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Developing a Gesture-based AR Exhibit: Differently-Guided Experiences for Complex Conceptual Learning in Science

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ABSTRACT: The purpose of this research was to design and evaluate the efficacy of a gesture-based exhibit with augmented reality (AR) for understanding complex scientific concepts. In particular, this study focuses on the effect of differently guided conditions in a gesture-based AR. We first present the design and development of a gesture-based AR exhibit about the conductor resistance phenomenon. An experiment was conducted to examine the effect of guided and unguided experiences on complex conceptual learning. In the experiment, 40 participants between 15 and 17 years-old were randomly assigned to either the guided (visual and docent explanation) or unguided condition. Their understanding of complex concepts was measured through the pre-test and post-test. The results indicate that while the participants increased cognitive understanding after experiencing the gesture-based AR exhibit, there was no significant difference between the two conditions. This may imply that the provision of extra guidance does not necessarily lead to better conceptual learning. In conclusion, this study provides some implications concerning the design of new types of immersive exhibits in museum contexts.

Keywords: Augmented reality, Informal learning, Science museum, Conceptual learning

1. Introduction

One of the main goals of science museums is to help visitors understand scientific phenomena and principles. Recently, science museums have been transformed by integrating emerging technologies in exhibit design. Underlying this transformation is the shift from object-based design to visitor experience design (Matuk, 2016). Object-based design refers to the use of real objects for knowledge transmission. As contemporary museums are increasingly concerned about supporting constructivist learning goals, it became important to design visitor experiences to be participatory, interactive, and immersive. This supports visitors in constructing knowledge based on their own experiences, interpretation, and perspectives (Freeman et al., 2016; Matuk, 2016). Augmented reality (AR) that integrates the physical and digital worlds has been proposed as a relevant strategy for designing interactive and immersive visitor experiences.

This study investigates two fundamental factors related to the design of immersive visitor experiences: the use of gestures and the provision of guidance. These two factors are related to the cognitive load that users may encounter during immersive experiences, which is one of the most critical design challenges (Dunleavy, 2014; Yoon et al., 2013). First, we suggest that gesture interaction using the body as an input source can be an effective design strategy to reduce potential cognitive load and to allocate more cognitive resources to higher-level learning processes. Gestures as a new type of user interface enable more intuitive and natural interaction (Fang et al., 2007). In problem-solving situations, gesturing reduces demands on cognitive resources and permits the allocation of more resources to perform tasks (Goldin-Meadow et al., 2001). Furthermore, conceptual learning can be enhanced when there is a high congruency between gestures and concepts to be learned (Antle et al., 2008; Han & Black, 2011). Despite such potential, little is known about the effects of gesture-based systems on cognitive learning, especially in the context of immersive learning environments.

Second, there have been attempts to reduce cognitive load in AR-integrated systems with the provision of guidance (Matuk, 2016). Dunleavy (2014) summarizes design strategies in AR-based learning to minimize cognitive load as (a) creating a simplified experience structure and increasing complexity gradually, (b) providing scaffolds that guide learning processes explicitly to achieve desired goals, and (c) replacing text with audio and video narrations. Although these strategies may be effective, there are also concerns about "overformalization" of learning experiences in highly-scaffolded AR-based learning (Yoon et al., 2013). This issue is particularly important in informal learning settings such as science museums since flexible and voluntary participation is central to visitors' experiences. For instance, Yoon et al. (2013) found that as scaffolds increased, the level of informal participation behaviors decreased in the science museum.

The issue of guidance and scaffolding is relevant to the design of interactive AR exhibits since managing users' cognitive load is a critical design challenge (Baydas et al., 2015; Dunleavy, 2014; Matuk, 2016). Whereas the tension between guidance and learning has been extensively debated in the literature on instructional approaches (e.g., Hmelo-Silver et al., 2007; Kirschner et al., 2006; Kuhn, 2007; Tobias & Duffy, 2009), little is known about this issue in the context of exhibit design and AR-based learning. Furthermore, previous research indicates the inherent dilemma of interactive exhibits. Allen (2004) suggests the need to take a critical stance on the dilemma between interactive elements and learning, by questioning whether integrating various interactive elements in exhibit design promotes more audience participation and better learning experiences. It is critical to go beyond the simple approach of "more is better" and to deeply examine optimal conditions for interactivity and guidance.

With this backdrop, the purposes of this study are to develop a gesture-based AR exhibit about complex science concepts and to evaluate its effect in differently guided conditions. The research question examined is "is there any significant difference between guided and unguided experiences in terms of the effect on complex conceptual learning?" Based on the lack of empirical research on guidance conditions in AR-based learning, we explore whether learning outcomes differ between guided and unguided experiences. This paper first presents the design and development of the gesture-based AR exhibit on the topic "Current and Resistance" to help users learn about complex invisible concepts. Then, we present a quasi-experimental study that investigated the effect of the gesture-based AR exhibit under differently-guided conditions on complex conceptual learning. The guidance used in the experiment included a visual explanatory panel and verbal explanation by a docent, the latter being the most commonly used technique for guidance in museum settings. Based on the key research findings, we attempt to draw some implications concerning designing new types of immersive exhibits in museum contexts.

2. Theoretical backgrounds

2.1. Interactive exhibit and gestures

According to Gardner (1995), an interactive exhibit is one type of participatory exhibit that allows visitors to directly experience the content in a way they can understand and appreciate. Gardner proposes four types of participatory exhibits depending on the presentation style and function: (a) hands-on exhibits, (b) interactive exhibits that stimulate sensory organs, (c) eyes-on exhibits that visitors observe visually, and (d) exhibits made up of design panels and simple image panels. Museum exhibits are moving from eyes-on exhibits to interactive exhibits by experimenting with emerging technologies for visitor engagement (Goff et al., 2018). In particular, gesture-based computing can support various physical interactions among visitors (Matuk, 2016).

Embodied cognition is essential to the design of gesture-based exhibits. While the conventional concept of cognition emphasizes cognitive representations and information processing in the human brain, embodied cognition holds that cognition is connected to the environment through bodily gestures rather than being an abstract proposition in the brain (Wilson, 2002). Wilson and Foglia (2017) contend that personal perceptions are based on body movements, which have a significant impact on visual attention, concept, memory, understanding of others, and even moral perception. Previous research has reported that gesture-based learning is effective in acquiring higher-level concepts and correcting misconceptions in science learning (Han & Black, 2011). For instance, Goldin-Meadow et al. (2001) reported that when learners were asked to memorize and explain a list of items, the performance level of learners who were allowed to use gestures was higher than that of learners who were restricted with the use of gestures.

The review of previous research on interactive exhibits and gesture-based exhibits reveals certain features that are likely to affect the success of visitor experiences. Here, we discuss three key features, which also informed the design of the gesture-based AR exhibit proposed in this study. First, an interactive design that promotes social interaction tends to promote more participation and engagement. For instance, Horn et al. (2012) analyzed family visitors using an interactive tabletop game in a natural history museum and found that gameplay elements significantly contributed to visitors' collaborative conversation, which subsequently influenced active prolonged engagement (APE) with the exhibit. Hinrichs and Carpendale (2011) also reported that the use of multi-touch gestures on an interactive table exhibit facilitated the emergence of social information exploration in the aquarium setting.

Second, it is important to provide natural mappings between gestures and concepts—meanings conveyed in the exhibit. The notion of "embodied metaphorical mappings" (Antle et al., 2008) is relevant for understanding the relationship between gestures and learning. Antle et al. (2008) introduce embodied metaphorical mappings to indicate that certain physical movements have metaphorical meanings that are cognitively mapped. For example, if an exhibit requires a movement to manipulate speed by manipulating tempo, it implicitly conveys the metaphorical meaning, "When the tempo gets faster, the speed gets faster. When the tempo slows, the speed slows down." As another example, many of the hands-on exhibits use power as input. These exhibits convey a built-in metaphorical meaning that an observer's "exertion" action consumes or accumulates more power or data (Lyons et al., 2012).

Third, interactive exhibits with manipulative experiences do not necessarily lead to enhanced immersion and interest of visitors, and sometimes can cause confusion and misconceptions. For example, the "Hot and Cold Coils" displayed at the Exploratorium provides visitors with learning opportunities through direct touching and manipulating of the exhibit. Despite such interactive experiences, Gutwill and Allen (2012) found that the length of time that visitors stay for the experience is rather short and that some visitors repeat meaningless actions. In the subsequent section, we further discuss this dilemma in interactive exhibits concerning the provision of guidance and visitor experiences, which is the central topic of our investigation.

2.2. Guidance in visitor experiences

With the movement toward constructivist learning goals, there have been extensive discussions about guided learning versus unguided or minimally-guided learning (Hmelo-Silver et al., 2007; Kirschner et al., 2006; Kuhn, 2007; Tobias & Duffy, 2009). Kirschner et al. (2006) define minimally-guided learning as "an approach where learners, rather than being presented with essential information, must discover or construct essential information for themselves" (p. 1), which is the method emphasized in constructivist learning approaches such as inquiry learning (IL) and problem-based learning (PBL). On the other hand, direct instruction refers to "providing information that fully explains the concepts and procedures that students are required to learn" (p. 1). Kirschner et al. (2006) argue that approaches under minimally-guided instruction are less effective than guided instruction since minimally-guided instruction poses heavy demands on working memory, especially for novice learners who lack relevant prior knowledge. Several scholars such as Hmelo-Silver et al. (2007) and Kuhn (2007), however, disagree with that argument and contend that PBL and IL are not minimally-guided learning, but embed many forms of scaffolding (e.g., benchmark lesson and just-in-time support) to help learners understand necessary disciplinary knowledge and also better manage problem-solving processes.

At science museums, guidance is provided in various forms including docents, labels, commentary panels, and audio narrations. These guiding methods can be broadly classified into linguistic, visual, and auditory scaffolding. In general, the role of guidance in visitor experiences can be understood for two purposes: to reduce cognitive load and to promote better conceptual understanding. First, visitors' learning from exhibits is achieved through cognitive information processing. Visitors selectively perceive sensory information to interpret the meaning of exhibits. The perception and reaction of visitors can change depending on how their senses perceive the exhibit at a sensory memory stage (Moreno, 2004). However, cognitive load may occur when information processing is concentrated on certain senses (Sweller et al., 1998). Subsequently, this cognitive load increases visitors' fatigue, which makes them either give up or avoid devoting cognitive resources to exhibit experiences. When information is presented in multiple forms, cognitive load can be reduced by dispersing them in the linguistic and visual processing of the working memory (Mayer & Moreno, 2003; Sweller et al., 1998). For instance, Sun and You (2019) found that personalized museum guides aligned with learning styles (e.g., visualizer or verbalizer) reduce cognitive load and help visitors better remember information.

Second, visitors are provided with appropriate guidance or explanation of exhibits to improve their understanding of objects, natural phenomena, or scientific principles. We discuss two forms of guidance frequently used in exhibit design: explanatory panel and docents. An explanatory panel as linguistic and visual scaffolding is the most commonly-used guidance in exhibit design. Falk (1997) reported that explanatory panels about scientific concepts are effective in conceptual learning. Similarly, Hohenstein and Tran (2007) found that explanatory panels that pose inquiry questions stimulate the audience's open discourse. Some studies, however, question the efficacy of linguistic scaffolds. Allen and Gutwill (2004) suggest that labels in interactive exhibits are not always useful because it is difficult for visitors to clearly understand the meaning that exhibit labels convey. The efficacy of explanatory panels is mainly evaluated in terms of *attracting power* and *holding power*. Attracting power refers to how many visitors pay attention to the explanation panel, whereas holding power refers to reading time. Korn and Jones (2000) argue that an explanation panel dealing with in-depth scientific concepts rarely draws visitors' attention, implying low attracting power. However, once visitors are attracted to the panel, it can maintain the viewer's attention for a certain period, thereby increasing holding power.

In addition to explanatory panels, museum docents have been suggested as effective for promoting cognitive learning (Braund & Lelliott, 2017; King & Tran, 2017; Shaby et al., 2019). For instance, Hooper-Greenhill (1999) suggested that the cognitive and affective stimuli provided by docents promote more active visitor-exhibit interaction. Guided learning by museum docents, however, can lead to different effects in cognitive and affective areas. A classic study by Stronck (1983) compared the effects between the structured tour guided by a docent and the less-structured tour guided by a school teacher. The results indicate that a guided tour by docents is effective for cognitive learning while a less-structured tour is more effective for promoting students' positive attitudes.

Concerning the tension between free-choice learning and structured learning, Gutwill and Allen (2012) conducted an experiment where visitors were randomly assigned to four conditions where the degree of structure and collaboration differ. They found that learning gains were higher under structured and collaborative conditions than under spontaneous and individualized conditions. Some studies, however, have reported that desired learning outcomes can be achieved under minimally-guided situations. For instance, Yasar and Gurel (2016) contend that the learning effect and visitors' interest can be high when there is a tight coupling between visitor behaviors and learning content induced by the exhibit design. The research on Physics Education Technology (PhET) also suggests that when an interactive simulation is designed to make conceptual models used by experts visible, it can increase learners' understanding of complex concepts (Wieman et al., 2008). Overall, the previous research findings on the provision of guidance in museum settings are inconclusive, which implies the need for more research on this topic.

2.3. Affordances of AR in museum experiences

Museums are embracing AR technologies to enhance interactive elements in exhibits and visitor experiences. The review of research on museum-based mobile learning indicates that AR was used with sensing and location technologies to provide visitors with personalized learning experiences (Lin et al., 2021). In general, two types of MR applications are used in the field of education (Lindgren & Johnson-Glenberg, 2013). The first type of application is a participatory simulation where learners are situated in the system, acting as one of the components. The classic example is a virus simulation where a learner wearing a Thinking tag acts as an agent and interacts with other agents to learn about the complex algorithm of controlling disease in a dynamic simulated environment (Colella, 2000). The second type of application is an interface responsive to users' physicality and location as input; this has been expanded with advances in computing methods that can detect and process location and biological data.

Some studies have investigated the cognitive function of gestures and AR systems in the field of science education. Smith et al. (2014) used a Kinect sensor to develop a simulation-based program that allows learners to see their appearance and arm motion and confirmed the effectiveness of learning the concept of angle through this gesture-based simulation. Their study demonstrates that effective conceptual learning can be achieved when learners understand meaning by linking physical movement with the visual image on the screen and can explain concepts in connection with personal experiences. Han and Black (2011) developed a simulation for mental-model learning based on the idea that learning with simulation including movement and animation can be effective for complex learning. Simulation programs that integrate learner movement and animation provide perceptually-enhanced learning experiences. Johnson-Glenberg et al. (2014) developed an AR learning environment in that learners can perform various chemical experiments through their body movements and found that learners could learn more effectively through sensory experiences and physical movement than through static learning.

However, the dominant use of XR technologies in museums thus far has been the creation of virtual museums, virtual tours, and augmented guides. A few studies have demonstrated empirical evidence of AR technologies on cognitive learning, mainly due to the limitations in evaluation methods and instruments. Among the few research studies available, the study by Yoon et al. (2013) is relevant to understanding the complexity of AR as scaffolding for learning experiences in science museums. The researchers compared the effect of six differently scaffolded conditions (i.e., device only, digital augmentation, posted questions, collaborative groups, posted knowledge building, and recorded knowledge building) on visitors' conceptual learning. Results indicate that conceptual learning gains are high in digital augmentation, posted questions, and collaborative groups. Another interesting finding is that as scaffolds increase, the level of informal participation behaviors decreases, except in collaborative groups. They also found that digital augmentation through AR is an effective scaffold for conceptual learning.

3. Developing a gesture-based AR exhibit

3.1. Design

3.1.1. Content design

In this study, the topic "conductor resistance" was specifically chosen to develop the gesture-based AR simulation since invisible concepts such as resistance, electrons, and voltage are challenging to understand in concrete and practical terms. In traditional classrooms, teachers demonstrate these "current and resistance" concepts using an experiment with real bulbs. However, since the difference in resistance values—which depend on connection methods—is small for the voltage of the battery used in a typical experiment, it is difficult to obtain experimental results that can accurately compare subtle differences.

From the perspective of embodied cognition, human gestures have a metaphorical meaning, and the exhibit design should consider the relevance of metaphors conveyed by specific gestures. However, the more complicated the metaphorical meaning, the more likely it is that there will be differences between the designer's intention and the visitors' interpretation. Action-concept congruency, hence, is essential to help visitors easily discover metaphorical meanings between bodily movement and cognitive mapping. Accordingly, we intended to design a gesture-based AR exhibit that delivers a high level of action-concept congruency.

Table 1 presents the relationships between actions by a user, representations in the exhibit, and concepts as learning content that we designed to achieve this action-concept congruency. Conductor resistance is a property of a conductor defined as the amount of opposition to the flow of electric current through a conducting medium. The resistance of a conductor is proportional to its length and inversely proportional to its cross-sectional area. To imply this relationship through gestures, the length of the conductor is changed by users' horizontal hand movements, and the cross-sectional area of the conductor is changed by users' vertical hand movements.

Table 1. The relationship between actions, representations, and concepts

Action (User)	Representation (Exhibit)	Concept (Learning content)
Hand movements in the single-player mode • Hold still • Move hands horizontally (related to X-axis) • Move hands vertically (related to Y-axis)	Change of • Length and thickness of the conductor • Brightness of the bulb • Numerical data of the resistance and the current intensity	• Single resistance control by variation of the conductor • Correlation with the brightness of the bulb and the current intensity • Correlation with the current intensity and the resistance
Hand movements in the first two-player mode • Hold still • Move hands horizontally (related to-X axis) • Move hands vertically (related to Y-axis)	Change of • Length and thickness of each conductor • Brightness of the bulb in the connected circuit • Numerical data of the resistance and the current intensity of the connected circuit	• Composite resistance in serial connection control by variation of the multi-conductors
Hand movements in the second two-player mode • Hold still • Move hands horizontally (related to X-axis) • Move hands vertically (related to Y-axis)		• Composite resistance in parallel connection control by variation of the multi-conductors

3.1.2. Design principles

A set of design principles were applied when developing the interface and tasks in the gesture-based AR exhibit to enhance user experiences and to promote conceptual learning through gestures and immersion. Here, we discuss three key design principles drawn from the literature on interaction design, embodied cognition, AR, and interactive exhibits (e.g., Antle et al., 2008; Dunleavy, 2014; Gutwill & Allen, 2012; Perry et al., 2008; Preece et al., 2015) that guided the design of our gesture-based AR exhibit system: (a) mirror-type display, (b) visual feedback, and (c) gamified collaborative tasks.

First, with a mirror-type display and simplified structure, we designed the affordance of the exhibit to be perceptually obvious to users so they understand how to interact and what to interact with. A mirror-type display allows users to recognize their images in real-time and perceive their gestures using balance and eyesight, which can promote instant participation (Park et al., 2016). Also, the control of the exhibit is visible with simple visual objects as indicators of the user's hand movements, which enables the user to intuitively grasp the meaning through those hand movements.

Second, we used a visual feedback mechanism and clear division of display areas to help users observe what actions were taken and completed (Perry et al., 2008; Preece et al., 2015). As presented in Figure 1, the display of individual users is divided into three zones. The title of the exhibit and instructions are shown in Zone 1. The icons symbolizing electricity are used to imply the learning content, and the instructions are presented in simple sentences. Zone 2 presents tasks, and various states such as individual resistance, total resistance, individual current intensity, and total current intensity that is displayed as numerical data. In Zone 3 that occupies the largest portion, users can see changes in their movements.

Figure 1. Interface design

Further, users can visually confirm the shape and size of the resistor and the change in bulb brightness resulting from their gestures. A two-dimensional virtual circuit graphic representing the change of resistance and current is overlaid on the user image drawn from the sensor. This allows users to recognize gestures (changes in hand movements) more easily. The visual feedback when matching a target resistance is overlaid on the screen. A countdown starts at ±15% of the target resistance value to help users intuitively identify how to move hands to match the target resistance value.

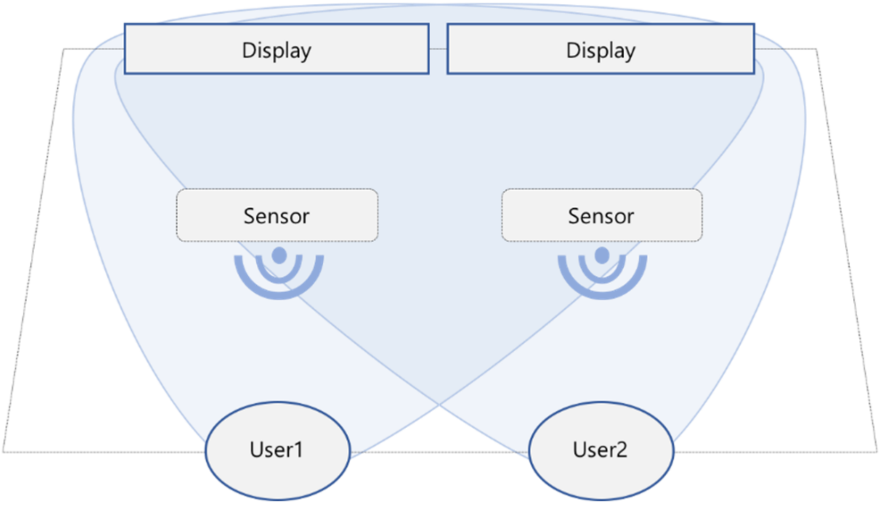
Third, the complexity in the experience structure was gradually increased with the gamified collaborative tasks to reduce cognitive load and to promote social interaction (Dunleavy, 2014). We maintained consistency in the interface design between single-player and two-player modes. Since the single-player mode contains relatively low-level concepts, the user can expend reduced cognitive load on learning basic principles involved in operating the exhibit and focus on relatively high-level concepts in the two-player mode. The tasks were also designed with gamification such as challenges, scores, and rewards. The collaborative task in the two-player mode was expected to promote more social interaction, which is an effective strategy to increase complex conceptual understanding (Horn et al., 2012: Yoon et al., 2013).

3.2. Development

The Kinect sensor was used to recognize and process users' motions. The sensor accuracy for detecting hands gesture was examined by several research studies that reported lower error rates of the Kinect sensor for gait and posture analysis (Clark et al., 2019; Ren et al., 2013). The simulation was developed using the Unity engine. An individual display was presented on the screen located in front of each user. Figure 2 illustrates the gesture-based AR exhibit design from a bird's-eye view.

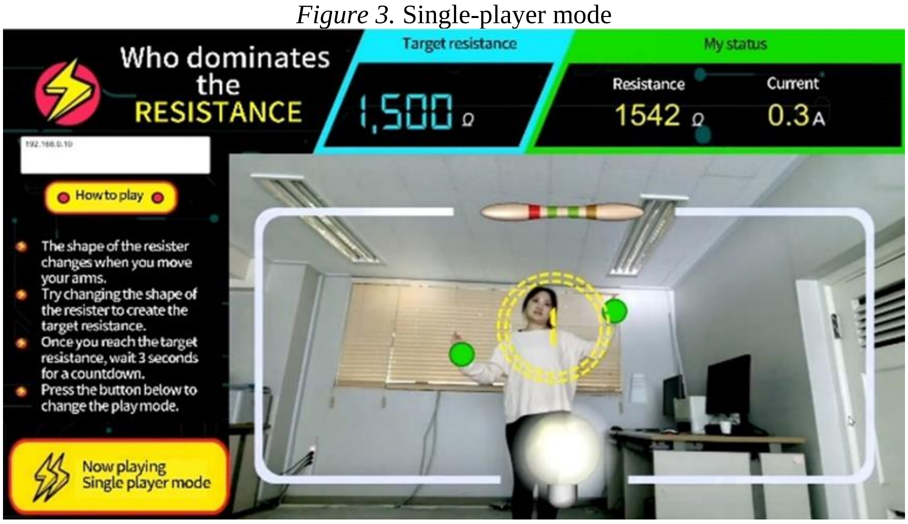
The designed scenario engages users in an interactive simulation to see the connection between their physical movement and the digital display. When visitors enter the exhibit area and stand in front of the sensor, the sensor starts detecting the visitors' gestures—hands movements in particular. The image of the visitors and the electric circuit appears on the screen. The visitors' hands movements change the length and thickness of the conductor that determines the resistance. Visitors can see the subsequent change of resistance values and current intensity through numerical data and bulb's brightness on the screen.

Figure 2. Gesture-based AR exhibit design: a macro view



The exhibit supports both single-player and two-player modes. In the single-player mode (see Figure 3), a user receives tasks to match specific resistance values. The task does not have a clear start or endpoint and is maintained until a target resistance value, given randomly, is achieved by users. When the user maintains a target value for three seconds, feedback on a successful attempt is provided, and a new value is given to the user. In the two-player mode, dyads are given the task of matching a target value collaboratively. Each user's gestures control the individual resistance values in the "serial connection" and "parallel connection" so that each user constitutes a circuit as a single resistor. In this case, the total resistance of the entire circuit needs to be achieved, not just the resistance of the individual circuit.

Figure 3. Single-player mode



4. Experiment method

4.1. Participants

After developing the gesture-based AR exhibit, we moved to the next phase to investigate its effect on complex conceptual learning in differently guided conditions. The research question examined was "is there any significant difference between guided and unguided experiences in terms of the effect on complex conceptual learning?" A quasi-experimental study was conducted with 40 middle and high school students (aged 15-17) who were recruited through convenience sampling. Since the exhibit used in this study conveys information about "current and resistance," which is taught in the ninth-grade (age 15) science curriculum in Korea, we recruited students from middle and high schools. The experiment was conducted in a lab setting due to the technical and logistical difficulty of installing the developed exhibit in a science museum. To comply with the ethics of human subject research, we explained the purpose and methods of the study before the experiment and obtained the informed consent form from all participants. They were voluntary and each received 20,000 won (about USD 20) gift card as an incentive for their participation.

4.2. Experiment design and procedures

In the experiment, participants were randomly assigned to one of two conditions: guided (n = 20) and unguided (n = 20). Table 2 shows the distribution of participants for each condition. The whole experiment lasted for two weeks and each session was about one-hour long.

Table 2. Experimental conditions

		Guided condition (n = 20)	Unguided condition (n = 20)	Total (n = 40)
Gender	Male	8	8	16
	Female	12	12	24

The guided group received explanatory visual guidance before interacting with the exhibit and verbal guidance by a docent during interacting with the exhibit. We selected verbal guidance by a docent rather than integrated on-screen guidance for two reasons. First, verbal guidance by a docent is one of the most commonly used types of guidance provided in museum learning settings. Second, our design intended to minimize the amount of textual information in the system so that users could focus on the augmented information mediated by their gestures. Table 3 presents the content of guidance presented to the guided group. Before the participants started interacting with the exhibit, the docent provided visual guidance of an electric circuit and two types of connection. During the single-player mode, the docent explained low-level concepts. When the participants switched to the two-player mode, the docent provided verbal guidance related to higher-level concepts. The unguided group did not receive any explicit guidance related to the concepts embedded in the exhibit. Only brief instructions about manipulating the exhibit were provided to the unguided group.

Table 3. Sample content provided to the guided group

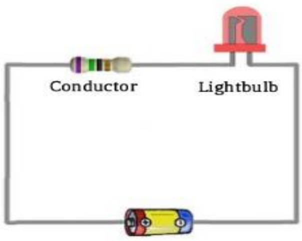
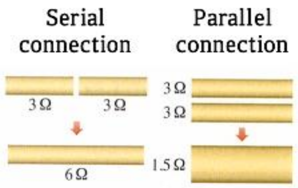
Level	Visual guidance	Verbal guidance
Low-level concepts		• Current is the rate of flow of electric charges that travel along an electrical circuit. • Resistance is a measure of the opposition to current flow in an electrical circuit. • If the material type of resistor is constant, the resistance is proportional to the length of the resistor and inversely proportional to the cross-sectional area.
High-level concepts		• If the voltage is constant, current and resistance are inversely proportional. • When several resistors are connected in series, the composite resistance becomes larger. • When several resistors are connected in parallel, the composite resistance becomes smaller.

Figure 4 presents the overall experiment procedure. A pre-test was conducted to measure the level of participants' prior knowledge about the topic. During the experiment, the participants interacted with the exhibit for 15 minutes in both single-player and two-player modes. The exhibit was arranged to be used by a dyad standing side-by-side and viewing the screen projected on the wall (see Figure 5). The exhibit first presented the single-player mode in serial connections, and then the two-player mode in parallel connections. In the single-player mode, the main tasks given to each user were to achieve a target value by changing the length and thickness of the conductor with their gestures. In the two-player mode, since two conductors were connected into one circuit, the dyad needed to collaborate in a problem-solving process. After using the exhibit, the participants took a post-test that included the same items as in the pre-test. The items were re-ordered and wordings were slightly modified to reduce the learning effect of repeated measures.

Figure 4. Experiment procedure

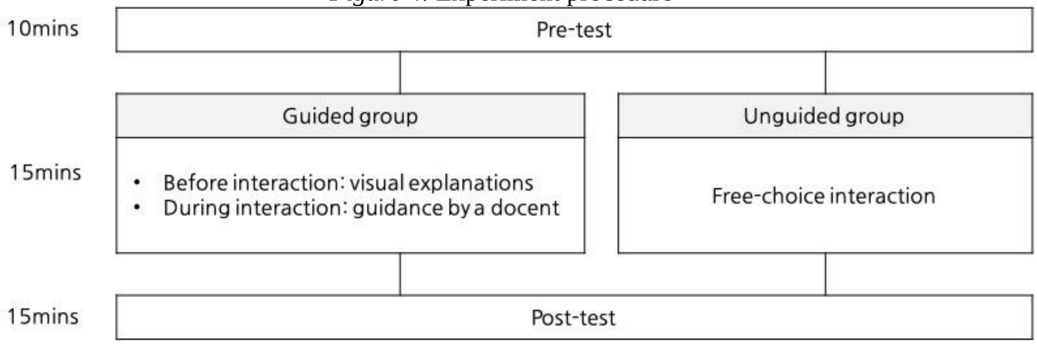
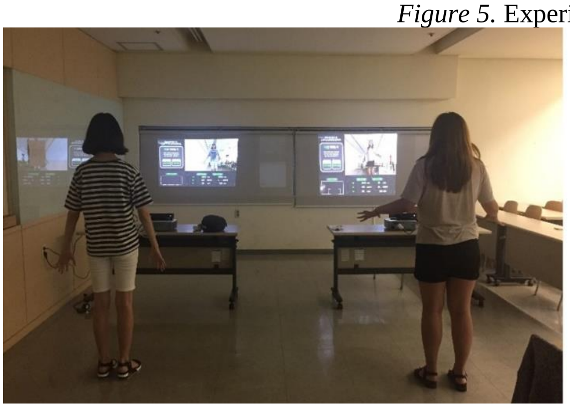


Figure 5. Experiment setup



Projectors
Image Brightness: 3,300lumens, Image Contrast Ratio: 30,000, Resolution: 800*600(SVGA)

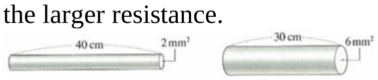
Computers
Processor: Intel Core i5, Graphics adapter: Intel HD Graphics 520, Connections: USB 3.0(with the sensor), Display Port(with the projectors), Operating System: Microsoft Windows 10 64bit

Sensors
Kinect for Windows, Developer: Microsoft, Type: Motion controller

4.3. Data collection and analysis

We assessed the cognitive learning effect with multiple-choice questions (see Table 4). The test included 16 questions, with eight items measuring low-level concepts (e.g., abstract concepts) and eight items measuring high-level concepts (e.g., relational principles). Here, we applied Gagne's (1965) hierarchical learning theory to classify the level of test items. According to Gagne, learning tasks for intellectual skills can be organized in a hierarchy according to cognitive complexity. Concept learning involves learning abstract concepts that do not have concrete physical characteristics. Principle learning, on the other hand, is connecting two or more concepts. While low-level questions measure the understanding of individual concepts and simple principles, higher-level questions measure relationships between multiple concepts and complex principles.

Table 4. Sample test items

Cognitive level	Type of learning	Concept/Principles	Sample item
Low-level	Single concepts, Simple principle	• Current • Resistance • Conductor • Conservation of charge • Resistance of a conductor	Considering that the two conductors are of the same material, choose which will make the larger resistance. 
High-level	Relational concepts, Complex principles	• Relationship between current and resistance • Series connection of resistors • Parallel connection of resistors	Which of the following is true regarding the relationship between resistance and current? (a) The larger the resistance, the larger the current. (b) The larger the resistance, the smaller the current. (c) Even if the resistance increases, the strength of the current does not change.

The questions were based on the science textbook published in the Korean Ministry of Education. To verify the content validity, one middle school female science teacher reviewed the test items with two students in her class. The teacher had a degree in Physics education and four years of teaching experience in a middle school. Since she collaborated with the research team on the design of the AR exhibit, she was able to evaluate the congruency between the test items and the exhibit design. Necessary changes, which were mostly changes in wording, were made based on their comments.

Test data were analyzed using SPSS. The Shapiro-Wilk test was conducted for checking normality. The normality at the pre-test was .56 while the post-test was .04. The Shapiro-Wilk test results showed that while the normality assumption was met for the pre-test data, the post-test data significantly deviated from the normal distribution. Hence, we used nonparametric statistics that do not require the normality assumption. The Wilcoxon signed-rank test was used to determine if the treatment affected test scores. The Mann-Whitney U test was used to examine the difference between the guided and unguided groups. The Mann-Whitney U test is suitable for testing the differences between two independent groups and is used with continuous scale data when normality cannot be assumed (Noh, 2015). The probability of significance (p-value) was set at .05.

5. Results

5.1. Comparison before and after exhibit experiences

To test the overall cognitive learning effect of the gesture-based AR exhibit, we examined the change in test scores before and after the exhibit experiences. Table 5 presents the descriptive statistics according to the level of item difficulty. The overall pattern indicates that the participants improved from the pre-test to the post-test for both low-level and high-level questions.

Table 5. Descriptive statistics (n = 40)

Level	Test	Mean	*SD*	Min-Max (0-16)
All	Pre-test	7.95	3.41	0–15
	Post-test	11.23	3.05	5–16
High-level	Pre-test	3.15	2.17	0–8
	Post-test	5.45	2.01	0–8
Low-level	Pre-test	4.50	1.73	0–8
	Post-test	5.78	1.62	2–8

As shown in Table 6, the Wilcoxon signed-rank test analysis revealed that the differences from the pre-test to the post-test were statistically significant. Based on the negative rank, all questions were z = –5.29 (p < .05), high-level questions were z = –4.88 (p < .05), and low-level questions were z = –4.03 (p < .05). Overall, the results show that the participants had significantly improved cognitive conceptual understanding after experiencing the gesture-based AR exhibit.

Table 6. Wilcoxon signed-rank test results pre-test to post-test (n = 40)

		N	Average rank	Sum of ranks	*z*	*p*
All	Negative ranks	1[a]	12.50	12.50	–5.29	.00*
(post-pre)	Positive ranks	38[b]	20.20	767.50		
	Ties	1[c]				
	Total	40				
High-level	Negative ranks	10[d]	15.70	157.00	–4.88	.00*
(post-pre)	Positive ranks	25[e]	18.92	473.00		
	Ties	5[f]				
	Total	40				
Low-level	Negative ranks	7[g]	9.29	65.00	–4.03	.00*
(post-pre)	Positive ranks	27[h]	19.63	530.00		
	Ties	6[i]				
	Total	40				

Note. [a] Post-test < Pre-test, [b] Post-test > Pre-test, [c] Post-test = Pre-test, [d] Post-test < Pre-test, [e] Post-test > Pre-test, [f] Post-test = Pre-test, [g] Post-test < Pre-test, [h] Post-test > Pre-test, [i] Post-test = Pre-test, *p < .05.

5.2. Comparison by guidance condition

Table 7 presents the Mann-Whitney U test results of cognitive learning effects according to the guidance condition. Overall, the unguided condition showed higher post-test scores than the guided condition for both low-level and high-level questions. However, the differences between the two groups were not statistically significant: $z = -1.31$ ($p > .05$) for all questions, $z = -.94$ ($p > .05$) for high-level questions, and $z = -1.29$ for low-level questions ($p > .05$).

Table 7. Mann-Whitney U test results of post-test by the guidance condition ($n = 40$)

	Guided ($n = 20$)			Unguided ($n = 20$)			Mann-Whitney U	z	p
	$M \pm SD$	Average rank	Total rank	$M \pm SD$	Average rank	Total rank			
All	10.55 ±3.36	18.10	362.00	11.90 ±2.63	22.90	458.00	152.00	–1.31	.19
High-level	5.15 ±2.23	18.80	376.00	5.75 ±1.77	22.20	444.00	166.00	–.94	.35
Low-level	5.40 ±1.64	18.15	363.00	6.15 ±1.57	22.85	457.00	153.00	–1.29	.21

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

6. Discussion

6.1. Implications of the main findings

The purpose of this study was to develop and evaluate a gesture-based AR exhibit for complex conceptual learning. In this section, we discuss the main findings and their implications. First, the gesture-based AR exhibit used in this study showed a significantly positive effect on the cognitive learning of scientific concepts. Regarding the item difficulty level, the test scores of both high-level questions and low-level questions significantly increased after interacting with the exhibit. This result is consistent with the study by Yasar and Gurel (2016), which found the relationship between the design elements and the learning content of exhibits influences learning effects. We attribute the positive gain to the careful consideration of the relationship between scientific concepts and intended actions in the gesture-based AR exhibit used in this study. For instance, the use of horizontal and vertical gestures was intentionally designed to correspond to a visual analogy for the change in the resistor's size.

Second, concerning the effect of differently-guided conditions, this study reveals that the provision of extra guidance does not necessarily lead to significantly improved conceptual learning. Our finding differs from the previous studies that reported the positive effect of structured guidance for cognitive learning (e.g., Grenier, 2009; Hohestein & Tran, 2007; Hooper-Greenhill, 1999; Yoon et al., 2013). One possible explanation is related to the intensity of verbal interaction for each condition. Our observation revealed that dyads in the guided group mostly used gestures without verbal interactions, whereas dyads in the unguided group appeared to have more frequent verbal interactions. It is possible that the guidance provided by the docent did not significantly enhance conceptual understanding during the exhibit interaction, but rather the meaning-making through verbal interaction in dyads was a more significant factor that influenced conceptual learning processes.

Overall, this research provides important findings of the efficacy of structuring museum experiences. With the increasing concern about cognitive load in immersive systems with AR/VR technologies, several design strategies have been proposed to reduce the potential cognitive load, such as providing explicit scaffolds, avoiding textual information, and providing video narrations (Matuk, 2016). This study suggests that in interactive exhibits that allow free-hand gestures and bodily movement, additional devices and human guidance (e.g., docents) to reduce cognitive load may not be necessary or effective if an exhibit is designed with careful consideration of concepts and gestures that allows visitors to easily recognize and initiate an interaction with an exhibit. Furthermore, methods for how to support collaborative meaning-making processes among visitors should be an important consideration when designing XR systems in museum settings. This is consistent with the finding by Yoon et al. (2013) on the efficacy of collaborative activities for conceptual learning in a science museum.

6.2. Limitations and areas for future research

We discuss some limitations of our study and, and suggestions for future research as potential solutions to each limitation. First, since this study was conducted with a small sample size under a controlled lab setting, the generalization of findings may be limited to similar contexts. Future research should examine more natural visitor experiences with a larger sample size in museum settings such as how visitors perceive their visit and remember their experiences after leaving the museum. Second, this study did not consider various personal and contextual factors such as the purpose of visiting a science museum, interest in science, and preferred exhibit types that might have influenced interactions and gesture patterns. Third, this study did not include a control group where users experience a non-interactive exhibit, due to the difficulty of recruiting sufficient participants and controlling multiple variables. Future research should be designed with a control group to further validate the empirical evidence of interactive AR exhibits. Forth, this study used the Kinect sensor to detect users' movements. While Kinect has been reported to have a fair accuracy for detecting large movements (e.g., moving arms), we do not rule out the possibility of detection failures in small and/or fast movements. Future research may consider using more accurate sensors for detecting gestures. Lastly, this study did not analyze verbal interaction in dyads since the main focus was on the analysis of conceptual understanding. Considering that the participants often showed collaborative discourse to solve tasks, subsequent research through discourse analysis would be useful to examine the effects of verbal interactions together with gesture usage patterns.

7. Conclusion

This study makes a valuable contribution to the design of gesture-based AR exhibits by providing empirical evidence on complex conceptual understanding, which is an under-researched area. Also, this paper presents a detailed explanation of the design principles of gesture-based AR exhibits that informs the development of similar XR systems. We suggest three takeaways from the key research findings in this study: (a) the provision of extra guidance in our gesture-based AR exhibit does not necessarily lead to improved conceptual understanding, (b) the efficacy of gesture-based AR exhibits is enhanced when the design embeds guidance that reduces potential cognitive load and increases action-concept congruency, and (c) it is important to engage and promote social interaction through game elements and challenging tasks to enhance conceptual understanding and collaborative meaning-making. We believe that these findings can be used to advance the larger research discourse on XR and the design of immersive learning environments by providing empirical evidence of gesture-based exhibits with AR.

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