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Design and Implementation of the Boundary Activity Based Learning (BABL) Principle in Science Inquiry: An Exploratory Study

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ABSTRACT: Guided by the Boundary Activity based Learning (BABL) principle, mobile technology-supported inquiry learning activities were implemented in a primary four science class in Hong Kong. An exploratory study was conducted to examine the effects of the BABL guided inquiry activities on students' learning performance and to explore how the key element, the boundary object, operated in different learning spaces. In the study, mixed research methods were used to evaluate students' conceptual understanding and their engagement in and attitudes toward BABL activities. The reciprocal interactions of students' cognition were qualitatively analyzed in terms of the forms and functions of boundary objects in the BABL environment. The results showed that students made significant improvements in conceptual understanding and were engaged in BABL activities. The study also revealed that the generation of abstract boundary objects, together with physical boundary objects, promoted students' learning and thinking as they shuttled between the classroom and the outside. This research contributes to informing educators about how to design and implement technology-supported teaching and learning through the use of boundary objects in crossing learning contexts.

Keywords: Boundary object, Boundary Activity based Learning (BABL) principle, Science inquiry, Crossing learning contexts

1. Introduction

Recently, a growing number of studies have investigated the relationship between learning in formal spaces and learning in informal spaces (Bonnette, Crowley, & Schunn, 2019). Many researchers have agreed that learning in informal spaces should not be viewed as an inferior form of learning but as a fundamental and valuable activity in its own right (Bell et al., 2009; Rogers, 2014). With the increasingly pervasive use of information and communications technology (ICT), wireless, mobile and ubiquitous technologies provide learners with various opportunities to link their experiences across multiple locations. Mobile learning has therefore been integrated into the teaching and learning of subjects (e.g., languages, math, science and music), from primary to university levels, both inside and outside of the classroom (Birch, 2017; Drigas & Pappas, 2015).

However, at a practical level, science learning in informal contexts receives less support than learning in formal contexts (Rogoff et al., 2016); consequently, collecting evidence of students' learning in informal contexts remains a challenge (Crompton, Burke, & Gregory, 2017). Much research in this area is descriptive and lacks a theoretical base (Anderson, Lucas, & Ginns, 2003). In the field of mobile learning, despite growing effort to create partnerships between schools and informal learning settings, the systematic documentation of such projects is limited (Shadiev et al., 2017). Moreover, few studies have been conducted concerning the structures required to support inquiry learning in informal contexts (Bai, 2019). As a result, there continue to be significant challenges in designing pedagogical learning scenarios in which learning takes place in both formal and informal spaces.

To address the abovementioned issues, many attempts have been done to improve learning synergy in formal and informal spaces through hybrid approaches (Lewin & Charania, 2018). Here we use learning in informal spaces which could accommodate the different patterns of learning activities, for example, informal learning (i.e., science museums, zoos and outdoor settings), out of classroom activities, and after-school programs (Tan, Jamaludin, & Hung, 2019). It fits the nature of the learning scenario in our study, where learning taking place in and out of the classroom but within the campus. Based on our year-long research efforts, we merge the merits of learning in formal and informal contexts via the notion of boundary objects, considering that few studies have explored the issue from the perspective of the generation of boundary objects. Boundary objects are generally defined as “entities that enhance the capacity of an idea, theory or practice to translate across culturally defined boundaries, for example, between communities of knowledge or practice” (Fox, 2011; Wenger, 1998) and have been applied in different fields (Fominykh et al., 2016). It is the first time we have used the notion of boundary objects to facilitate the connection of learning in different contexts through the design and generation of boundary objects in either abstract or physical patterns (Sun & Looi, 2018), in the field of mobile learning. In this study, we continued to consolidate the principle of boundary activity based learning (BABL) to guide the design and implementation of science inquiry learning supported by mobile technologies, with the objectives of promoting students’ learning, identifying the boundary objects that enable cohesive learning, both inside and outside of the classroom, and determining students’ cognitive transition trajectories in different learning spaces.

2. Theoretical framework

2.1. Facilitating the negotiation of science learning in formal and informal spaces

According to the hybrid view, formal learning and informal learning are not separate learning patterns: informal learning can take place in a formal learning context, and formal learning can take place in an informal context (Hofstein & Rosenfeld, 1996). Numerous studies have discussed the positive effects of connecting learning in formal and informal spaces and of creating structures to orchestrate learning activities in both contexts. As Falk and Balling (1982) noted, without orientation during outdoor learning activities, students are likely to focus on aspects of the environment that are irrelevant to learning. Gerber, Cavallo and Marek (2001) compared science learning in enriched and impoverished informal contexts. The study suggested that students improved their scientific reasoning skills the most when interacting with various informal learning contexts. Regarding the design of informal learning activities, researchers have offered valuable insights into the use of structures that can help to organize field trip activities better. For instance, Patrick, Mathews and Tunnicliffe (2013) suggested that field trips should incorporate problem-solving skills, be closely tied to the curriculum, focus on standards, and consider students’ needs. Sharples et al. (2014) proposed scripted learning methods of conducting outside-the-classroom inquiry activities.

Mobile learning offers new ways to extend education outside of the classroom and into the conversations and interactions of everyday life (Wang, Fang, & Miao, 2018). Mobile technologies possess a number of specific features that enable students to conduct authentic inquiry learning activities (Hwang & Tsai, 2011; Pu et al., 2016; Santos & Ali, 2012). Science projects created using mobile technology have demonstrated the efficacy of mobile learning as a means to improve students’ achievement, collaboration, motivation, and attitudes (Bano et al., 2018).

In brief, learning activities involving formal and informal contexts should be connected and well organized. Moreover, mobile technology is an effective tool for managing learning activities both inside and outside of the classroom. Regarding different learning settings, “sites of negotiation,” “boundaries,” and “border crossings” are useful and significant metaphors for understanding the mutual interaction of learning experiences and investigating the nature of learning (Aikenhead, 1996).

2.2. Foundations of the Boundary Activity-based Learning (BABL) principle

The BABL principle has been proposed and developed to guide the design of learning in multiple settings by responding to the negotiation and mutual interaction of cognition in crossing learning contexts. The BABL principle incorporates three components: (1) Boundary object: the boundary object is a prerequisite to designing boundary activities that ties together learning in and out of the classroom and monitors the learning process in informal spaces, in particular. The use of boundary objects allows learning activities in informal spaces to be integrated with learning activities from the standard curriculum. (2) Structure: the boundary activity is conducted in a pre-, during, and post-activity pattern to guarantee the continuum and stability of cognition or skills developed across the learning contexts. (3) Learning objectives: the learning objectives of the boundary activity should be defined based on the curriculum standard and the characteristics of the contextual variables in practice (see Sun & Looi, 2018; Sun & Looi, 2019). The underpinnings of the BABL principle are explained as follows.

2.2.1. Concept of the boundary object

Boundary objects are conceived as linkages that are plastic enough to adapt to local needs and the differing constraints of the various parties using them, yet robust enough to maintain a common identity across different sites. They can be any element that has the capacity to be understood by actors in more than one setting (Fox, 2011; Star & Griesemer, 1989). The creation and management of boundary objects are key processes in developing and maintaining coherence across intersecting social worlds (Star & Griesemer, 1989). Under this perspective, in examining issues of cross-cultural science education, Aikenhead (2001) proposed that learning about science is a cross-cultural event for most of students. Dealing with cognitive conflicts that arise from cultural clashes enables students to make sense of their learning, both inside and outside of the classroom.

Cognitive transition is considered smooth when its movement from one setting to another is harmonious and uncomplicated, with a merging of common sociocultural characteristics (Phelan, Davidson, & Cao, 1991). The smoother the cognitive transition between different learning contexts, the better the academic achievement and attitudes toward learning that students may attain (Costa, 1995). Based on this perspective, Akkerman and Bakker (2011) defined boundary objects as artifacts that articulate meaning, address multiple perspectives, and fulfil a bridging function. A boundary object can be either abstract or concrete (Cartwright & Mendell, 1984). It is a type of connecting link between communities of practice that can take the form of an artifact, document, term, concept, or other forms of ratification, around which communities of practice organize their interconnections (Wenger, 1998). Boundary objects in mobile learning scenarios are usually represented by concept maps, drawings, photos, videos, notes, or other relevant log data related to learning. However, they may take different forms as abstract patterns (Sun & Looi, 2018).

With respect to the BABL principle, boundary objects are the key elements in boundary activities. The investigation of students' cognitive transitions in different learning contexts mainly focuses on exploring the forms and functions of boundary objects in building students' knowledge and on exposing the mechanisms of boundary interaction.

2.2.2. The forms and functions of boundary objects

Various attempts have been made to explore the use of "boundary objects" in border-crossing contexts. Looi et al. (2009) investigated the occurrence of cognitive processes in a seamless learning context. One of the most significant processes in the operation of a cognitive system is the coordination between internal and external structures. Otero et al. (2011) proposed the use of external representations for understanding interconnections between individual cognitive processes, group processes, and the contributions that specific artifacts bring to the overall process. Wong, Chen, & Jan (2012) further emphasized the role of mediating artifacts in facilitating learners' effective transitions between scenarios in seamless learning. Several classes of mediating artifacts were identified: (1) subject matter artifacts, (2) physical artifacts, (3) socio-cognitive/non-physical artifacts, and (4) outcome artifacts. To foster community crossing interactions for sustained knowledge building, Zhang et al. (2018) proposed synthetic boundary objects in the form of idea thread syntheses, which indicated triggering students' deep thinking and reflection in different communities.

The above-mentioned studies share the view that establishing linkages between different learning contexts through boundary objects can improve cognitive interactions between individuals and collaborative groups. However, the functions of boundary objects vary according to the topic, subject, pedagogy, learning context, and technology. This observation of functional variability gives rise to further questions that motivated this study.

3. Research purposes and questions

We conducted an exploratory study with the following objectives: to investigate the impact of science inquiry guided by the BABL principle on students' learning performance, engagement, perceptions, and attitudes toward boundary activities inside and outside of the classroom, and to obtain insights into the forms and functions of boundary objects when students were engaged in reciprocal interactions of cognition in and out of the classroom. The following research questions were answered:

(1) To what extent did the students improve their conceptual understanding of science in the BABL science inquiry activities?

(2) How were the students engaged in reciprocal interactions of cognition in and out of the classroom?

(3) What were students' perceptions of and attitudes toward the boundary activities in the BABL science inquiry?

4. Methods

4.1. Participants and research contexts

As this investigation was the first pilot study to integrate the BABL principle into the Hong Kong Primary General Studies curriculum, small sample size was preferred (Johanson & Brooks, 2010). Consequently, a Grade 4 class of 37 students (10–11 years old) from a local primary school and their science teacher participated in this project, after giving their consent for data collection. The school's history of implementing e-learning and STEM education guaranteed that the participants could effectively adapt the proposed tools. Prior to the actual implementation of the BABL lessons, the teacher attended a professional development session facilitated by the first author. The power analysis showed that the sample size of 37 could achieve a power of .98, with an effect size of .95.

4.2. Lesson design for BABL guided science inquiry

In this project, a BABL lesson plan and corresponding teacher guide were developed on the topic of Energy, as prescribed by the Hong Kong Primary General Studies guidelines. As Table 1 shows, the BABL guided inquiry activities were scripted into four phases: (1) Context and Questions, (2) Investigation, (3) Sharing and Discussion, and (4) Conclusion (Bybee, 2009). To facilitate the smooth transition of cognition processes in and out of the classroom, structures were set in place for boundary activities in the form of pre-, during, and post-patterns according to a change in venue (Eshach, 2007). Besides, the learning objectives, as the integral components of the BABL principle, were articulated cohesively in the lesson plan to link learning in informal and formal spaces. Teacher and student interactions were mediated by boundary objects generated with the use of technological tools: nQuire-it (with Sense-it) and Schoology.

The nQuire-it learning system was developed by The Open University, UK. It enables teachers to create science projects and students to upload and comment on science data collected by mobile sensor toolkits using Sense-it. Figure 1 shows the basic interface of the Sense-it app and a generated real-time data chart. Schoology is a learning management system that enables teachers to upload teaching materials and design inquiry activities step by step, while monitor students' progress and learning processes in and out of the classroom. Figure 2 shows the design of inquiry learning activities supported by the BABL principle in Schoology. Android tablet mobile devices were provided to support Sense-it activities planned for outside of the classroom. In practice, two or three students shared one tablet.

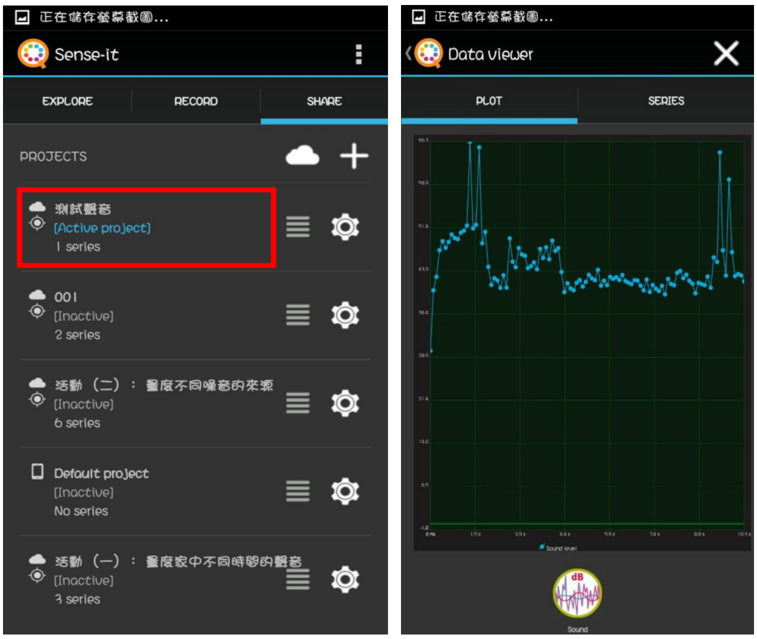


Figure 1. Sense-it app and data chart

Table 1. Lesson plan for BABL-guided inquiry

BABL inquiry topic: Energy – Solar power				
Inquiry phase	Teacher activity	Student activity	Resources	Venue
1. Context and Questions	• Introduction: solar energy and its application in daily life.	• Recognize solar energy.	Textbooks, websites, books and newspapers	Classroom (Pre-boundary activities)
2. Investigation	• Provide instruction on the inquiry task: exploring the intensity of sunlight. • Guide students to join the project in the nQuire-it platform. • Provide instructions on how to explore sunlight in the classroom. • Provide instructions on how to explore sunlight outside of the classroom.	• Work in groups: thinking about and discussing the task. • Join the project "Investigating sunlight" in nQuire-it. • Collect sunlight data in the classroom and upload the data to nQuire-it. • Discuss where, when and how to investigate sunlight outside of the classroom.	Sense-it: light sensor; Schoology Sense-it: light sensor	
	• Guide students to explore the strength of sunlight in groups outside of the classroom. • Preview/check students' work in nQuire-it and take note of some special cases, mistakes or deficiencies for real-time adjustment and support.	• Explore sunlight outside of the classroom. • Upload the sunlight data to nQuire-it.	Sense-it: light sensor; nQuire-it	Outside of the classroom: school garden, lobby, sports ground, balcony (During boundary activities)
3. Sharing & Discussion	• Guide students to review other groups' work and comment on it; highlight the work that receives the most positive/negative feedback. • Guide students to share reflections in Schoology.	• Review other groups' work. • Indicate "like" or "dislike" of others' work with comments. • Reflect on the experience and process of nQuire-it inquiry.	nQuire-it Schoology	Classroom (Post-boundary activities)
4. Conclusion	• Guide students to conclude the lesson and share their reflections.	• Draw conclusions and discuss the application of solar energy in daily life.	Schoology	

Figure 2. BABL-guided inquiry learning activities on Schoolog

4.3. Data collection and analysis

This study used one group pre-test–post-test quasi-experimental research design. Multiple types of data were collected to enable methodological triangulation (Fredricks et al., 2018). Figure 3 shows the data collection process.

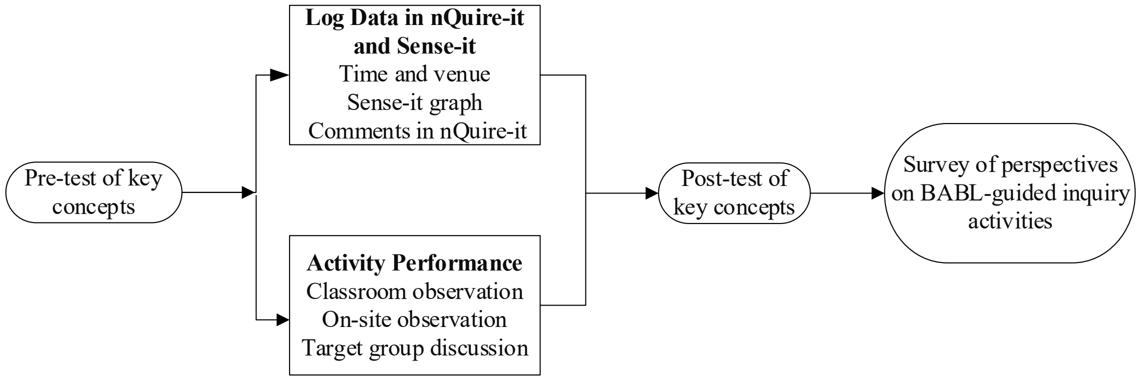


Figure 3. Data collection process

(1) Pre-and post-tests: To investigate students' conceptual understanding of key concepts, pre- and post-tests with identical test items were adopted. The test measured the understanding of the intensity of sunlight and the sources of sunlight in daily life. Altogether, five multiple-choice questions (two points each) and one open-ended question (five points) were included, for a total score of 15 points (20 mins). Q1 was concerned with the application of solar power in daily life. Q2, Q3, and Q5 were concerned with the times and locations of the strongest solar power. Q4 was concerned with ways to prevent overexposure to intense sunlight. Q6 was an open-ended question that required students to list the daily applications of solar power (two points) and to explain the mechanisms involved (three points). All of these items were drawn from standard academic tests and textbooks. An example question is

Q2. When is the sunlight the strongest?

A. Early Morning B. Noon C. Dusk D. Evening F. Other

The items' levels of difficulty and cognitive domains were based on the six levels of the revised Bloom's Taxonomy (Anderson et al., 2001). They were identified as Level 2 – Comprehending/Understanding: item 1; Level 3 – Applying: items 2 and 5; Level 4 – Analyzing: items 3 and 4; and Level 6 – Evaluating: item 6. To ensure the reliability and validity of the test items, two researchers and two experienced teachers reviewed and discussed whether the questions were appropriate. Each teacher had more than six years of science teaching experience. The Cronbach alpha's score was .845, indicating good internal consistency of the test. For the analysis of the pre-and post-test scores, a descriptive statistic was applied to summarize the overall results and to assess the normality of the tests. A paired sample t-test and an item analysis were used to compare the differences between the pre- and post-test results and between the students' responses to the questions.

(2) Students' log data and comments: To uncover the students' reciprocal interactions of cognition in and out of the classroom, log data (including time and date, location, data charts and comments) in nQuire-it was analyzed and served as the key body of evidence for profiling the boundary interactions experienced by students in the two learning contexts (Patten, Arnedillo Sánchez, & Tangney, 2006). Figure 4 shows the location and date of data collection presented in the nQuire-it system.

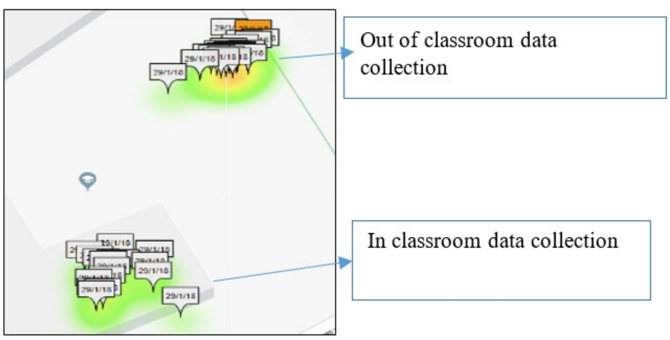
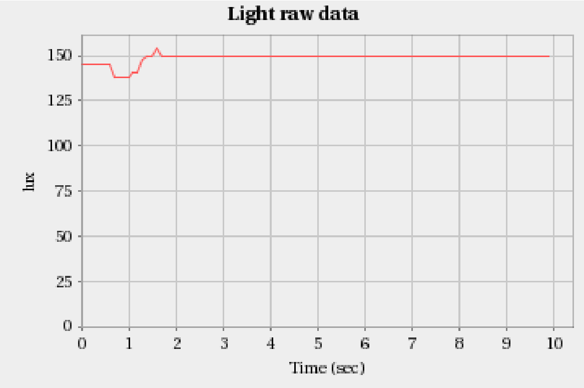
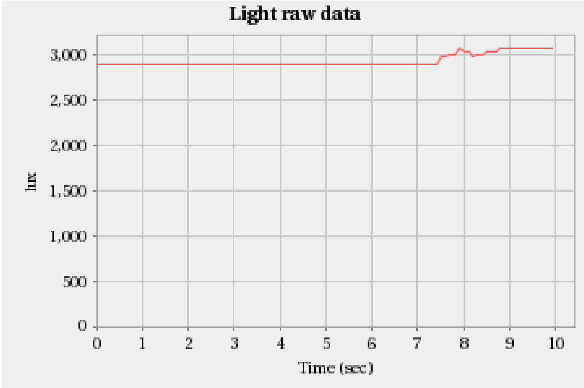


Figure 4. Students' data collection inside and outside of the classroom, using Sense-it

Moreover, as an important artifact of the physical boundary objects, the data charts in and out of the classroom were calculated in terms of the totals and means generated by each group. For example, two data charts on raw light, collected by the light sensors in the classroom and in the school garden, are shown in Figures 5 (a) and (b).



(a)



(b)

Figure 5. (a) Light data collected in the classroom, (b) Light data collected in the school garden

The students' comments on their classmates' data charts were retrieved in the system and reviewed qualitatively as valuable evidence for assessing their reciprocal interactions of cognition in terms of thinking and understanding where abstract boundary objects in the representation of new concepts or understanding might be generated (Stahl, 2000). The coding and analysis were conducted independently by the first author and one researcher, and the inter-rater reliability coefficients were calculated as .85 for the data charts analysis and .88 for the comments analysis. Both coefficients indicated good inter-rater reliability.

(3) Observations and discourses: Three groups with two students for each were selected as targets from 17 groups. To ensure the same conditions of the groups (i.e., gender, collaboration skills, performance in normal classes), group characteristics were further discussed and identified by the teachers. Observation of target groups is a principal means of collecting qualitative data, as it enables researchers to observe a certain amount of interaction and achieve in-depth understanding of a topic in a limited time (Morgan, 1997). The researchers focused their observations of the three target groups on the groups' levels of engagement and reciprocal interactions of cognition during boundary activities.

Specifically, students' group discussions were videotaped, annotated, and transcribed in qualitative terms (Derry et al., 2010). Discussion is a common language for negotiating meaning across the boundaries of two learning contexts (Fominykh, et al., 2016). Two dimensions of coding methods were used (Lee & Irving, 2018) that involved discussions of boundary objects in three stages of boundary activities: (1) boundary object forms, e.g., abstract boundary objects and physical boundary objects, and (2) boundary object functions, in terms of cognitive transition. The inter-rater coding consistency of the qualitative data reached 93%, on average, which indicated good reliability.

(4) Survey of students' perceptions of and attitudes toward BABL guided inquiry activities. A survey was administered to investigate the students' perceptions of BABL guided inquiry activities, especially regarding the connections between formal learning and learning in informal spaces. The survey consisted of 12 questions on a 5-point Likert scale. The survey's dimensions were based on the three dimensions used in the Science Outdoor Learning Environment Inventory (Orion et al., 1997) that focus on (1) Environmental interaction: Interaction in outside activities (Q1, Q7); (2) Integration: The connection between in-class and out-of-class learning (Q2, Q3, Q4, Q5, Q6); and (3) Preparation and organization: Organization (Q8); and one dimension of Learning involvement (Brom et al., 2017): Motivation for outside activities (Q9, Q10, Q11, Q12). An example item of the 5-point Likert scale is *Q1. I discuss our tasks with my group members during outdoor inquiry activities.* For each dimension, the researchers designed the question items to fit the nature of the study and the topic. After discussions with two researchers and one experienced teacher, the survey was moderately revised, and the Cronbach alpha score was .860, indicating good internal consistency (Taber, 2018). A descriptive data analysis of the survey results was conducted to expose differences in the proportion of students' agreement with individual items.

5. Results

5.1. Changes in students' conceptual understanding

We first checked the normality distribution of the test scores in the pre- and post-tests using a q-q plot. The results showed that both test scores followed the normal distribution. The descriptive statistics of the pre- and post-test scores revealed a general improvement in the students' conceptual understanding after participating in the BABL guided inquiry activities. The results of a paired sample *t*-test indicated that such improvement was not only observable but significant (Mpre = 9.89, SDpre = 3.30; Mpost = 10.88, SDpost = 2.36; $t(36)$ =-2.939, p = 0.01) (Table 2).

Table 2. Results of the paired sample *t*-test

Test	*n*	*M*	*SD*	*t*	*p*
Pre-test	37	9.89	3.30	-2.939	.006*
Post-test	37	10.88	2.36		

Note. $^*p < .05$.

The results also showed a substantial increase in the percentage of correct answers. There was a 15% increase in correct answers to Q1 (Level 2) and 20% and 24% increases in correct answers to Q2 and Q5 (Level 3), respectively. For Q3 and Q4 (Level 4), the numbers of correct answers rose by 31% and 15%, respectively. In the open-ended question, the percentage of correct responses rose from 56% in the pre-test to 85% in the post-test. These results suggest that most of the students achieved a higher level of cognition concerning the key concepts involved in this topic.

5.2. Mechanisms of students' reciprocal interactions of cognition in and out of the classroom

5.2.1. Student engagement: Analysis of log data in nQuire-it and Sense-it and target groups' performance

The analysis of the data charts generated in the nQuire-it system suggested that nearly 90% of the students used the light sensor to collect data, both inside and outside of the classroom. This finding suggested that most students were engaged in the BABL activities. In the Investigation phase, all 17 groups collected light intensity data and uploaded the data charts to nQuire-it. A total of 89% of students successfully collected data in a collaborative manner, and 62.5% generated data charts for both inside and outside of the classroom. A descriptive data analysis showed that the average number of data charts generated by each group was 2.94, with the totals for the groups varying between one and nine (47 in total). In addition, the numbers of in-classroom data charts (i.e., 23) and out-of-classroom data charts (i.e., 24) were almost equal, indicating that the students performed equally well both in-classroom and out-of-classroom, without preference for the activity venue.

When the students returned to the classroom during the Sharing and Discussion phase, they reviewed their classmates' data charts through nQuire-it and indicated whether they "liked" or "disliked" them. On average, each chart received four "likes" and two "dislikes." The fact that each chart was reviewed by six students, on average, implied the students' active participation in peer review and assessment. More importantly, most students not only gave a general, summative assessment (such as a "like" or "dislike") but also provided formative feedback, which either justified their comments or represented their own interpretations of the data charts. Altogether, 30 students commented on their classmates' work, providing 25 positive comments and five negative ones. One student was especially active in commenting on his classmates' work. He noted that a sharply curved data chart meant "it [sunlight] changes a lot" and that the charts showed him "it's too dark" in the classroom, but "it [sunlight] is very bright" in the school garden. Such observations showed that peer comments on physical boundary objects could engage students in conceptual understanding and reasoning. Importantly, such comparison of the charts in and out of classroom might trigger the generation of abstract boundary objects.

During classroom activities, despite performing differently, most students were highly engaged. For some students, this activity was stimulating and motivating, as it was different from traditional science activities (Figure 6). As the activity unfolded, the three target groups were found to be interacting in effective ways. In Group 1, one student asked when the group could go outside for data collection, as she considered the classroom was not bright enough. This question implied that the student was motivated and engaged in her own process of reasoning. She wished to investigate more about the data outside. This self-reflection was probably the venue of generating abstract boundary objects (Pimmer, 2016). Group 2 attempted to block the light using textbooks during their data collection, as they wanted "to see whether the value (of light intensity) would be smaller." They tested it and were quite happy that their "guess was correct." In Group 3, the students were excited to discuss and share their data chart with the other groups (as illustrated in Figure 7). We transcribed and excerpted their discussion as follows:

Sa: What does your chart look like? Let me have a look.
Sb: Wait a moment; we need a few seconds. Okay, here you are.
Sa: The light looks very stable here, but mine is unstable. Mine is a little curved. Yours is flat.
Sc: I think you may be moving the tablet when you are using the app.
Sd: Yes, I agree with you. Please don't move next time.
Sa: I will do the test again. Let's see whose chart is more stable.

The above discourse emerged spontaneously, rather than being encouraged by the teacher or researchers. When students were involved in group comparison and reasoning, their motivation and engagement were triggered naturally.

Figure 6. Students engaged in the nQuire-it activity

Figure 7. Two groups discussing their findings

5.2.2. Reciprocal interactions of students' cognition in BABL guided inquiry activities

Further efforts were made to describe students' learning trajectories throughout the holistic learning experience, with a focus on capturing the forms and functions of boundary activities, especially for invisible and unexpected boundary objects in the form of abstract boundary objects during reciprocal interactions of students' cognition in crossing borders. According to data analysis of the three target groups' discussions, although the students were given the same instructions at the pre-, during, and post-boundary stages, they reacted in quite different ways. Table 3 provides a summary of students' foci of discussion related to the forms and functions of boundary objects at different stages of boundary activities. The first column indicates the forms and functions of boundary objects identified during the group discussions. The checkmarks represent the presence of boundary objectives.

It was found that most discussions concentrated on the functions of boundary objects that linked the application and transformation of the related knowledge, especially for during and post-boundary activities. These discussions were likely to generate abstract boundary objects we did not anticipate in the lesson design. Students who discussed the use of nQuire-it and Sense-it in their pre-boundary activity went directly to play with the light sensors in the Sense-it activity, as they were already familiar with the tools. They were interested in generating and observing the line charts (physical boundary objects) that described the intensity of light, and they became very curious (triggered by abstract boundary objects) when the shapes of the charts changed as they moved around. While investigating the light intensity in the classroom, they waved their pads or used their textbooks to block the light (control variables). They also carefully examined whether the actual charts fit their expectations (hypothesis-verification). With the classroom data in hand, some students were eager to collect data outside the classroom for comparison (comparison).

Table 3. Students' discussions inside and outside of the classroom

Discussion	Pre-boundary activities	During boundary activities	Post-boundary activities
Use of tools (the medium of boundary objects)	√	-	-
Observation of data charts (function of boundary objectives)	√	√	√
Shape of charts (function of boundary objects)	√	√	√
Comparison of charts (function of boundary objects)	-	√	√
Expectation of more comparisons (function of boundary objects)	-	√	√

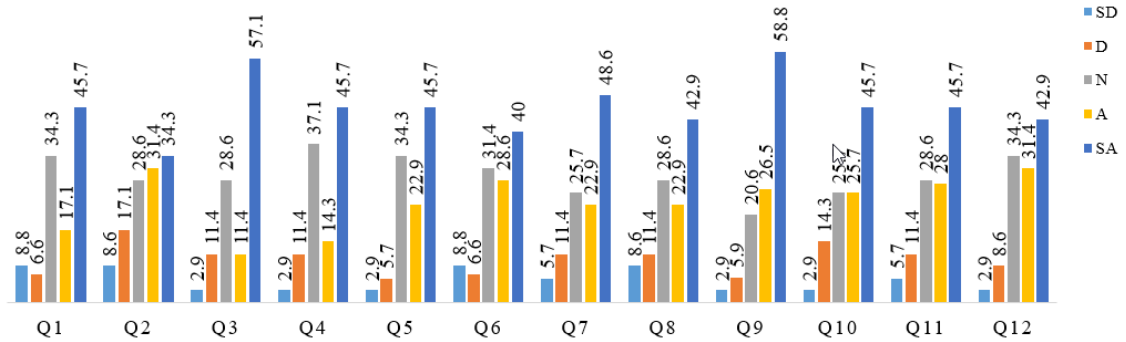
During the Sharing and Discussion process, they became deeply thoughtful as they compared and commented on each other's data charts (review and comment). These observed data exposed the forms of abstract boundary objects (i.e., control variables, hypothesis-verification, comparison, review, and comment) and the functions of boundary objects in students' knowledge transformation, engagement, and reasoning in crossing learning contexts, which were not anticipated in the lesson plan.

Specifically, some interesting and encouraging observations were captured, as follows. (1) Target Group 1 was determined to generate a "better" chart, in which the value of the intensity of sunlight would be higher and represented by a stable curve. To achieve this, they moved to the other side of the school garden, where the sunlight was stronger. (2) Target Group 2 planned to conduct several tests, compared the data charts generated in different locations, and took turns to collect data. (3) When the students were asked, "How do you connect your activities inside and outside of the classroom?" two of the six students mentioned they wanted to compare the intensity of sunlight collected outside with that collected in the classroom. One student said, "I know they are different because the source of light is different. One is light, and the other is sunlight." Another student further explained, "I can see that the value of the chart in the classroom is less than that of the one outside the classroom, because sunlight is a very powerful form of energy." Therefore, students elaborated their conceptual understanding and deepened their thinking when interacting with boundary objects (i.e., charts, control variables, comparison, concepts of sources of light) in and out of the classroom.

5.3. Students' perceptions of and attitudes towards boundary activities in BABL guided science inquiry

The proportion of student agreement on perceptions of and attitudes toward boundary activities was analyzed, as Figure 8 shows. The sum of the percentages of "agree" and "strongly agree" was calculated to represent students' main selection of each item. The first batch of survey questions concerned the relationship between learning inside and outside of the classroom (i.e., Q2, Q3, Q4, Q5, and Q6). As indicated by the students' responses to Q3 (68.5%), more than half of the students agreed that they had more opportunities to elaborate conceptual understanding developed in the classroom and relate it to their outdoor activities. Q4 and Q5 concerned whether knowledge attained outside could help students' learning in the classroom and whether the out-of-classroom activities could improve their thinking. Once again, the responses were positive, with 60% for Q4 and 68.6% for Q5. The proportion of positive responses to Q2 was also above 60% (65.7%), meaning that those students agreed that the out-of-classroom inquiry was related to their learning in the classroom and the data collected outside could be studied in the classroom later.

The second batch of survey questions examined the students' attitudes toward the post-boundary activity (i.e., Q1, Q7, and Q8). On average, over 60% of the students reflected that the teacher reviewed the data they collected in the outdoor activities and then discussed it in the classroom, which provided them with an opportunity to learn from their classmates. The final batch of survey questions (i.e., Q9, Q10, Q11, and Q12) explored the students' attitudes toward BABL guided inquiry. It shows that 85.3% of the students agreed the out-of-classroom activities done with their partners (Q9), 71.4% thought they had made a great effort in the inquiry activities (Q10), 73.7% felt they were engaged in the mobile learning activities (Q11) and 74.3% said they would like to use Sense-it to do outdoor activities when studying other science topics (Q12). These results suggest that students had a positive attitude toward the BABL inquiry activities.



*SD-Strongly disagree, D-Disagree, N-Neutral, A-Agree, SA-Strongly agree

Figure 8. Students' responses to the survey questions

6. Discussion and conclusion

Using mixed research methods, this exploratory study presents the impacts of BABL principle guided science inquiry activities on students learning performance and engagement and clarifies the mechanisms of students' reciprocal interactions of cognition in crossing learning contexts. In this study, learning takes place inside and outside of the classroom, on campus, to create scenarios of learning in formal and informal spaces.

6.1. Impact on students' conceptual understanding

To answer RQ1, the statistical analysis of the pre- and post-test results confirmed the students' changes of conceptual gains before and after the intervention. The analysis of the question items showed students' general improvement and achievement at different levels of cognition. Moreover, students' responses to the open-ended question became more active and accurate. These results offer strong evidence of the effectiveness of BABL learning in students' science learning.

6.2. Mechanisms of the students' reciprocal interactions of cognition in and out of the classroom

Log and discourse data were collected and analyzed to answer RQ2. Based on the analysis of the log data, students' engagement was verified by their active participation in nQuire-it activities during the Investigation and Sharing and Discussion phases. Not only did the students generate data charts with great zeal both inside and outside of the classroom, they also showed a great willingness to review and comment on their classmates' work, as was reflected in their discourse during the data collection. These results echo the finding that peer feedback is intended to actively and deeply engage students in learning (Moore & Teather, 2013). Meanwhile, the shared artifacts and methods contributed to providing the capacity to negotiate interests and transform knowledge, as reported in relevant studies (Carlile, 2004; Polman & Hope, 2014).

To clarify the mechanism of reciprocal interactions of cognition based on boundary objects, some valuable and unexpected findings were obtained. Prior to implementing the BABL learning activities in a real context, we expected the generation of boundary objects, in the form of either physical or abstract boundary objects, would improve the interaction and negotiation of students' cognition between formal and informal contexts. In the lesson plan, these boundary objects consisted primarily of physical artifacts (i.e., data charts, comments) generated inside and outside of the classroom, and we did not know what the abstract boundary objects would be. However, the study found that abstract boundary objects were also created and leveraged by the students in the form of conceptual understanding, scientific methods (i.e., hypothesis-verification, comparison, control variables) and thinking skills (i.e., reflection). The generation of abstract boundary objects accompanied the physical boundary objects. Our findings indicates that the boundary objects have different meanings and identities in different social worlds that they inhabit, and they are dynamic and have emergent characteristics (Pimmer, 2016).

Students' comments regarding the data charts expressed their further thinking about the reasons for data differences across different learning contexts. As mentioned above, one student provided explanations and conducted a critical reflection on why three different data charts were generated inside and outside of the classroom. This observation shows that the students' critical reflection as an abstract boundary object promotes knowledge construction inside and outside of the classroom context (Fominykh et al., 2013; Wang, Woo, & Zhao, 2009).

In analyzing the students' discussions, it was found that most focused on the functions of boundary objectives. We determined that the students formed hypotheses regarding the shapes of data charts, based on comparisons between the conditions of data collection inside and outside of the classroom. Such hypotheses served as abstract boundary objects for students to elaborate their understanding of the sources of light and the factors of sunlight intensity, which we did not expect prior to the BABL activities. These types of findings suggest that knowledge is not static and that the tension involved in the interaction between mediational boundary objects (whether they are physical or abstract) and the individuals using them tends to result in a continuous process of knowledge transformation and creativity (Wertsch & Rupert, 1993).

Moreover, our findings built on previous discussions of the roles of boundary objects in the knowledge transition process and how different types of cognitive transition can be triggered by diversified forms of boundary objects (Marheineke, Habicht, & Möslein, 2016). Such findings suggest that reciprocal interactions of cognition between learning inside and outside of the classroom do not rely solely on physical boundary objects. Rather, abstract boundary objects, generated by cross-referencing formal learning and learning in informal spaces, can mediate such reciprocal interactions.

6.3. Students' perceptions of and attitudes toward boundary activities in BABL guided science inquiry

The survey results indicate that most of the students believed that the BABL environment made them more collaborative and enabled them to connect the knowledge and skills they gained inside and outside of the classroom. They expressed a desire to continue using nQuire-it and Sense-it when studying other science topics. Similar results that the mobile learning experience and its external representations (ERs) can help to engage students in deep learning have been shown (Choi, Land, & Zimmerman, 2018). The more that people's innate psychological need for relatedness between different learning contexts is fulfilled, the more their motivation to learn will be triggered (Zainuddin, 2018).

To conclude, the consideration of the BABL principle in science inquiry supported by mobile technology in this study is within the domain of "science as culture" theory (Aikenhead et al., 1996), which postulates that boundary interaction is, in fact, the interaction between communities related to the learners' science learning. In seeking to identify the key episodes for realizing smooth transitions between different contexts, and in borrowing insights from relevant studies of boundary crossing (Hung & Chen, 2007), while incorporating the insights provided by Johnson's (1995) exploration of the stages and transitions in cognitive development, we suggest metaphorical terms for two patterns of cognitive transition in BABL environment. These patterns are "horizontal cognitive transition" and "vertical cognition transition." The term "horizontal cognitive transition" refers to a continuum of knowledge in different learning contexts. The term "vertical cognitive transition" is more related to knowledge elaboration or progression, in which deep, critical thinking or new understanding in a formal learning context is triggered by boundary objects generated in informal learning spaces. This type of transition can involve the formation of ideas, thoughts, hypotheses, or understanding in the informal learning context. It can also be explained by Bench's (1999) view that "[m]ost current accounts of learning transfer attribute cause or agency for the process to the abstraction and representation of knowledge by individual minds (p. 108)." We expect that the frequency of these two types of cognitive transition is closely related to students' learning achievements and cognition development in border-crossing contexts (Tsurusaki et al., 2012). Although not all of the groups in our study followed this learning trajectory, cognitive transition was salient in the BABL guided inquiry activities, and this type of interactive learning deserves further investigation.

7. Limitations, implications, and further research

This study has some limitations. First, it was an exploratory study and involved only a small group of learners. It did not apply an experimental design with a control-experimental group comparison. However, as an exploratory study, this investigation had its own merits, as it demonstrated the potential of the BABL principle for guiding the design and implementation of inquiry learning activities. Since many studies have considered models of learning designs with a specific focus on facilitating interactions between out-of-classroom learning and in-classroom learning, our lesson design and research findings contribute to the field of mobile learning in border-crossing learning contexts. These findings may inspire educational researchers and practitioners to reinforce the connections between in-class and out-of-class learning through the use of boundary objects and to improve cognitive interactions between learning in both formal and informal spaces.

Future investigations with a rigorous experimental design will be conducted to study the ways that learning switches between in-classroom and out-of-classroom settings and how students can achieve cognitive transformation through the generation of abstract boundary objects, or other forms of boundary objects.

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