs, since they used the TPACK framework during their remote internships (during the pandemic) to create online teaching settings and contents for elementary school students. We observed a quality gain in the pre-service teachers created content and new teaching patterns, while using pedagogical frameworks. Therefore, we elaborated a pedagogical framework for our professional development course.

3. Pedagogical framework

Based on the literature review and the theoretical references, we designed a pedagogical framework (Figure 1) for outdoor task design with two major components (i.e., outdoor trails, STEAM integrated approach) and two subcomponents (i.e., process and content skills). This pedagogical framework, served, on one hand, to guide pre-service teachers' professional development in applying STEAM in their trail and tasks design and on the other hand to identify possible teaching patterns (e.g., tasks in the trails, use of technologies, connections to real-world).

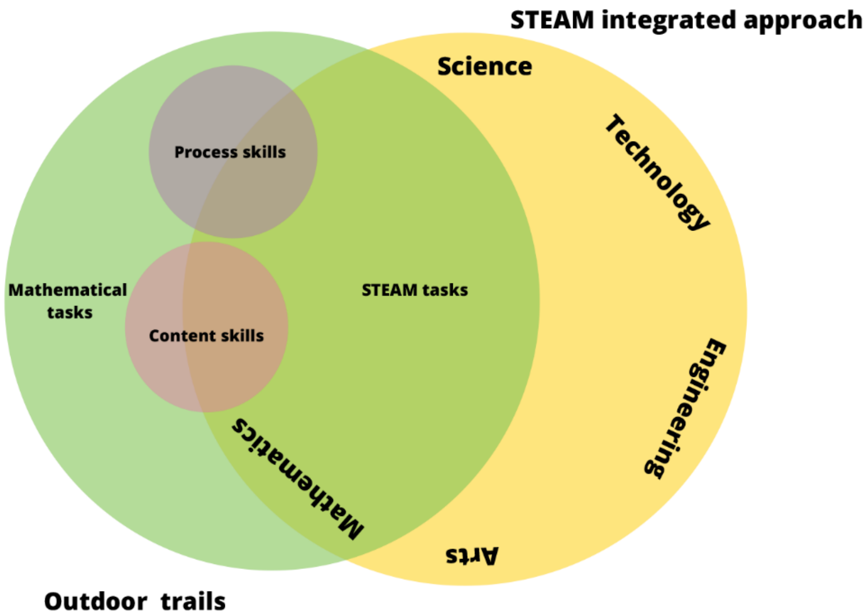

Figure 1. Pedagogical framework

3.1. Outdoor trails

Any structured learning activity outside the classroom can be qualified as learning STEAM outdoors (Kendall, Murfield, Dillon, & Wilkin, 2006). Moreover, such learning activities provide direct experiences with the real world (Moffett, 2012). Such structured learning activities support the interaction between STEAM and the environment in which students live, with real-world problems (Blum, 2013) by reinvesting skills learned in school. However, as written by Beard and Wilson (2006), being outside is not stimulating mathematics and in this case, STEAM skills alone. The tasks should be structured and conceived, according to the findings of Vos (2015) by subject matter experts (SMEs) in STEAM didactics.

To support these structured outdoor learning activities in STEAM, since pre-service teachers are not yet SMEs in STEAM didactics, we referred to MathCityMap, which allows creating outdoor trails with tasks related to mathematics and STEAM (Jablonski & Ludwig, 2020) in an organised guided approach. Pre-service teachers are guided in MathCityMap (https://mathcitymap.eu; Figure 2) by responding to a set of predefined elements (e.g., visual identification of the chosen GPS coordinate, task description or hints) and respecting criteria and effects on trail designs (e.g., uniqueness, attendance, activity, various ways of solution).

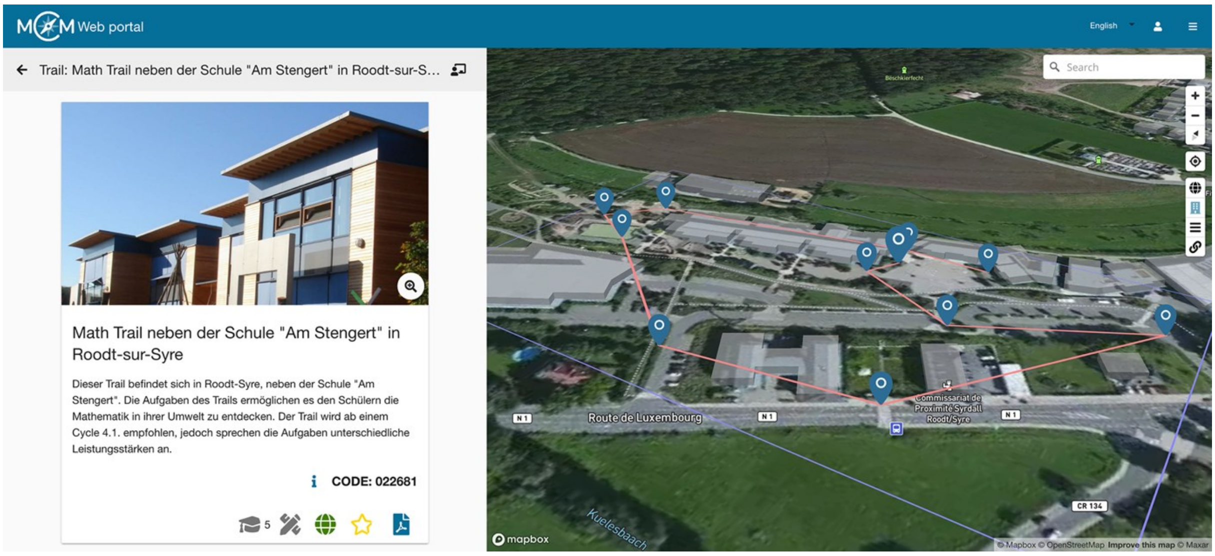

Figure 2. Users view of the MathCityMap web portal showing a trail with tasks bound to GPS coordinates

In MathCityMap, students navigate through trails and get descriptions and potential hints of tasks (Figure 6) as well as a sample solution (Figure 4). Pre-service teachers' outdoor trails are connected to places in environments which are of interest to learning activities (e.g., architecture, market square). These places or objects of interest in the real world are at the beginning of an outdoor trail design process and determine a development direction (e.g., STEAM disciplines) of the design process. According to Brown and Bogiages (2019), for an integrated STEAM approach, at least two disciplines and practices (e.g., mathematics and science) are needed. However, real-world places or objects can promote inequities among the use of the different STEAM disciplines. Moreover, as pointed out by English (2016), some of the STEAM disciplines tend to be more represented than others in education. Thus, we clarified for pre-service teachers, the integrated STEAM approach in outdoor trails, to ensure a higher variety of the STEAM disciplines in the trails.

3.2. Integrated STEAM approach

We used an integrated STEAM rather than a STEM approach which is described as "an instructional approach, which integrates the teaching of science and mathematics disciplines through the infusion of the practices of scientific inquiry, technological and engineering design, mathematical analysis, and 21st-century interdisciplinary themes and skills" (Johnson, 2013, p. 367). Kelley and Knowles (2016), argued similarly in their conceptual framework for integrated STEM and highlighted the importance of connecting real-world problems to the different subjects. Hence, in the outdoor trails, elementary school students interact with real-world problems in outdoor places. Besides, depending on the places, students need to apply creative thinking to identify and connect real-world information to in-class learnings. In this creative thinking process, students "decompose a complex problem using convergent thinking and then apply the corresponding solution to the real world" (Land, 2013, p. 552). Arts within STEAM, as reported in research (Conradty & Bogner, 2018), cultivates creative thinking process and further supports students with new accessibilities to STEM. During the outdoor trail design process, pre-service teachers needed to consider different contents and skills from STEAM disciplines out of the curriculum for elementary schools and seek interconnections. This was a rather new approach in their teachings, as they regularly reflected only one discipline as mentioned earlier. However, using MathCityMap and after the preparation tutorials, connections between disciplines can become more visible to pre-service teachers. Figure 3 shows an example of an outdoor task related to arts, technology, engineering and mathematics. In this task, you have to use AR (technology) to find out which geometric shape (mathematics) fits the architecture (arts) and model it accordingly (engineering). The chosen GPS spot in MathCityMap, in this case an architecture construction, is guiding how disciplines in STEAM could be connected or used in the task.

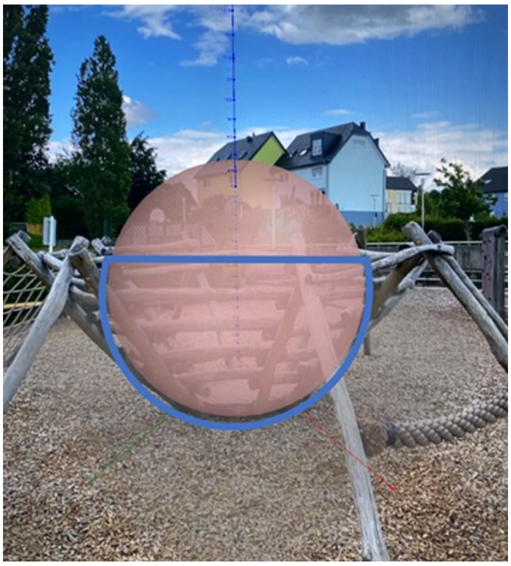

Figure 3. Task involving STEAM

The use of technology in MathCityMap within a STEAM approach is possible through AR (e.g., GeoGebra 3D Graphing Calculator), GPS tasks and digital measurement tools (e.g., protractor application). These technologies engage in a modelling process of real-world problems (Cahyono et al., 2020). Further, using AR to represent shapes in real-world has proven to support students' learning in solid geometry (Liu, Li, Cai, & Li, 2019). However, many created outdoor tasks refer to the use of analogue measuring instruments (e.g., triangle ruler, measuring tape). Some outdoor tasks even relate to more uncommon scholar engineering, like measuring the height of a tree (Figure 4) with an isosceles right-angle triangle (ruler) (Gellert, Gottwald, Hellwich, Kästner, & Küstner, 1990, p. 243).

Figure 4. Measure the height of the tree with a triangle ruler

As shown in the pedagogical framework, there are mathematical tasks and STEAM tasks. However, both typologies of tasks are built upon mathematical skills. They referred to process skills (e.g., problem solving) due to their relations to real-world problems and content skills (e.g., distance of a segment), depending on the nature of the task.

3.3. Tasks in outdoor trails

Blum and Leiß (2007) stated in their model on real-world problems that students modulate information with process skills and connect real-world to mathematical models. With the use of educational technology, in this case MathCityMap, process skills are widely supported and developed (Liljedahl, Santos-Trigo, Malaspina, & Bruder, 2016). Process skills have been described by various researchers and organisations. Thus, we wanted to establish a common understanding between international references (NCTM, 1999), mathematics didactics references (Selter & Zannetin, 2019) used in elementary schools and the national curriculum (MENFP, 2011). We categorised the process skills from the different references and created connections between the definitions. We were able to identify four major skills based on our analysis of references (Table 1).

Table 1. Process skills

Skills	Description
Problem Solving	Engage in a task where the resolution method is not known in advance. Transfer skills and knowledge in this task to find a solving path.
Reasoning and Proof	Argue, communicate, analyse and justify the conjectures made in the task.
Representation	Represent conventional or unconventional models to solve the task.
Modelling	Modulate, connect and communicate mathematical concepts to solve the task.

According to Schukajlow et al. (2012), the process of modelling real-world problems with mathematics, is not a linear but an iterative process. Thus, elementary school students try out, discuss, draw schemes, and reason their solving process iteratively during the tasks in the outdoor trails. To illustrate process skills in these tasks and to evaluate our classification, we undertook testing with a class. 16 elementary school students (age 10 to 12) completed some outdoor trails and were observed actively using process skills while solving tasks (Figure 5).

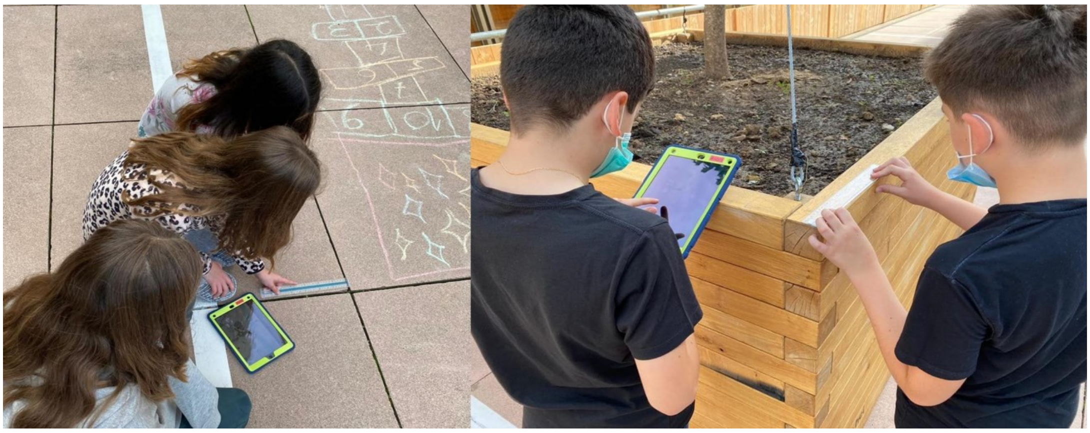

Figure 5. Elementary school students solving outdoor tasks on measuring segments and calculating volumes

Figure 6. Calculate the volume (in m^2) of the raised garden bed

In addition to process skills, the tasks refer to content skills from the national curriculum (e.g., recognise shapes or solids). In Figure 6, for example, the task requires geometric and measurement content skills. Besides the recognition of the correct solid, students need to remember and apply the formula of the volume of the rectangular cuboid and transform the result into the requested unit of measurement. Within an integrated STEAM approach connected to real-world problems and situations in the outdoor trails, students were able to solve these complex tasks with several content and process skills.

4. Data analysis

In the pedagogical framework, we described the integrated STEAM approach and process and content skills used in the outdoor trail creation process. There were many different possibilities in connections of STEAM disciplines, outdoor places and objects. In the professional development on integrated STEAM approach with pre-service teachers, we set up a teaching methodology and tested this framework. During our research, we wanted to identify how these outdoor trails with educational technology (e.g., MathCityMap) are likely to develop teaching patterns in STEAM and wherever our methodology would need improvements for further courses.

4.1. Sample description

Our sample consisted of 35 female and 14 male first-year pre-service teachers enrolled in the Bachelor's degree at the University. The pre-service teachers were in their second term and taught basic mathematics educational principles regarding numbers and operations, geometry and technology usage.

4.2. Process description

The study started in the second half of the semester, after the schooling at home (Kreis et al., 2020) started and was thus entirely conducted remotely. The findings on fully online courses on pre-service teachers' technological and pedagogical skills development (Corry & Stella, 2018) suggested potentially positive outcomes. Furthermore, we included the cooperation, role models, tutorials, feedback on pre-service teachers' support, and theory and praxis alignments to ensure the pre-service teachers' support. Thus, the pre-service teachers created groups with two or three members. They created overall 21 outdoor trails with 10 to 18 tasks per trail (259 in total) and received remote guidance from the lectures. The creation process of the outdoor trails was organised into three different phases (Figure 7).

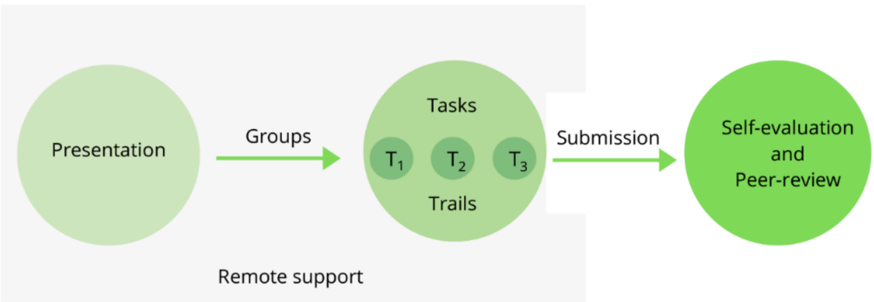

Figure 7. Outdoor trail creation process

In the first phase, pre-service teachers received an introduction into MathCityMap and outdoor trail examples, fulfilling all evaluation criteria. Alongside this, the lectures indicated several possibilities to create tasks with digital or analogue measurement tools. The duration of this online session was 90 minutes including pre-service teachers' questions. Resources on technology and trail and task examples remained available and the pre-service teachers were allowed to send in further questions during the whole process. Before the second phase, pre-service teachers formed their groups with two or three members on the University Moodle™ platform. Proximity of residence was an advantage for the intended collaboration. This choice was made to support peer learning throughout our teaching in the Bachelor's degree, and we aimed to prepare the pre-service teachers working in teams rather than as individuals for their future teaching career. Furthermore, according to findings of Guskey (2003), working together and sharing ideas is important to become a reflective practitioner.

In the second phase, the pre-service teachers were developing the tasks and the trail. Several groups responded to the offer of up to three tutorials of approximately 10 minutes to receive additional guidance and explanations. Most questions were about technical issues (i.e., PDF creation of the trail) and tasks' presentation (i.e., cropping of the pictures, wordings). Some groups asked for guidance regarding AR in their tasks and received a brief introduction in the 3D creation process using GeoGebra. Overall, in each tutorial, we adapted our scaffoldings to fit the questions and needs for support. Moreover, we encouraged (with additional guidance) to experience new technologies (e.g., AR) or new points of views (e.g., connecting arts, mathematics and technologies).

In the third phase, the trails were self-evaluated and peer-reviewed based on five questions. We will report on the evaluation process in upcoming papers.

4.3. Instrument description

We adopted a mixed-methods triangulation (Creswell & Clark, 2011) with quantitative and qualitative instruments to identify teaching patterns through cluster analysis (quantitative) based on coded data (qualitative) for research question 1. Moreover, we used the coded data to describe upcoming needs from this first experience for research question 2. We originated our qualitative coding on the designed pedagogical framework to identify STEAM integrated teaching characteristics with a similar grounded theory approach (Corbin & Strauss, 2014). Thus, out of the data, we identified codes that would most likely describe STEAM integrated teaching in outdoor trails (e.g., characteristics of sciences in the tasks, mathematical skills or technology use). We identified codes for the cluster analysis throughout iterative coding (open, axial and selective) and further obtained findings on necessary improvements in our teaching setting (e.g., needed scaffoldings in sciences didactics or peer interactions) during the coding process. Furthermore, each task was tagged by the dominant content skill (e.g., segment measurement). The final coding for cluster analysis (Table 2) was binary (0 = not present; 1 = present).

Table 2. Final codes

Code	Description
S	Science
T	Technology
E	Engineering
A	Arts
M	Mathematics
MPS1	Problem solving
MPS2	Reasoning and Proof
MPS3	Representation
MPS4	Modelling
MCS1	Numbers and Operations
MCS2	Geometry
MCS3	Measurement
MCS4	Data Analysis and Probability
AR	Augmented Reality
GPS	Global Positioning System
C	Calculator
DMI	Digital Measuring Instruments
AMI	Analog Measuring Instruments

Following findings of Antonenko, Toy, and Niederhauser (2012), we chose cluster analysis (CA) with variables from the different outdoor trails to identify groups in teaching patterns. Thus, this data mining allowed us to identify clusters (e.g., groups of teaching patterns), without recordings screens, analysing log files or interpreting the pre-service teachers' self-reports in times of confinement and social distancing. Further, we decided to use CA to develop a differentiated, tailored support for each cluster in the upcoming courses. Among the different methods in CA, we used a hierarchical cluster analysis (HCA) based only on the integration of the fields Science, Technology, Engineering, Arts, and Mathematics (STEAM) in the tasks of the outdoor trails. The other codes, like the use of different technologies (e.g., AR, GPS, C or DMI) or contents and process skills, which added valuable details, were used during the description of the identified clusters, along with the collected field observations (e.g., tutorials and course interactions).

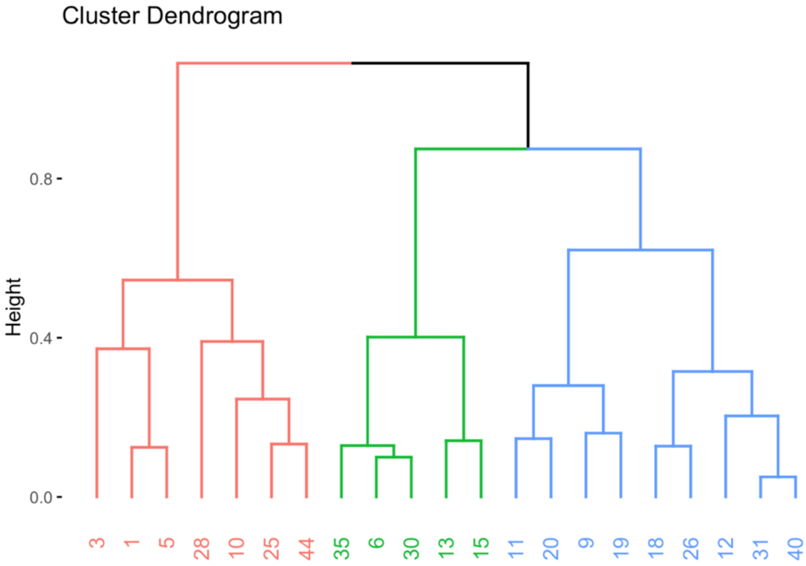

Figure 8. Cluster Dendrogram of the trails based on the integration of STEAM fields

Before starting the cluster analysis, we converted the five field variables to percentages, to get comparable continuous data. The following statistical analysis was done using R (R Core Team, 2020). The HCA for our concept of a cluster in this project used Ward's agglomeration method (i.e., minimal increase of sum-of-squares) and the euclidean metric for calculating dissimilarities. The corresponding dendrogram suggested a cut into three clusters (Figure 8) represented by three colours. The horizontal axis of the dendrogram represents the trails, labelled by a given number for each trail. The vertical axis of the dendrogram indicates the height where similar clusters are combined into a bigger cluster starting with single-element clusters. These calculations relied on the package factoextra (Kassambara & Mundt, 2020). This number of clusters was verified using the package NbClust (Charrad, Ghazzali, Boiteau, & Niknafs, 2014), which provided 30 indices for determining the number of clusters. The number of outdoor trails per cluster varied from 5 (cluster 2) to 9 (cluster 3).

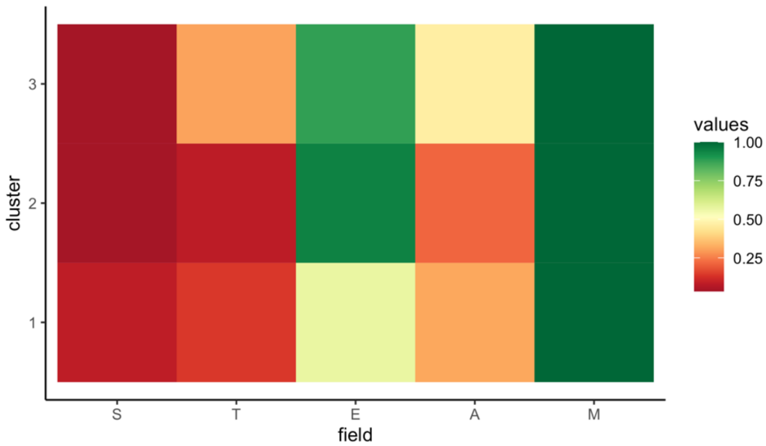

Figure 9. Cluster Heatmap of the trails based on the integration of STEAM fields

The mean percentages per cluster of the integration of STEAM fields (Figure 9) range from 100% (Mathematics) to 3.3% (Science in cluster 2). One could argue that both mathematics and sciences are cornerstones of STEAM. Thus, a course orientation in one or the other direction results in higher mathematics or sciences in the outdoor trails.

5. Results and discussion

5.1. Research question 1: Teaching patterns

In every cluster on teaching patters, the outdoor trails' tasks were based on the previously defined processes and content skills. Only the representation skill (11.1 %) was present less often in the trails for the process skills.

Those tasks required the use of technology for representation or reconstruction of shapes and forms. There have been fewer tasks on data analysis (5.9 %), which could partly indicate the missing science in the outdoor trails. However, the nature of the educational technology, which was initially conceived only for mathematics education, could possibly as well support this tendency. Most of the outdoor tasks were based on topics in geometry (58 %) and requested measurements. The cluster analysis and its interpretation revealed three major patterns in the creation of outdoor trails within an integrated STEAM approach. In general, pre-service teachers used mathematics in each task and almost no science.

5.1.1. Cluster 1: Trails with mainly mathematics tasks

In cluster 1 were 7 (33.3 %) outdoor trails with 82 (31.6 %) tasks created by 14 female and 2 male pre-service teachers. In this cluster, the tasks were less marked by an integrated STEAM approach. Nevertheless, all tasks related to mathematical content and process skills, but the other fields of STEAM were almost all under 50% for the different trails. The cornerstone of mathematics strongly guided the groups within this cluster. According to Shaughnessy (2013), mathematics must be made explicit and transparent in the integrated STEAM approach to connect to the other STEAM disciplines. Not every pre-service teacher recognised all possibilities in mathematics and connections to STEAM. This aligns with the observations during the courses in winter term, where we observed that pre-service teachers need further teaching and learning on mathematical language, models and didactics.

Engineering (56.9 %) was present in every second task, but without being connected most of the time to technology. In these trails, the groups of pre-service teachers created mostly tasks using analogue measuring tools (e.g., triangle ruler) to perform tasks in the content area of measurement. Thus, the use of technology (13.9 %) was rather low and only a few tasks related to technologies in the trails. 31.4 % of the tasks targeted arts mainly by counting or measuring elements from architecture or monuments (e.g., counting the number of windows). The implementation of science (8.3 %) within the outdoor trails and tasks was low, only some tasks included science (e.g., earth science with the cardinal directions).

In this cluster, pre-service teachers employed a traditional approach, close to the tasks described in the textbooks in mathematics course, with low interactions between STEAM disciplines. Similar to the findings of Adalberon, Hauge, and Säliø (2019), this could be due to the new situation or as mentioned earlier to low mastery in mathematics. Furthermore, the lack of analysing teaching and learning situations within the use of new educational technologies (Blomberg, Sherin, Renkl, Glogger, & Seidel, 2014) could lead to use of self-experienced learning situations rather than new innovative teaching.

In some tutorials, we were able to identify uncertainties regarding technologies and connections to places or objects in real-world. Pre-service teachers were not confident in identifying all possible connections in the different selected GPS spots and choose tasks close to the ones in textbooks. With these groups of pre-service teachers, an analysis of their outdoor trails and tasks should be done to evaluate each in its possibility to integrate science, technology, and arts to crossover STEAM.

5.1.2. Cluster 2: Trails with combined mathematics and engineering tasks

In cluster 2 were 5 (23.8 %) outdoor trails with 60 (23.2 %) tasks created by 6 female and 6 male pre-service elementary school teachers. In this cluster, the outdoor trails were dominated by mathematics (100 %) and engineering (94.7 %). Many outdoor tasks combined engineering with analogue measuring tools (e.g., measuring tape). Yet, tasks based on engineering are close to design-based learning settings (e.g., designing household artefacts in school) and have often been experienced by the pre-service teachers in their own learning. Moreover, similar to the National Research Council (2011), engineering could have been used in the tasks to make these more relevant for students, as engineering is widely present in real-world situations and problems.

The use of technology (8 %) was again very low for this cluster, although it could have been used in several engineering tasks. The pre-service teachers did not really integrate technologies in the tasks, apart from some uses of an application to measure a segment with GPS, which is per se integrated in MathCityMap. The low integration of technologies could be related to insufficient time pre-service teachers had (Chittleborough, 2014) and more probably low perceived skills in technologies (Lemon & Garvis, 2016).

21.3 % of the tasks touched art (e.g., completing the missing numbers of grapes of an artistic representation). Even though art was present, foremost combined with engineering, it could have been more. During the tutorials, some groups showed high motivation while presenting tasks related to arts. This was similar to Myunghee et al. (2013) ‘s findings, who reported that arts increased motivation and facilitated connections to other STEM disciplines. However, the interconnections of arts, mathematics and engineering were few in the task designs.

Like cluster 1, science (3.3 %) was very lowly represented in the outdoor trails for cluster 2. Only a few tasks connected to the discipline or practices of sciences. Although Bossé, Lee, Swinson, and Faulconer (2010) identified large interconnections between process skills in mathematics (i.e., NCTM process standards) and sciences skills, this alone does not ensure that pre-service teachers would identify these connections (L. Madden et al., 2016). The disciplines have been thought separately in schools, and therefore, it may be difficult for them to connect both science and mathematics in the same tasks.

5.1.3. Cluster 3: Trails with (S)TEAM tasks

In cluster 3 were 9 (42.9 %) outdoor trails with 117 (45.2 %) tasks created by 15 female and 6 male pre-service elementary school teachers. In this cluster, the outdoor trail tasks were marked by an integrated STEAM approach with again mathematics (100 %) and engineering (88.3 %) dominating the tasks. Far more tasks (30.7 %) than in clusters 1 and 2 relied on the use of technologies (e.g., AR to identify solids). Further, pre-service teachers employed a variety of measuring apps, from distances to angles. Some trails were essentially technology guided, and the groups experimented with different applications. This pattern in the integrated STEAM approach could be similar to the findings of Tondeur et al. (2020), related to technological and pedagogical knowledge of the individual pre-service teachers, which influenced the groups.

Arts (46.5 %) were often present in the tasks. Combined with technologies and engineering, architectures, monuments and outdoor paintings were used in these cluster’s trails to work on different content skills. Examples of the (S)TEAM integrated approach were the reconstruction of missing shapes with AR, measuring the diameter on building entrances and analysing patterns in painted floor art. In the tutorials, the pre-service teachers presented tasks that were close to the ones we demonstrated in the introduction session and tasks where they clearly experimented with technology, engineering and arts.

Based on these correlations, we could observe dynamic teaching interactions, which were reproduced in their trails. In the upcoming courses, we need to encourage these pre-service teachers to share their experiences and support their peers as peer-coaches. According to Britton and Anderson (2010), peer-coaching can significantly support emerging teachers to develop the requested skills. Thus, we will need to develop training sessions for those peer-coaches to support our professional development courses. However, as for the other clusters, the number of tasks, including science (3.4 %) was low. As mentioned earlier, pre-service teachers may not connect science and mathematics in outdoor trails.

5.2. Research question 2: Possibilities and hinderances

In the second research question we investigated possibilities and hinderances on this professional development experience using integrated STEAM approach and technology through outdoor trails. Based on perceptions from the lecturers, coded data and field observations, the important turnovers in this experience were (a) acceptance to teach STEAM, (b) the pedagogical framework, (c) supportive teaching environment and (d) peer interactions.

During and after this experience, we were able to identify high acceptance (higher than regular course teachings) and examination results were better than in previous years. Most of the pre-service teachers seemed to engage more positively with STEAM disciplines than they normally would when taught separately. However, similar to the findings of Michaluk, Stoiko, and Stewart (2018), the support of attitude and beliefs through a structured course on integrated STEAM should reinforce teaching skills and allow the development of patterns in order to fully integrate STEAM.

The pedagogical framework guided the design process and allowed pre-service teachers to learn skills in integrated STEAM approach with outdoor trails. However, pre-service teachers should work over a longer period with the pedagogical framework, to develop skills and deeper understandings for outdoor trails, similar to frameworks like TPACK (Tondeur et al., 2020). According to findings of Philipp et al. (2016) a closer guidance in the process with clearer instructions on the tasks (i.e., indicate the topics and methods to employ) could lead to a more diverse task outcome, including science. This course experience, however, endured only one semester.

We saw many opportunities in integrating technology, which was present in nearly half of the trails at the end of the analysis. Pre-service were supported during the tutorials to try out new technologies and approaches. AR was shown to be very useful to combine all process skills in mathematics and connect the different STEAM topics (Sırakaya & Alsancak Sırakaya, 2020). However, since we connected not all pre-service teachers in the same amount of time and intensity, an online tutoring system, similar to a previous research (Haas, Kreis, & Lavicza, 2020), to develop skills in the use of technology in outdoor trails, could be an added support. Pre-service elementary school teachers could by then receive a guided approach on the use of AR for the tasks in the outdoor trails.

Pre-service teachers worked in groups to create outdoor trails within an integrated STEAM approach. Overall, this was experienced positively and should be a good preparation for upcoming teaching in the Bachelor's studies. Nonetheless, we need to identify how the peers worked together, which roles they attributed to themselves and how they managed the STEAM approach jointly. However, we estimate that, similar to Buchanan and Stern (2012), peer interaction supports the pre-service teacher in professional growth.

6. Conclusion and way forward

This first professional development with pre-service teachers on STEAM integrated approach with outdoor trails was very rich in its outcomes. Although held in fully remote teaching, we observed innovative teaching approaches while working with hands-on activities in real-world, supported by educational technology. Furthermore, pre-service teachers experienced STEAM, through collaboration, in a very positive and motivating way.

In general, we estimate that this kind of professional development could be significant for upcoming or even in-service teachers. Hence, teachers interconnect STEAM disciplines in an outdoor trail through the educational technology MathCityMap's guidance in an efficient approach. However, a pedagogical framework should be made available for teachers over a more extended period and of course, adapted to further investigations. In upcoming professional development sessions, we will closely monitor how pre-service teachers collaborated and made pedagogical choices in their task designs.

Overall, the use of technology was significant in this experience and was a valuable tool for learning STEAM didactics. Pre-service teachers received a supportive structure in their task and trail designs, and as lecturers, we were able to observe how a professional growth in their teachings. The promotion of this approach could, lead to a change in STEAM perception in school communities.

7. Limitations of the study

This study had time constraints and several restrictions due to restrictions imposed by the pandemic. Further, there is still a limited number of research on outdoor trails with STEAM integrated approaches in higher education and in elementary school teaching.

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Implementation of an Andragogical Teacher Professional Development Training Program for Boosting TPACK in STEM Education: The Essential Role of a Personalized Learning System

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ABSTRACT: Several previous studies have indicated that teachers require knowledge to enhancing technology-integrated instructional practices for representing and formulating the content to students. Therefore, the technological pedagogical content knowledge (TPACK) framework is essential for advancing teacher professional development (TPD) programs while using technology-integrated teaching. Moreover, personalized learning systems have been increasingly recommended to improve the quality of professional teacher development. This TPD study was based on andragogy theory and the TPACK framework. This study implemented an andragogical TPD outreach program integrating a TPACK-oriented personalized learning system as a 2-year face-to-face training mode for TPACK-focused science, technology, engineering, and mathematics (STEM) education to in-service STEM teachers from secondary schools in northeastern Thailand. They were employing a pre-post intervention design method, this paper reports on an ongoing longitudinal investigation of the influence of the TPD program, disseminated in four 2-day intensive training workshops, on 153 in-service teachers' TPACK development. The study measured participants' changes of the cognitive outcome on how to teach STEM situation-related photosynthesis, friction, light and vision, and composite materials with digital technology using multiple-choice TPACK tests embedded in the proposed personalized learning system. The results showed in-service STEM teachers' incremental TPACK improvement from the implementation of the TPD intervention. The results indicate the alleged superiority of the integrated personalized learning system as a critical part of promoting TPACK development in STEM education.

Keywords: Personalized learning, Mobile technology, Andragogy, Teacher training, STEM education

1. Introduction

Previous research has indicated that, while students from primary education receive learning activities in the fields of science, technology, engineering, and mathematics (STEM), they tend to have less interest and motivation for STEM learning, especially in Western countries and more prosperous Asian nations (Thomas & Watters, 2015). Importantly, students' STEM interests and motivation are major prerequisites to promoting meaningful STEM learning. They are closely related to their future career choices associated with STEM disciplines (Christensen & Knezek, 2017; Maltese et al., 2014). Concerning this problematic issue, several nations continue to transform the conventional subject learning-related STEM disciplines and grow STEM education improvement to meet the twenty-first century's environmental, social, and economic challenges (English, 2016; Kelley & Knowles, 2016). Regarding the global urgency, the demand for preparing a STEM workforce equipped with STEM skills and competencies has been increasingly acknowledged worldwide, and the need for an educational transformation of science, mathematics, and technology education and development into integrated STEM education and STEM professional development has been pointed out by educational researchers, practitioners, and developers (Cheng et al., 2020; Honey et al., 2014). In addition to the growing global interest and substantial endeavor to promote STEM, not only do all students need a more robust integrated and holistic approach to STEM education, but STEM teachers are also needed to educate and prepare for gaining high-quality STEM teaching competency (Kajonmanee et al., 2020; Srisawasdi, 2012; Srisawasdi, 2015). Educational reforms and efforts should increase STEM teacher supply through well-designed teacher professional development (TPD; Jong, 2019a; Jong, 2019b). Research about TPD shows that it is most effective when the process of professional learning is active, consistent with intrinsic motivation, focused on individual performance, and reflecting actual progression (Harris, 2016). As such, the TPD program movement is widely related to the intervention that can support the diagnostics of individual trainees, provide customized professional learning opportunities, situate active learning within professional learning communities, and then be used to monitor adult teachers' progression (Joyce & Calhoun, 2010). To be effective, it is crucial to consider the conceptual theory of andragogy, which refers to methods and principles used to facilitate adult learning, particularly creating a professional development class conducted with an adult STEM teacher audience. To generate a true mirror of pedagogical methods teachers employ with their students, the andragogy should be concerned with the enhanced education of the teaching forces to improve the quality of education received at the K-12 level (Marshall, 2019).

As Chai (2019) and Fore et al. (2015) indicated, TPD has been laying the foundation for reforming education. Thus, professional development is a growth-promoting learning process that empowers STEM teachers to adopt an integrated and holistic approach to teaching STEM and going through it yearly to improve the quality of integrated STEM teaching competencies. However, there is still a lack of TPD studies for integrated STEM education (Al Salami et al., 2017; Cavlazoglu & Stuessy, 2017; Chai, 2019; Chai, Jong, & Yan, 2020). The approach to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson and bound by STEM practices within an authentic context or real-world situation to enhance student learning (Kelly & Knowles, 2016; Moore et al., 2014). In the context of integrated STEM education, the teacher's role is to design and implement STEM instructional practices to facilitate students achieving higher-order thinking competencies, such as problem-solving via active participation and their creative thinking abilities via teamwork, using knowledge and skills (Bell et al., 2018; Condon & Wichowsky, 2018; Hwang et al., 2020; Lee, 2015). Therefore, providing teacher knowledge is key to effective STEM instructional practices, especially technology-enhanced STEM education (Kajonmanee et al., 2020; Hwang et al., 2020; Nikou & Economides, 2019).

Regarding teacher knowledge, Shulman (1986) pointed out that it is necessary to engage teachers in representing and formulating the content/subject that makes it comprehensible to others. In other words, teachers need to use a particular tool to deliver content to students rather than substitute or augment content with available tools. In line with this concern, Mishra and Koehler (2006) suggested teacher knowledge of how to effectively teach with a proper technology; that is the framework of technological pedagogical content knowledge (TPACK), making for effective technology-enhanced teaching. Thus, TPACK can be regarded as an effective technology-integration model for TPD (Chai, Jong, & Yan, 2020; Lee et al., 2019; Pondee et al., 2021). In addition, teachers would think first about what they want students to know and how they will blend technology into STEM content; therefore, Chai (2019) indicated that teachers should activate and expand their TPACK for STEM lesson design. However, training teachers to teach STEM lessons with technology effectively is a complex task, particularly regarding their different instructional profiles and characteristics. To respond to the demand for multiple knowledge applications for teaching with technology in STEM education, the technology of a personalized learning approach seems to hold considerable promise with the usefulness of data analytics in future TPACK-based professional learning (Angeli et al., 2014). Moreover, personalized learning technology could prove highly effective with adaptive operation and systems in situated professional development (PD; e.g., TPACK-STEM; Timotheou et al., 2017). Therefore, the connections between TPACK, STEM, and personalized learning systems could contribute to a composite framework to analyze and promote TPD quality in STEM education. Thus, this study employs the TPACK framework as the theoretical basis for designing STEM teachers' TPD programs and then implementing the programs via the integration of personalized learning systems to cultivate their TPACK regarding integrated STEM education.

Finally, a TPACK framework that explains essential knowledge types has been suggested as a requirement of effective technology integration for teachers. Similarly, for adult teachers to use technology effectively in their STEM instruction, TPACK is essential. This effort may foster connections between TPD and andragogy in the fields. It is necessary to advance teachers' TPACK in STEM education and contribute to a composite framework to analyze the quality of andragogical TPD approaches for STEM teachers. Hence, this study will examine a TPD intervention implemented to develop TPACK in the STEM education of in-service teachers in Thailand. The intention is to provide an answer to the following question: Does an andragogical TPD intervention program emphasizing TPACK in integrated STEM education, with the support of a personalized learning system, affect in-service science teachers' TPACK improvement?

2. Literature review

2.1. Andragogy in Teacher Professional Development (TPD)

In the past decade, scholars have identified factors for successful PD. For example, practicing or training content knowledge alone is not sufficient; teachers must also learn the appropriate pedagogies to foster student learning (Shulman, 1986; Mishra & Koehler, 2006). Improving instructional knowledge and skills among teachers is through PD with sustained learning periods (Garet et al., 2001). To avoid failure of school improvement, teachers should be active participants rather than passive receptacles of knowledge through PD (Darling-Hammond et al., 2017). In addition, researchers have indicated that teacher professional development (TPD) programs providing specialized training to adult teachers generally have more significant and positive influences on learners' outcomes (Connors-Tadros & Horwitz, 2014; Zaslow, 2014). To be effective, PD needs to address the principles and methods of adult learning and training for teachers, and the focus must shift to a rigorous process of capacity building for adults so that the way of handling their educational needs is viewed differently from that related to children. As indicated by Knowles (1980), andragogy refers to the procedure for supporting the learning of adults, while pedagogy refers to the strategy that teachers use to teach students. Thus, andragogy is an educational approach that explicitly considers adult learning needs, andragogical principles, and highly suitable methods for any form of adult education (Loeng, 2018). It is well known that teachers have to improve their competencies to harmonize with their anthroposphere particularly, and the andragogical approach, developed extensively by Malcolm Knowles, is a well-lauded response to the TPD approach that considers adult learning needs. According to Knowles' (1980) perspective on andragogy, Chan (2010) summarized the six following main assumptions based on andragogy:

- Self-concept: Adult learners are self-paced, autonomous, and independent.
- Role of experience: Adults tend to elicit and apply their previous experience to learn.
- Readiness to learn: Adults tend to be ready to learn what they believe they need to know.
- Orientation to learning: Adults learn for immediate applications rather than for future uses. Their learning orientation is problem-centered, task-oriented, and life-focused.
- Internal motivation: Adults are more internally than externally motivated.
- Need to know: Adults need to know the value of learning and why they need to learn.

According to the premises of andragogy theory, Carpenter and Linton (2016) reported that the learners' opportunity to engage in direct learning, collaborate with others, and contribute to the learning of others motivate high levels of enthusiasm for their TPD experiences, where active learning, autonomy, and collaboration are key features to indicate effective PD for adult teachers. In addition, Tsuda et al. (2019) applied the framework of andragogy theory to create a series of intensive workshops supporting elementary school teachers' development of unique teaching perceptions regarding the societal shift toward depopulation. The findings indicated the importance of providing context-specific PD, where a problem-centered approach and self-directed processes are essential for effective TPD.

2.2. TPACK for teachers in STEM education

Recently, the TPACK framework has offered opportunities for providing teaching knowledge and guidance in professional teacher development programs. According to Mishra and Koehler's (2006) framework, it currently seems to be the single most significant factor in the success or failure of TPD in STEM education. Since STEM education is increasingly drawing attention from different parts of the world, there is currently an emerging call for STEM education to be synthesized with the TPACK framework for TPD, and the integration of STEM education and the TPACK framework is considered as a means to advance the state of affairs (Chai, Jong, & Yan, 2020). Moreover, technology is integral to TPACK and STEM education, and TPACK and STEM aim to develop students' twenty-first-century capacities (Chai, 2019). Scholars have emphasized the importance of providing the TPACK teaching model to let teachers understand and apply it in classrooms based on the knowledge addressed across technology, pedagogy, and content (Koehler & Mishra, 2005; Koehler & Mishra, 2008; Mishra & Koehler, 2006; Thompson & Mishra, 2007). Thus, interest and challenges have grown in incorporating the TPACK framework into teacher education to support the knowledge development of teaching in teachers (Janssen et al., 2019). Most of these studies have intended to design and develop technology-integration learning interventions to foster teachers' development of TPACK (Voogt et al., 2013). To be effective in promoting TPD in STEM education, these two fields of study—TPACK and STEM—need integration because teachers' competencies in technology integration and facilitating interdisciplinary STEM-based learning are both likely to enhance students' knowledge and skills that are crucial to their career prospects (Chai, Rahmawati, & Jong, 2020; Parker et al., 2015). To establish effective STEM classrooms, teachers must acquire specific knowledge related to TPACK to use educational technologies in particular STEM-specific learning situations (Milner-Bolotin, 2012; Pondee et al., 2021).

2.3. Personalized learning systems for TPACK PD

In the past decade, personalized learning systems have been used across contexts, particularly for supporting students' learning achievement, attitudes, and motivations, such as mathematics (Hwang, 2003; Panjaburee et al., 2010; Lin et al., 2011; Panjaburee et al., 2013; Wongwatkit et al., 2017), computer science courses (Chookaew et al., 2015; Latham et al., 2014; Wanichsan et al., 2021), and physical education (Huang et al., 2011). Nonetheless, the personalized learning systems concerning PD are mostly few studies. It might be because training teachers to know how to teach effectively with technology is undoubtedly a complex task, and it demands the application of various bodies of knowledge related to teaching (Angeli et al., 2014). Therefore, it is challenging to improve the quality of teaching and promote TPD, the personalized learning approach is a considerably process-based method of TPACK development (Harris, 2016), and scholars are increasingly considering personalized learning resources as an effective way to improve teaching competencies with technology for teachers (Angeli et al., 2014; Kajonmanee et al., 2020). Personalized learning systems, which consider individual differences and tailor specific learning paths and experiences to current situations and learning needs, have become increasingly crucial for TPD. To support professional teaching development in the digital era for teachers, researchers and developers have attempted to develop technological solutions, such as online-mediated personal learning platforms, to support TPACK development. Angeli et al. (2014) proposed an adaptive and interactive electronic learning system for fostering teachers' TPACK, called e-TPACK. The system has been designed and developed specifically to promote teachers' ongoing TPACK development by personalizing the content presented to them in the form of technology-enhanced instructional scenarios. Moreover, this online learning system and approach show a particular role of personalized learning analytics and are also helpful with the logistics of planning TPD to further develop teachers' TPACK.

Regarding the pedagogical application of personalized learning systems for STEM teachers' TPACK development, Kajonmanee et al. (2020) developed a TPACK-oriented personalized learning system to personally foster their essential teaching knowledge with particular content and digital technology. The system corresponds to three simple phases—the diagnostic, customization, and monitoring phases—as described in the next section. The results of the study indicated a promising effect of the TPD-embedded personalized learning system intervention on improving in-service teachers' TPACK in STEM teaching practice.

3. The Andragogical TPD-enhanced TPACK in teaching STEM (TPACK-STEM TPD)

3.1. An Andragogical TPD model for enhancing TPACK in the teaching of integrated STEM education

As is known worldwide, one way to improve instructional knowledge and skills among teachers is through TPD programs. The study presented in this paper focuses on a TPD instructional model emphasizing an andragogical approach for providing specialized training to adult teachers and enhancing positive influences on their TPACK of integrated STEM education. The main goal of the andragogical TPD model is that teachers, who are adults, learn to improve their TPACK in STEM education in relation to their needs, emphasizing how to implement the TPD using a personalized learning system in a supportive role. The proposed TPD model is expected to support all teacher professional learning design activities, and when integrated with a personalized learning system, the model promotes TPACK. Figure 1 shows the main components of the andragogical TPD.

The andragogical TPD model for the TPACK-STEM workshop is divided into four main phases (see Figure 2), with the following structure:

(1) The first phase (motivation phase) consists of two sessions. To prepare teachers to learn what they need to know, to meet adults' readiness-to-learn and need-to-know assumptions (Knowles et al., 2005), the first session is an introduction to instructional pain points in conventional science classes, findings from research-based learning innovation, and seamless STEM learning and its potential advantages. Then, the second session comprises self-paced learning on TPACK-STEM with a personalized learning system, the Khon Kaen University (KKU)-TPACK. This session will address self-concept and internal motivation assumptions for adult learning (Knowles et al., 2005), supporting learners in believing that they are responsible for their lives. With the KKU Smart TPACK system, the teachers can develop their latent self-paced learning skills and are motivated by intrinsic rewards using a sense of accomplishment to complete their TPACK.

(2) The second phase (conceptualization phase) comprises a seamless STEM learning authoring tool—a seamless mobile application called KKU-iNote—and a tour of its learning process through interaction in the learning-how-to-learn workshop. This phase emphasizes the adult's role of experience (Knowles et al., 2005), which is a way to encourage the adult to learn by drawing on previous teaching experiences. Participants carry out a complete seamless STEM learning process for a sample lesson using the detailed step-by-step practice for this phase. Participants then experience the student role and are expected to explore and conceptualize the learning process designed for integrated STEM education perspectives.

(3) The third phase (consolidation phase) comprises a presentation of a learning-how-to-teach workshop that addresses adults' orientation to learning assumptions (Knowles et al., 2005). In this phase, participants apply the same learning process, supported by KKU-iNote, to an integrated STEM learning lesson within the participants' teaching context located in the curriculum guidelines. Moreover, participants are expected to select one or several lessons to design integrated STEM lessons and implement them in the upcoming class after the workshop. This phase can support the assumption that adults learn for immediate applications rather than for future uses. In other words, adults prefer tasks that engage them to deal with authentic problems.
(4) The fourth phase (recommendation phase) consists of the two following sessions: (i) repeatable self-paced learning on TPACK-STEM with the KKU Smart TPACK system as a reviewing process of their TPACK progression, and (ii) a reaction to discuss the TPACK result and to draw the final main lessons learned from the workshop addressing TPACK of the lesson. Those sessions have prepared them for the readiness-to-learn and need-to-know assumptions, as done in the first phase.

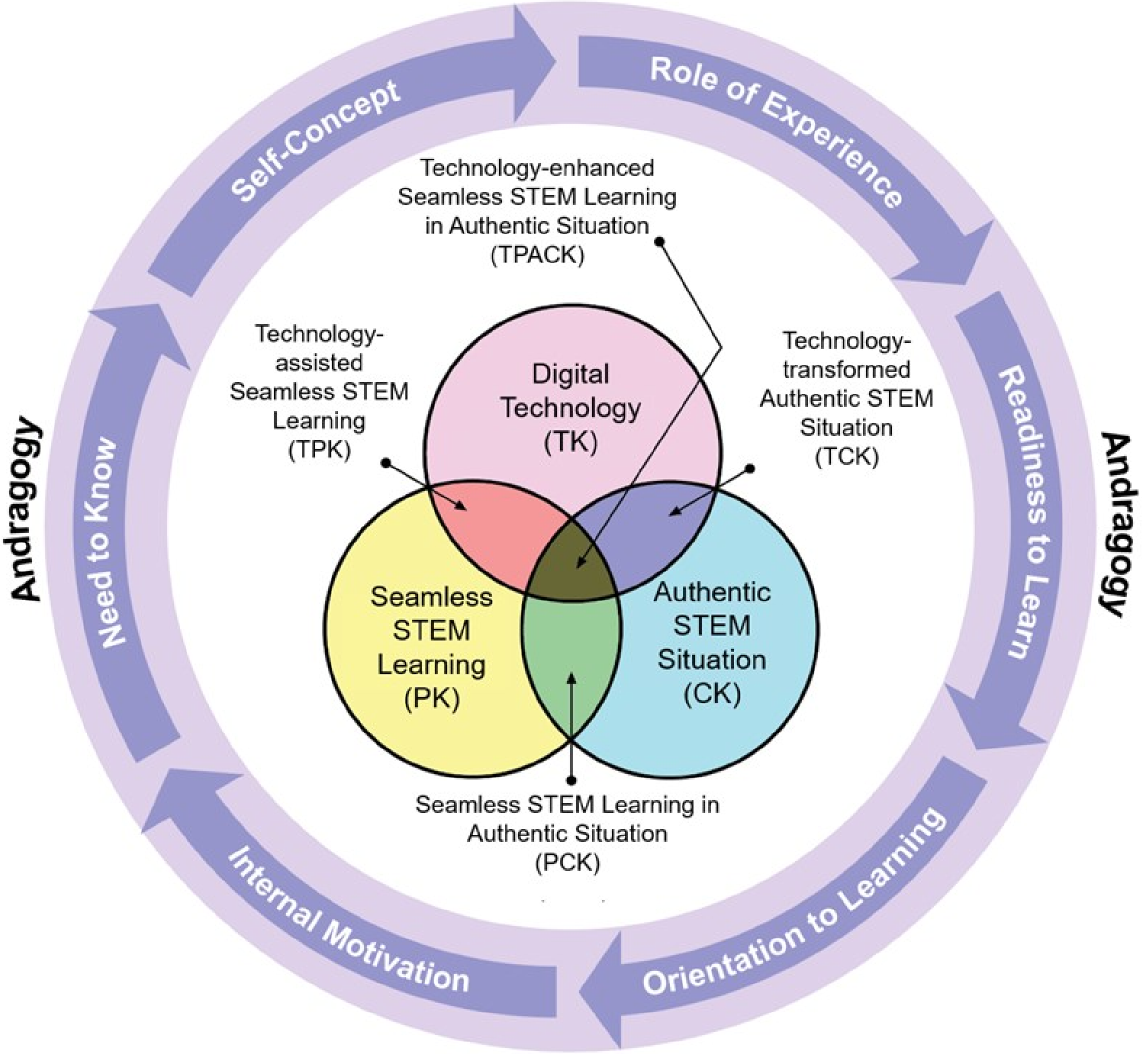


Figure 1. The framework of the andragogical teacher professional development model for enhancing in-service teachers' TPACK

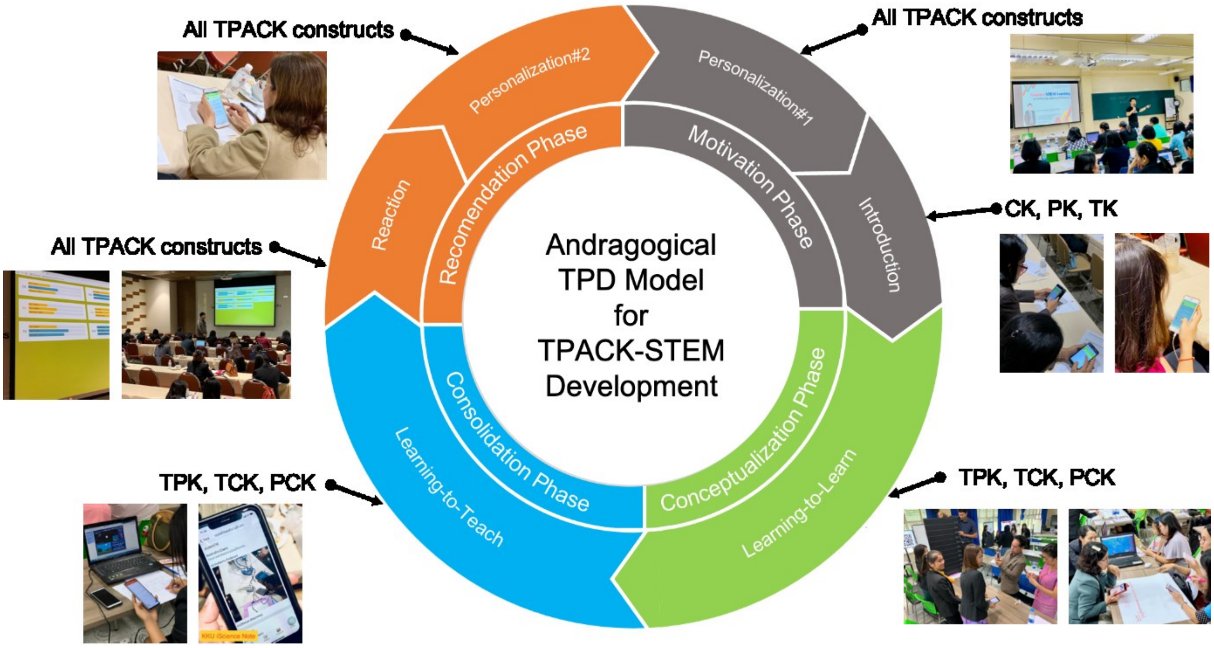


Figure 2. Design of the andragogical teacher professional development model for intervening in-service teachers' TPACK in STEM education

3.2. The TPACK-oriented personalized learning system

A personalized learning system is an adaptive learning environment that fits well with different learners' different learning goals and capabilities and is adapted for learners' specific needs; it is available on the learner's mobile device anywhere and anytime (Kajonmanee et al., 2020). Regarding the TPACK framework, the personalized learning system should have the ability to modify professional learning lessons using different TPACK parameters. In this study, a TPACK-oriented personalized learning system produced by KKU Smart Learning Academy (KKU-SLA), called the KKU Smart TPACK application, is a mobile-assisted professional learning system for teachers to personally cultivate their essential knowledge of teaching any particular content with the support of technology; they can accomplish this by focusing on their learning needs and capabilities in an anywhere and anytime learning manner. In this study, the TPACK-oriented personalized learning system was created as a professional learning environment for STEM teachers regarding their prior knowledge of teaching and learning style and differences in equipment and network qualities (Kajonmanee et al., 2020). However, empirical evidence has not supported an association between applications of learning styles and educational outcomes (Kirschner, 2017). Evidence-based practices have guided educators to create proper learning environments by balancing support and learning opportunities to encourage students' motivation (Brophy, 2013; Toste, Bloom, & Heath, 2014). Thus, this may be done by creating learning material that incorporates students' preferred learning styles and allowing them to choose instruction (Chookaew et al., 2015; Panjaburee & Srisawasdi, 2016; Wongwatkit et al., 2017; Thanyaphongphat, & Panjaburee, 2019). This empirical evidence has suggested that learning styles remain a challenge throughout education courses. Given this challenge, this study applied the Felder-Silverman learning style model (Felder & Silverman, 1988) to classify the participants into visual learners who remember best and prefer to learn from what they have perceived from visual information (e.g., pictures, diagrams, symbols), and verbal learners who get the full benefit out of textual representations. The system is a machine-centered adaptivity technology created with a set of predefined rules. At the same time, the adaptable personalized learning mechanisms are those functions in which teacher trainees can intervene and personalize the TPACK of STEM education learning lessons for themselves. For promoting teachers' ongoing advancement of TPACK in a self-paced and personalized manner, the system has been designed and developed explicitly corresponding to three simple main phases—the diagnostic, customization, and monitoring phases. The system's support to those three phases by a single platform using different combinations of tools and representations is another distinctive feature. This system process typically begins with the *diagnostic phase*, where the users (teacher trainees) have had their personal context analyzed by the system algorithm; that is, the personal learning style and all essential knowledge are clarified following the TPACK framework to apply the desired TPACK knowledge objects, define the learning pathways, and identifying particular kinds of learning materials for which the user needs to improve. This study's online learning material file types include video, pdf, ppt, and HTML. Figure 3 shows screenshots of two diagnostic templates available in the proposed system after the trainees completed a learning style questionnaire and TPACK test validated by educational experts.

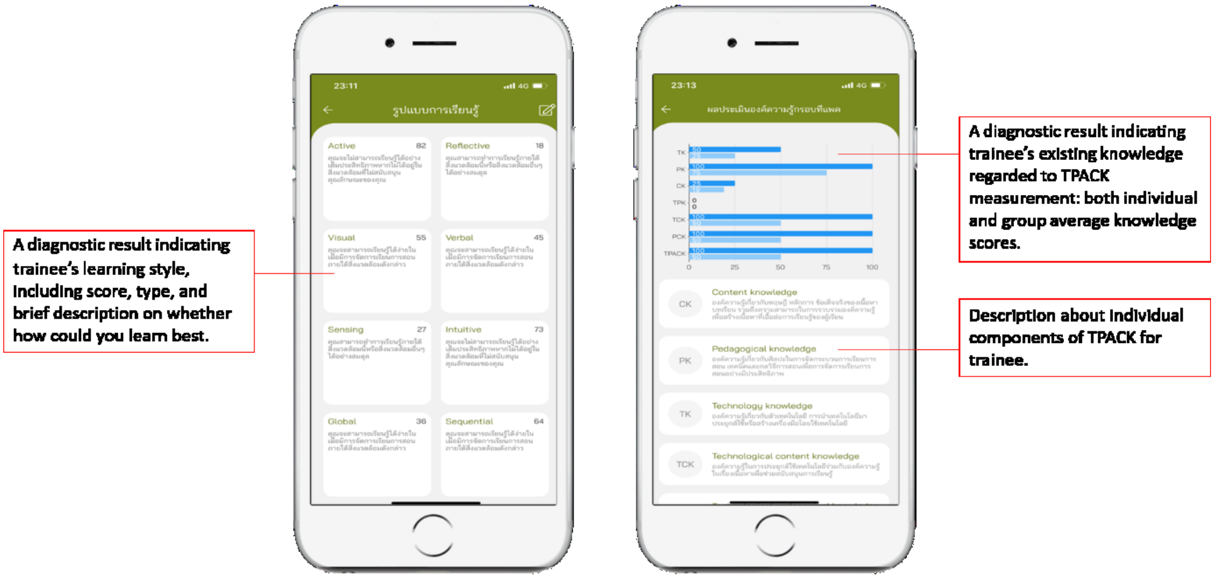


Figure 3. Screenshots of the TPACK-oriented personalized learning system showing the learning style (left) and TPACK (right) diagnostic templates

After diagnosing their learning style and prior teaching knowledge, teachers can start the *customization* phase—the process of selecting and sorting different kinds of learning material based on the user's learning style and the device's capabilities, which include the flow of learning contents and associated resources that users are expected to follow. In addition, this phase seeks to ensure personalized and uninterrupted mobile learning for users. Figure 4 shows screenshots of the two customization templates available in the proposed system.

Figure 4. Screenshots of the customization phase screens showing the learning materials regarding the TPACK diagnostics results (left) and an example of learning content following TPACK constructs (right)

The final step of the system is the *monitoring* phase. In this phase, a user can view the learning styles and the TPACK learning progress for individual topics via the mobile application. Moreover, the user can compare previous performance with the performance of other users in the project to reflect and visualize the current status of the TPACK. Figure 5 shows a screenshot of the monitoring template available in the proposed system.

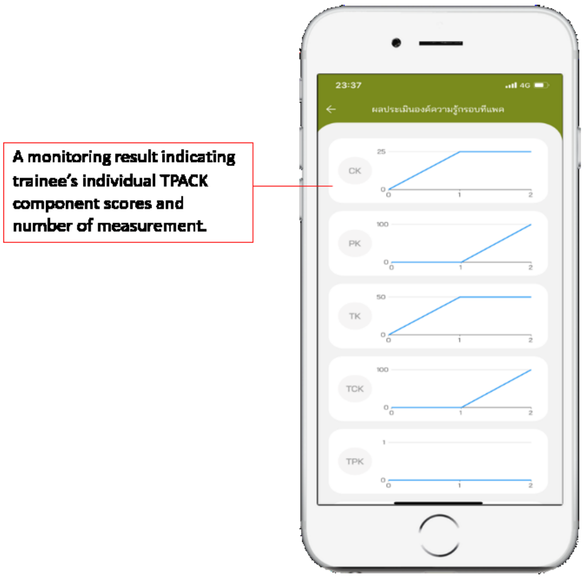


Figure 5. Screenshots of the monitoring phase screens showing an accumulation of individual TPACK results

4. The Study

The research question addressed by this study is as follows:
RQ: Does an andragogical TPD intervention program emphasizing TPACK in integrated STEM education support a personalized learning system that affects in-service science teachers' TPACK improvement?

A quantitative research setting framed the study. Because this research focuses on the in-service teacher training context, supported by the particular learning system and structured according to a specifically designed TPD training intervention program, which is approached in conditions that are as authentic as possible, mostly relying on statistically significant results or generalizations. The study involved in-service teachers from a large-scale educational improvement project called KKU-SLA, initiated by KKU in 2016 and funded by the university to promote social devotion to local communities. The KKU-SLA project targeted the quality improvement of compulsory education in science, mathematics, and the English language by implementing KKU in-house learning innovations in the three fundamental subjects. The KKU-SLA implemented by Smart Learning Innovation Research Center is an educational improvement project for secondary schools located northeastern region of Thailand. The ultimate aim of the project is to renovate middle school science, mathematics, and English education regarding the national basic education core curriculum of Thailand for gaining expected science literacy, mathematics literacy, and reading literacy in students aged 13–15 years. To achieve better learning outcomes in science, mathematics, and English, the project also focused on promoting the students' global and digital literacy and twenty-first-century skills needed in the specific subject matter. Currently, this project involves 218 secondary education schools from 19 provinces located in northeastern Thailand. In the project, there were approximately 1,617 in-service science, mathematics, and English language teachers and 1,671 middle school students from the participating schools who have joined the KKU-SLA project. In the context of smart science learning innovation for the project, the in-service science teachers voluntarily participated in a TPD intervention-training program focused on developing their TPACK in STEM education. In this study, the results of the first 2-year TPD intervention-training program are described and reported. According to reach a large sample size, it is less likely that outliers in the study can adversely influence the results the research question wants to achieve impartially.

5. Methods

5.1. Participants

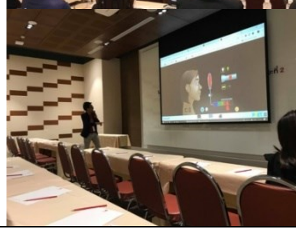
The study was carried out in the context of a series of TPD intervention-training sessions following the instructional model presented in Figure 5. The TPD program was instructed by four of the authors of this paper and involved 153 in-service teachers (119 women and 34 men) from 208 secondary education schools located in northeastern Thailand, who were teaching seventh-, eighth-, and ninth-grade science classes. Their teaching experience was ranked from 2 to 34 years, and they had about 10.5 years of teaching experience on average. Most held a bachelor's degree, and some held a master's degree in education. Moreover, they all had some experience of using digital technology for science classes before this study.

The present study used a pre-experimental research method to examine the effect of the TPD intervention program on teachers' TPACK in integrated STEM education. The research team adopted the methodology that measured changes in individual TPD intervention during the study period. Pre-intervention and post-intervention measures were used to assess the effect of the TPD interventions on cognitive outcomes for in-service teachers' TPACK of integrated STEM education.

5.2. The Andragogical TPD intervention training workshops

To foster the in-service teachers' TPACK in integrated STEM education through the TPD program, four intensive training interventions have been designed following the TPACK framework and with the support of the personalized learning system, KKU Smart TPACK. In the present study, all in-service teachers voluntarily attended four 2-day intensive training workshops from August 2018 to June 2019. Table 1 shows the series of TPACK-oriented TPD meetings for STEM in-service teachers considered in the present study.

Table 1. Description of the TPD intervention program fostering STEM in-service teachers' TPACK

Intervention program	Date	The topic of STEM learning situation	Digital technology focused	Illustrative picture
TPD #1	August 2018	Composite materials	Hands-on sensor laboratory	
TPD #2	November 2018	Friction	Mobile application (built-in sensor)	
TPD #3	January 2019	Photosynthesis	Computer simulation	
TPD #4	June 2019	Light and vision	Blended laboratory (hands-on sensor laboratory and computer simulation)	

5.3. Research instrument

To examine the significant effects of the TPD intervention program, the researchers assessed TPACK improvement by comparing its scores before and after receiving the individual intervention. To assess in-service teachers' TPACK in integrated STEM education, the researchers developed closed-ended multiple-choice questionnaires measuring the TPACK were developed and the instruments employed in this study (see an example in the appendix), which were then validated by the research panel, consisting of an expert in each field of science education, educational technology, and teacher education. The measurement instruments were embedded into the KKU Smart TPACK mobile application. For all four TPD interventions, there were 14

TPACK question items for TPD #3, and the questionnaire reliability was 0.75; moreover, there were 13 TPACK question items for TPD #1, #2, and #4, and the questionnaire reliabilities were 0.71, 0.74, and 0.71, respectively. The questionnaires consist of measured items of content knowledge CK (five to six items, depending on the number of main concepts), PK (two items), TK (two items), technological content knowledge (TCK; one item), Pedagogical content knowledge (PCK; one item), technological pedagogical knowledge (TPK; one item), and TPACK (1 item). The questionnaires required 45 minutes to complete. Examples of TPACK-measured question items are displayed in the appendix.

5.4. Data collection and analysis

To monitor the development of in-service science teachers' TPACK in integrated STEM education during this study, the teachers completed questionnaires before and after the TPD training interventions (pre-post comparison). To be more precise, there were four 2-day intensive workshops indicated as the TPD intervention program in this study, and there were four phases of training intervention. For Day #1, the face-to-face training started with a full self-paced professional learning session with the personalized learning system. In the session, teachers could learn independently and individually with the system in two steps—self-monitoring as a pre-test (45 minutes) and self-paced learning with TPACK materials (45 minutes). In the following session (90 minutes), the participants interacted with a situational introduction (90 minutes) targeting instructional pain points in authentic classroom contexts and findings and solutions from research-based learning innovation. Both sessions were distinguished as the motivation phase (180 minutes). They participated in an entire session of learning how to learn and roleplay as a learner, using the mobile-assisted STEM learning innovation created by the project session (180 minutes) in the conceptualization phase. They were encouraged to conceptualize the integrated STEM learning process with collaborative, hands-on practices in a learning community. For Day #2, the first session (180 minutes) started with a whole practical work of learning how to teach, with the support of mobile-assisted integrated STEM learning with an authentic learning task produced by the project, representing the consolidation phase. Here, the teachers were facilitated to consolidate the teaching practice of seamless STEM learning with mind-on instructional design and hands-on manipulation in both individual and collaborative modes. In the next session (90 minutes), all trainees monitored their TPACK results from the system and were encouraged to engage in a critical discussion about TPACK of the STEM learning lesson (45 minutes); they were then reflected particularly to conclude how to implement the STEM learning experience in school science class (45 minutes). In the final session (90 minutes), the participants repeated interacting individually in whole self-paced professional learning with the personalized learning system in two steps—self-monitoring as post-test (45 minutes) and self-paced learning with TPACK materials (45 minutes). To this end, trainees were allowed to conduct self-paced professional learning with the personalized learning system as much as they needed to address their TPACK comprehension. Figure 6 displays the structure of TPD intervention with the integration of the personalized learning system.

In addition, Figure 7 presents the data collection procedures along with the timing of TPDs 1, 2, 3, and 4. At the beginning of TPD#1, the participants were administered a questionnaire on TPACK in integrated STEM education. It was regarded as the pre-test data, meaning that the participants were elicited their TPACK in integrated STEM education training without the personalized learning systems before participating in the TPD interventions with the personalized learning system. Around 2 months later, at the end of TPD#2, the participants respond to the questionnaire again, as the 1^{st} mid-test data. Similarly, around one month later, at the end of TPD#3, the participants respond to the questionnaire again, as the 2^{nd} mid-test data. Post-test data were collected using the questionnaire again at the end of TPD#4, around 4 months after the 2^{nd} mid-test. That is to say, the 1^{st} mid-, 2^{nd} mid-, and post-test data reflected the participants' TPACK in integrated STEM education training with the personalized learning system of this study.

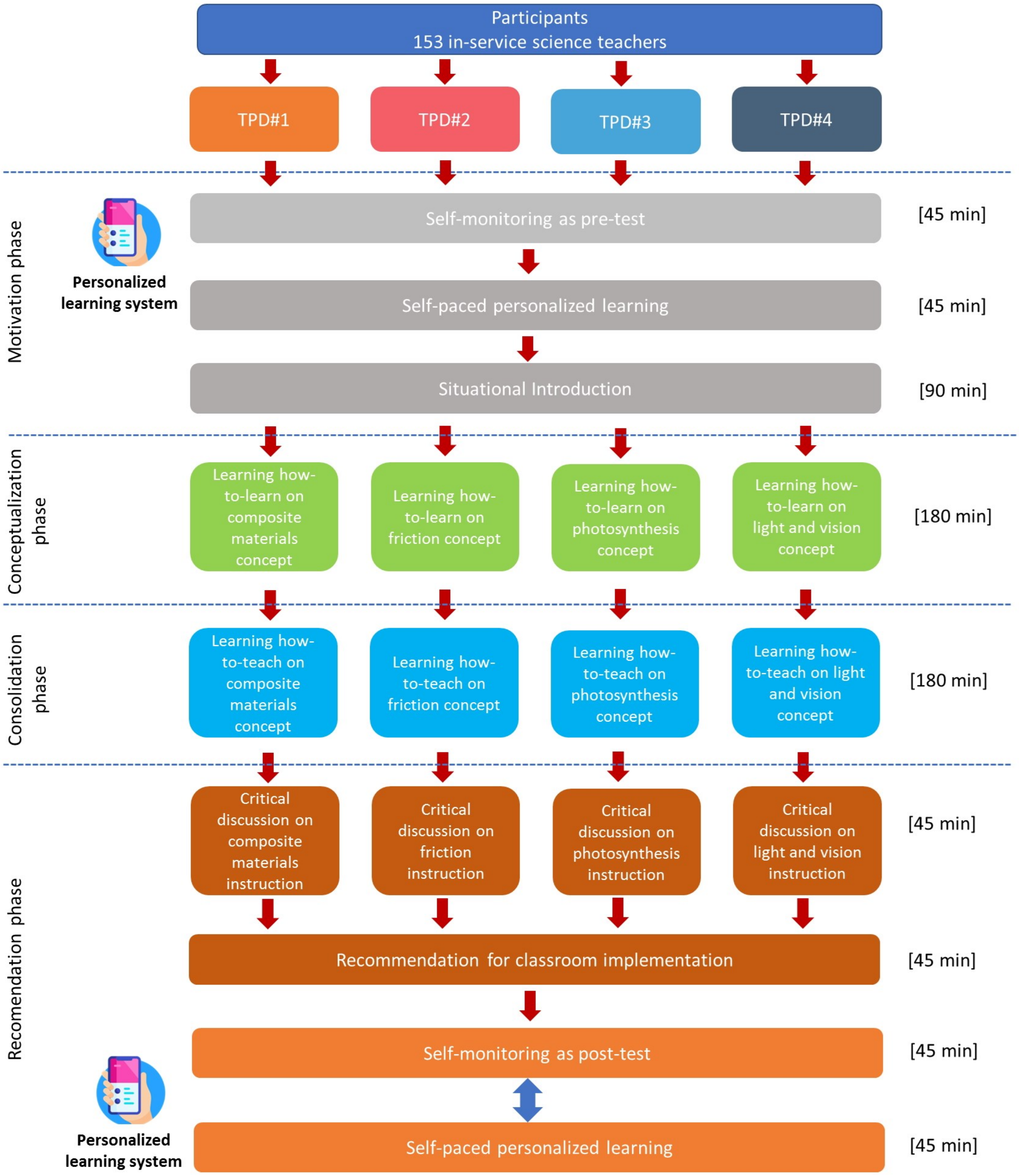


Figure 6. Structure of the TPD intervention with the support of the personalized learning system

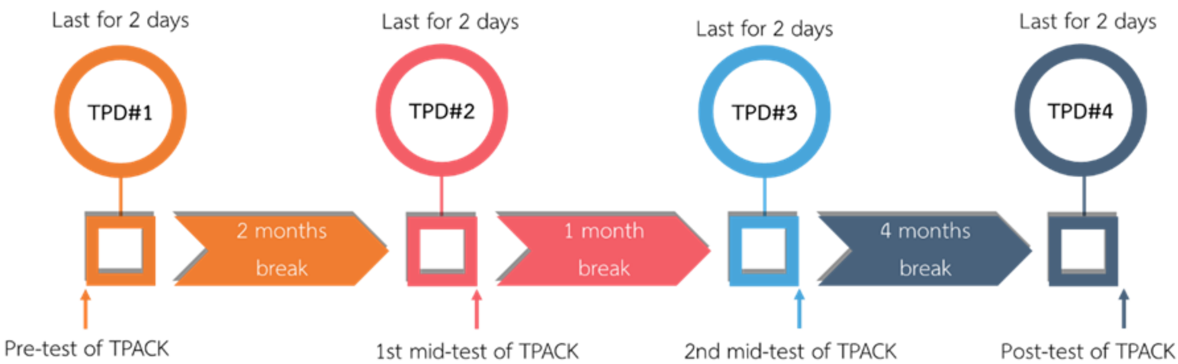


Figure 7. Procedure for data collection in TPDs 1, 2, 3, and 4

6. Results

6.1. TPACK pre- and post-test scores for each TPD program

After eliciting data from the participants during the training workshop, the researchers cleaned the data by eliminating faulty and incomplete data. For instance, some teachers who did not finish the tests during the workshop session were excluded from the data. This study used IBM SPSS Statistics 26 as the analytical tool. To compare the pre- and post-intervention mean scores and ensure that the test scores did not violate the assumption of normal distribution (based on the Shapiro–Wilk test), the paired *t*-test was used to compare the experimental conditions. A p-value $< .05$ was taken as significant. If the difference between the pre- and post-test scores was significant, the effect size and 95% confidence interval were calculated. For a descriptive overview, the researchers reported the mean scores and standard deviations of in-service teachers' scores regarding the TPACK components.

The quantitative data in this study were collected on two different occasions to address the research question—at the beginning and the end of the TPD intervention program. Following the purpose of this study, the hypothesis was that there would be no statistically significant difference between in-service teachers' total TPACK scores in STEM education (TPACK-STEM; pre- and post-intervention scores). The descriptive findings from this study of in-service teachers' mean (*M*) and standard deviation (*SD*) values on the seven scales of TPACK-STEM are reported in Table 2. The descriptive findings in Table 2 reveal an increase in all TPACK constructs and the total scores.

Table 2. Results of descriptive statistics for all components of TPACK for the four TPD intervention programs

TPACK Components	TPD #1 Composite Materials		TPD #2 Friction		TPD #3 Photosynthesis		TPD #4 Light and Vision	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)
TK	0.47 (0.50)	0.84 (0.60)	0.82 (0.82)	1.28 (0.72)	1.05 (0.7)	1.19 (0.62)	1.28 (0.63)	1.38 (0.61)
CK	2.36 (1.03)	3.09 (1.41)	2.46 (0.85)	2.79 (0.86)	4.65 (1.11)	4.76 (0.95)	3.38 (1.13)	4.03 (0.97)
PK	0.60 (0.62)	0.47 (0.50)	0.33 (0.53)	0.59 (0.64)	0.78 (0.58)	0.86 (0.59)	0.97 (0.74)	0.81 (0.59)
TCK	0.60 (0.50)	0.60 (0.50)	0.69 (0.47)	0.87 (0.34)	0.51 (0.51)	0.62 (0.49)	0.56 (0.50)	0.84 (0.37)
TPK	0.38 (0.49)	0.47 (0.50)	0.44 (0.50)	0.69 (0.47)	0.46 (0.51)	0.62 (0.49)	0.38 (0.49)	0.69 (0.47)
PCK	0.49 (0.51)	0.76 (0.43)	0.72 (0.46)	0.90 (0.31)	0.49 (0.51)	0.62 (0.49)	0.31 (0.47)	0.66 (0.48)
TPACK	0.49 (0.51)	0.58 (0.50)	0.28 (0.46)	0.44 (0.50)	0.46 (0.51)	0.54 (0.51)	0.47 (0.51)	0.59 (0.50)
Total score	5.38 (1.51)	6.80 (1.59)	5.74 (1.53)	7.56 (1.83)	8.41 (2.35)	9.22 (2.31)	7.34 (2.19)	9.00 (2.11)

To test the statistical hypothesis, the preliminary assumptions were checked, and no serious violations were detected. Then, a paired-samples *t*-test was conducted to evaluate the impact of each TPD intervention on in-service teachers' TPACK-STEM pre- and post-test scores. There was a large and statistically significant increase in their TPACK-STEM scores from pre- to post-intervention for each program as follows: TPD #1 Composite Materials Program, $t = 5.407$, $p < .001$, $\text{Eta}^2 = 0.399$); TPD #2 Friction Program, $t = 6.459$, $p < .001$, $\text{Eta}^2 = 0.523$; TPD #3 Photosynthesis Program, $t = 2.906$, $p < .01$, $\text{Eta}^2 = 0.190$; and TPD #4 Light and Vision Program, $t = 4.554$, $p < .001$, $\text{Eta}^2 = 0.401$, as shown in Table 2. The intervention significantly increased in-service teachers' TPACK in STEM education. Overall, the in-service teachers' TPACK in STEM education significantly improved after participating in the andragogical TPD intervention programs as measured by the increase in total TPACK scoring. Figure 8 displays the statistical analysis results for evaluating the effects of TPD interventions on TPACK development.

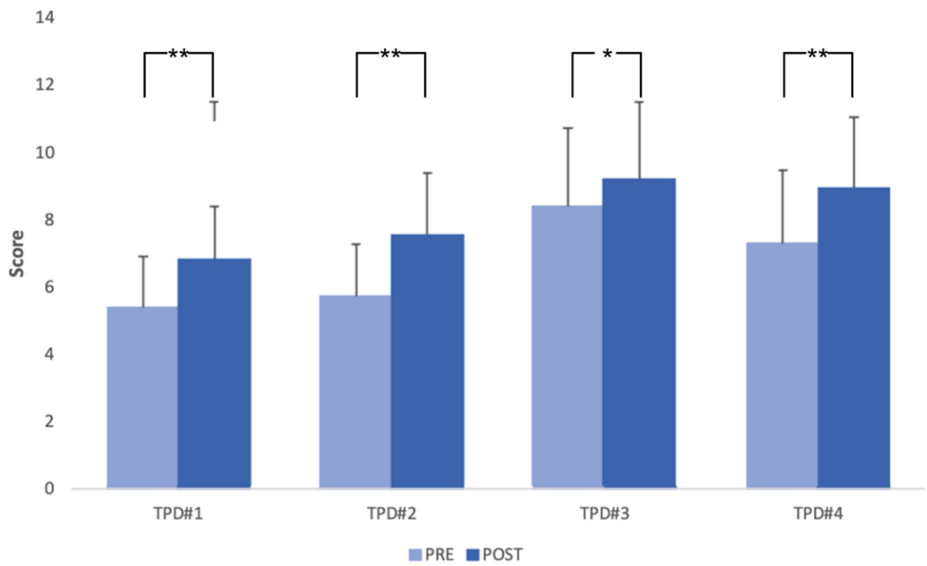


Figure 8. Results of TPACK in integrated STEM education development for each andragogical TPD intervention program (*Note.* $^{*}p \leq .01$; $^{**}p \leq .001$; Total $N = 153$)

6.2. TPACK scores across the four TPDs

The data collection procedures along with the timing of TPDs 1, 2, 3, and 4 were framed to further data analysis about the in-service teachers' improvement of TPACK in integrated STEM education during the TPD interventions with the support of the personalized intervention learning system. This study performed one-way repeated-measures ANOVA and pairwise comparisons on the TPDs of TPACK across the pre-, 1st mid-, 2nd mid-, and post-test results using IBM SPSS Statistics 26. This data analysis also measured the effect size, as conducted by partial eta squared, for each of the TPACK components. Those effect size values are 0.01, 0.06, and 0.14, representing small, medium, and large differences across the tests (Cohen, Manion, & Morrison, 2018).

The mean scores of the TPACK questionnaire, and their *F*-values and effect sizes, are presented in Table 3. It was found that the participants had significant improvements after training with a personalized learning system (i.e., TPDs 1, 2, 3, and 4) compared to that without a personalized learning system for TK, CK, TPK, PCK, and total score. It is noticed that significant improvement was found on CK after the participants completed TPD#3, and further significant improvements were found after TPD#4 for CK and total score. It is suggested that training with the personalized learning system itself could help the participants improved their CK and total score of the TPACK component. For PK, TCK, and TPACK, although there were trends of further improvements after training with a personalized learning system (i.e., TPDs 1, 2, 3, and 4) compared to that without personalized learning systems, the differences were not statistically significant. Regarding the partial eta squared values, the differences of improvement across the TPDs 1, 2, 3, and 4 with a personalized learning system suggest large effect sizes for all TPACK components compared to training without personalized learning systems.

Table 3. Results of mean score comparisons of TPACK components across pre-, 1st mid-, 2nd mid-, and post-test

TPACK Components (Total 100)	Pre-test Mean (*SD*)	1st mid-test Mean (*SD*)	2nd mid-test Mean (*SD*)	Post-test Mean (*SD*)	*F*-value	Effect size	Pairwise comparison
TK	18.75 (4.35)	60.94 (6.63)	57.81 (5.55)	68.75 (5.38)	15.525*	.334	Pre < 1st mid Pre < 2nd mid Pre < Post
CK	43.75 (3.86)	55.00 (2.98)	79.69 (2.87)	80.62 (3.42)	28.895*	.482	Pre < 2nd mid Pre < Post 1st mid < 2nd mid 1st mid < Post
PK	26.56 (5.49)	31.25 (5.38)	39.06 (4.88)	40.62 (5.23)	1.525	.047	
TCK	65.62 (8.53)	84.37 (6.52)	68.75 (8.32)	84.37 (6.52)	1.675	.181	

TPK	31.25 (8.32)	71.87 (8.07)	65.62 (8.53)	68.75 (8.32)	5.312*	.146	Pre < 1st mid Pre < 2nd mid Pre < Post
PCK	53.12 (8.96)	87.50 (5.94)	65.62 (8.53)	65.62 (8.53)	3.235*	.095	Pre < 1st mid
TPACK	53.12 (8.96)	40.62 (8.82)	56.25 (8.91)	59.37 (8.82)	.852	.027	
Total score	39.42 (2.09)	57.21 (2.56)	66.29 (2.84)	69.23 (2.87)	25.114*	.448	Pre < 1st mid Pre < 2nd mid Pre < Post 1st mid < Post

Note. $^{*}p < .05$.

7. Discussion

Researchers have reported that the regular implementation of TPD based on the concept of pedagogy or the pedagogical approach downgrades the impact of TPD to promote adult teachers' professional learning (Kubalíková & Kacian, 2016). In this study, the longitudinal experiment showed that the andragogical TPD intervention program integrating a personalized learning system could improve in-service teachers' TPACK in STEM education. These positive findings are consistent with numerous studies showing that andragogical principles and practices, collaborative, classroom-based, and research-informed approaches in TPD, positively influence teaching performances and competencies (Garet et al., 2001; Loxley et al., 2007). In addition, the findings can be further explained in accordance with Knowles's et al. (2005) theory of andragogy in terms of the aspects of "self-concept," "role of experience," "readiness to learn," "orientation to learning," "internal motivation," and "need to know."

Regarding "self-concept," "readiness to learn," "internal motivation," and "need to know," the TPACK-oriented personalized learning system played a vital role in the trainees' self-directed process on what they believe they need to know and encouraged them to autonomously accept responsibility for their professional learning as being in adult education. This result echoes the argument about the importance of self-directed, autonomous, and independent manners, underlining an assumption based on the andragogy (e.g., Carpenter & Linton, 2018; Chan, 2010; Tsuda et al., 2019). During the motivation phase, personalized learning technology-facilitated their self-paced learning of and self-monitoring of TPACK in STEM education and prepared them to learn actively and know precisely what they should focus on as active learning participation in the conceptualization and consolidation phases. This supportive training environment using autonomous technology is a perfect learning path for the facilitation of self-paced learning and allows an adult to follow the path that most appropriately reflects the need to learn (Fidishun, 2000). Moreover, the function of learning analytics could customize and personalize adults' learning such that they learn only essential contents that fit well with their professional learning status or problem, and this is consistent with Knowles et al. (2005), who mentioned that adults expect new knowledge to have an immediate impact on their lives and not to be used only in the future. In terms of facilitating STEM teachers' TPACK with the support of a personalized learning system, KKU Smart TPACK, in this study, it seemed that the KKU Smart TPACK plays a dominant role in promoting their TPACK improvement in STEM education. This result is consistent with Gynther (2016) and Ma, Xin, and Du (2018), who found that personalized learning for teachers positively influences their PD. Personalized learning systems represent a recent advancement in technology that has created new opportunities for learners to exercise more control over how and where their learning occurs, making learning a continuous process (Cook & Gregory, 2018). Moreover, Kajonmanee et al. (2020) reported that creating a personalized learning environment concerning in-service teachers' different learning styles and TPACK problems could significantly improve their professional learning outcomes in almost all knowledge domains in the TPACK framework.

As for the "role of experience" and "orientation to learning," the trainees were impressively immersed in the conceptualization and consolidation phases to gain adult active and collaborative learning experiences in the sessions of learning how to learn and learning how to teach related to technology-enhanced STEM education. Through interacting with both interactive hands-on and mind-on sessions, adult trainees had opportunities to learn new essential knowledge and skills for integrated STEM education by drawing from their previous inquiry-based teaching experiences. Moreover, what they learned from the previous motivation phase was targeted directly as problem-oriented and real-life-focused, and they were assigned a series of training tasks for immediate applications in the workshop rather than for future use. According to the results, our findings are consistent with previous studies that suggest active learning and collaboration are key components of effective

TPD for adults' professional learning (e.g., Carpenter & Linton, 2016; Garet et al., 2001; Ronfeldt et al., 2015). For the recommendation phase, the critical discussion and drawing of conclusions about TPACK of STEM learning lessons in school science class assisted in boosting the trainees' "internal motivation" and "self-concept" via the andragogical principle. As such, in terms of implementing an adult learning paradigm or andragogy as a theoretical platform into TPD intervention equipped with the personalized learning system in this study, the researchers think that the use of adult learning theory and practice in planning and providing principal professional learning is critically important to promote a better quality of TPD for TPACK in STEM education development.

8. Limitations and future directions

The results of this study highlighted the importance of incorporating andragogical principles and practices and integrating personalized learning systems into TPD for STEM education. However, this study has two major limitations. First, the participants were purposefully selected from regions and school districts involved in the KKU-SLA project in Thailand, and the number of participants was small. Therefore, the statistically significant results of TPACK improvement in this study may not be contextualized to other countries or generalized to all in-service STEM teachers working in Thai secondary school education. Second, the researchers focused on quantitative inquiries to capture the effect of andragogical TPD intervention programs equipped with TPACK-oriented personalized learning systems; they did not use any qualitative inquiry in the analysis. To better capture the effect on teachers' TPACK, both quantitative and qualitative inquiry methods should be synergized and emphasized in tandem. They should be utilized to examine the effect of the proposed TPD intervention and gainfully understand the transformation of professional knowledge related to TPACK. Based on these limitations, there remains a need for further investigation, and therefore, the researchers suggest some guidelines for future studies. First, future research should be implemented in other subjects to investigate the results that might be affected by these differences and comparative studies between trainees who have received and have not received the application of andragogy and/or the integration of personalized learning systems. Second, to increase meaningfulness, future research is needed to investigate the effect of andragogical TPD intervention and the role of personalized learning systems on TPACK development, using quantitative and qualitative inquiry practices that will advance the development of TPD intervention.

9. Conclusion

This study aimed to train in-service teachers, who are adult learners, to be equipped with TPACK of integrated STEM education through andragogy-oriented TPD intervention programs with the support of a personalized learning system. The results showed a promising effect of the TPD intervention on improving adult teachers' professional knowledge of pedagogically integrating digital technologies into their STEM teaching practice in specific STEM-related situations. The findings from this study directly contribute to the growing body of research on PD for adult teachers in several ways, as described below.

Overall, this andragogical TPD intervention program of TPACK-STEM was largely successful at improving in-service teachers' technological integration comprehension of digital technologies in their integrated STEM teaching. The findings of this study hold implications for policy, practice, and future research. Related to policy, the study findings suggest the practical implication that educational systems need to think through what types of PD are most important because the challenge is that adult learning through PD initiatives is better self-paced. Therefore, there could be a perceptual disconnection between the system and the individual teacher's perceived professional needs. To respond to this result, andragogy could be the suitable catalyst for the policy of TPD improvement. For practice, this study sheds light on several ideas. First, andragogy—or adult learning theory—should be used to upgrade the instruction of teachers and their learning process into the role of adult learners, not students. Second, integrating personalized learning systems as an essential part of teacher professional learning ecology could maximize the andragogical TPD implementation. Finally, PD in STEM education could be fully aligned to TPACK to improve STEM teachers' professional learning. This study also has many implications for future research related to TPD for STEM teachers' improvement. From the findings of this study, the TPD intervention should include a follow-up phase of professional learning involving STEM teachers from the training workshops engaged in improving their designs. Moreover, more TPACK-oriented TPD research for STEM teachers needs to be conducted regarding andragogy or adult learning theory to maximize their TPACK improvement by redesigning the professional learning activities for individual workshop sessions.

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Appendix

An example of close-ended question items for in-service STEM teachers' TPACK measurement.

1. CK: Which item below is not categorized as a fundamental type of materials in materials science? (TPD #4: Composite Materials)
a) Tin materials
b) Metal materials
c) Polymer materials
d) Ceramic materials

2. PK: Which approach below is not the way to manage science instruction that emphasizes a learner's investigating capability and scientific explanation based on evidence? (TPD #1: Photosynthesis)
a) Cooperative learning
b) Inquiry-based learning
c) Problem-based learning
d) Project-based learning

3. TK: Which item below is a technology tool that can support visual learning in science and promote performing multiple variables in science experimentation? (TPD #3: Light and Vision)
a) Computer simulation
b) Digital game
c) Augmented reality (AR)
d) Video

4. TCK: According to a specific characteristic of the photosynthesis concept, which technology could transform the concept into concrete content that is observable and adjustable? (TPD #1: Photosynthesis)
a) Computer animation
b) Digital game
c) Mobile sensor
d) Computer simulation

5. TPK: According to an inquiry learning process, students have to inquire about phenomena, interpret data, and acquire evidence. What is the technological attribute that fits the learning process? (TPD #2: Friction)
a) Illustrating moving images along with their descriptions
b) Displaying the results of variables' relationships and including mathematics features
c) Offering rewards and scores when an investigation is completed appropriately
d) Providing feedback immediately after completing an investigation

6. PCK: Which of the instructional strategy processes below could appropriately promote students' learning process regarding the friction concept in the science classroom? (TPD #2: Friction)
a) The teacher presents and narrates keywords and theoretical backgrounds of the phenomenon, then allows the students to perform a hands-on experiment using equipment that simulates the real situation of motion.
b) The teacher begins with a social issue and then lets the students learn through a problem-solving process related to the phenomenon.
c) The teacher begins with a problem/question that leads to exploration. Then, the students predict the result regarding the problem/question, after which they perform experiments and conduct discussions.
d) The teacher assigns a task for the students, then lets them design approaches to continue researching issues, topics, or situations of interest related to the phenomenon until appropriate answers are obtained through a methodical process.

7. TPACK: To enable students to gain a complete conceptual understanding of scientific phenomena, in terms of whether wavelengths of light affect reflection and refraction and what the reflection and refraction of light at different wavelengths will be like when moving through different mediums, how should the teaching work be performed? (TPD #3: Light and Vision)
a) Letting students predict what will happen from the red laser beam experiment by observing the real phenomenon using laser light through various mediums and recording the result as an explanation
b) Designing instruction for the students to develop workpieces or models based on the principle of reflection and refraction of white light through various media under the close guidance of a teacher
c) Determining the emerging issues related to reflection and refraction situations and letting them design solutions using the available tools and equipment
d) Assigning students a task to explore the topic through computer simulations that can change the wavelength of light and type of medium to lead to the conclusion about the phenomenon of reflection and refraction