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Students' online interactive patterns in augmented reality-based inquiry activities

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A B S T R A C T

探究性学习已经进入到K-12教育中并有了很大的发展。教育者关注探究性学习中的知识分享活动。本研究旨在研究基于位置的增强现实技术是否可促进在五步引导探究性学习活动中的知识分享。因此选择（被试），通过序列分析和内容分析，AR组能够促进学生知识建构的交互。

Inquiry learning has been developing for years and many countries have incorporated inquiry learning into the scope of K-12 education. Educators have indicated the importance of engaging students in knowledge-sharing activities during the inquiry learning process. In this study, a location-based augmented reality (AR) environment with a five-step guiding mechanism is developed to guide students to share knowledge in inquiry learning activities. To evaluate the effectiveness of the proposed approach in terms of promoting the knowledge sharing behaviors of students, an experiment has been conducted in an elementary school natural science course. The participants were 57 fourth-grade students from an elementary school in Northern Taiwan, divided into an experimental group of 28 students who learned with the AR-based approach and a control group of 29 students who learned with the conventional in-class mobile learning approach. The students' learning behaviors, including their movements in the real-world environment and interactions with peers, were recorded. Accordingly, the learning patterns and interactions of the two groups were analyzed via lag-sequential analysis and quantitative content analysis. It was found that, in comparison with the conventional inquiry-based mobile learning activity, the AR-based inquiry learning activity is able to engage the students in more interactions for knowledge construction. The findings of this study provide guidance for helping teachers develop effective strategies and learning designs for conducting inquiry-based learning activities.

1. Introduction

AR是当今教育的一个趋势，强调通过观察学习,多方面的思想和调查,以及知识共享。研究性学习……但是，研究性学习不同的教育方式会导致不同的结果。

In recent years, many researchers have applied location-based augmented reality (AR) to inquiry-based science education (Bressler & Bodzin, 2013; Chang, Wu, & Hsu, 2013; Sollervall, 2012). This application has become a major trend in contemporary science education (Cheng & Tsai, 2012), and emphasizes learning through observation, multifaceted thoughts and inquiries, and knowledge sharing (van Zee & Roberts, 2006). A hands-on approach is also encouraged for completing experimental activities. Inquiry learning methods encourage students to extend personal experiences from exploration, gain knowledge in the process of finding answers, summarize the data collected, and share their findings and conclusions with peers during the learning process. Undergoing these processes can correct mistakes in the learner's original knowledge and ideas, and guide the formation of correct knowledge and cognition. More importantly, sharing findings and discussing with peers enable students to learn and think from different perspectives. Inquiry-based teaching methods correspond to the teaching philosophies valued in natural science education (Capps & Crawford, 2013). Nevertheless, different guidance approaches might lead to different influences on the effectiveness of peer interactions and collaborations. Therefore, this research aims to analyze students' knowledge-sharing behaviors, such that feasible suggestions can be provided to teachers or educators as a reference when developing activities or adopting guiding strategies for knowledge sharing or cooperative learning activities.

户外学习

The prevalence of outdoor education has increased considerably in recent years (Bloom, Holden, Sawey, & Weinburgh, 2010). Students can use those outdoor learning experiences to understand and establish new knowledge and concepts regarding the topic being studied

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(Auer, 2008; Upadhyay & DeFranco, 2008). On the other hand, Teachers can incorporate knowledge regarding ecology that students gained through outdoor learning into formal classroom instruction to improve student comprehension (Eick, 2012). However, inquiry learning in an outdoor environment is challenging. Students are easily distracted during interactions and communication with many peers, and excessive knowledge and information can cause interference, rendering it difficult for students to concentrate on learning tasks related to the current topic. This makes it difficult for learners to apply the knowledge gained through outdoor learning to classroom learning or daily life (Kamarainen et al., 2013). Therefore, designing a mechanism that assists learners in group discussions is essential for enhancing the knowledge construction phase (Hou, Sung, & Chang, 2009). Previous research has indicated that group discussions generated by peer cooperation to find answers to questions can result in higher level thinking and cognition. However, the lack of appropriate strategies or mechanisms for facilitating the discussion process in cooperative group discussions can severely affect and limit the knowledge construction phase of students. Regarding this issue, numerous scholars have proposed the use of technology mechanisms to assist in knowledge sharing during the cooperative discussion process, thereby guiding the learners to achieve higher levels of knowledge construction (Hou, 2012).

2. Literature review

2.1. Inquiry-based learning

Inquiry-based learning is primarily a pedagogical method based on the investigation of questions, scenarios or problems (Kuhn, Black, Keselman, & Kaplan, 2000). By the process of investigation and collection of science data, inquiry activities provide a valuable context for learners to acquire, clarify, and apply an understanding of science concepts (Edelson, Gordin, & Pea, 1999). Furthermore, many teachers try to develop learners' investigation skills, data analysis and critical thinking using inquiry-based learning. They adopt activities related to the natural world to allow students to observe events and objects in the physical world from various facets, and to develop an understanding of how scientists explore the natural world (Hmelo-Silver, Duncan, & Chinn, 2007).

The advantages of inquiry learning are that it can lengthen the retention period of new knowledge, increase problem solving flexibility and creativity, and increase student learning motivation (Lord & Orkwiszewski, 2006). When inquiry learning is used in science subjects, it shows great potential for increasing students' understanding of scientific knowledge and their engagement in science. Rather than forcing students to learn according to a fixed process, students should be encouraged to explore, research, and think about the knowledge they have gained. They should use appropriate assistive technology to gather data, then process and formulate a reasonable explanation for the collected information. Students should then analyze the explanations of others while communicating their own viewpoints. Finally, the knowledge that students have learned should be assessed (Wilhelm & Walters, 2006; van Zee & Roberts, 2006).

The main elements of the inquiry learning process are how to define the research questions, the focus of learning, and the roles played by both students and teachers. Students play a crucial role in learning. Field explorations, interviews, research, and other guided methods encourage students to actively explore, stimulating new cognitions about the learning objectives and resulting in a more profound understanding and awareness. The role of teachers is to guide students and to establish a learning environment that facilitates the students' learning process.

The traditional approach to informal education has been criticized for creating artificial classroom contexts wherein the learning activities and resources become divorced from their meaning in real life situations (Herrington, Reeves, & Oliver, 2010). The advocates of authentic learning argue for the creation of more meaningful learning situations. Authentic learning requires that the contexts used for learning reflect real world contexts in which the skills and competencies will be deployed. Mayer (2001) also emphasizes that presenting text and corresponding illustrations in an integrated manner could benefit students more than in a separate mode. These AR-based inquiry scenarios can cover a wide range of domains from observation and interaction through to accessing real scientific instruments over the Web to conduct more realistic experiments.

The inquiry learning model was proposed by scholars and researchers at the University of Illinois at Urbana-Champaign (Li, Moorman, & Dyjur, 2010). The characteristics of inquiry-based instruction include (a) a project focus on authentic problems and issues that are relevant to the learners and the real world, (b) defining questions for learners to be studied and directions that learning takes, (c) learning what happens (and how it happens?) through fieldwork, design, construction, interviews, experiments, and other explorations that lead learners to new insights, and (d) deep understanding after thinking. The 5-stage learning strategy is explained as follows: first, the appearance of a question can stimulate the curiosity of students; this is the "ask" stage. Through observing phenomena and testing to gather data, students attempt to answer and resolve questions; this is the "investigate" stage. When students begin to form connections among the gathered information, they develop creative thinking regarding the information; this is the "create" stage. Learners share the knowledge they have learned through discussion; this is the "discuss" stage. Finally, through reactions to the questions and the research process, a new conclusion may be formed; this is the "reflect" stage. The results of the reflect stage may generate a new cycle (Li et al., 2010).

2.2. Augmented reality

In contemporary education, many educators and researchers have enthusiastically used location-based AR in teaching and learning (Bower, 2008; Dalgarno & Lee, 2010; Dunleavy, Dede, & Mitchell, 2009; Kye & Kim, 2008). Because acquiring information through this technology is more intuitive, it can stimulate learners during the learning process to actively observe, to formulate multiple assumptions through observations, to carefully assess the validity of observed phenomena and the rationality of proposed hypotheses, and to formulate a final hypothesis after refuting multiple proposed hypotheses. Location-based AR can increase the frequency of the described learning process, enabling students to be more immersed in scientific thinking while learning. Increased student immersion and frequent peer interactions during the learning process can result in high-level thinking, a thorough understanding of the topic, and enhanced absorption of the course material (Dalgarno & Lee, 2010; Squire & Jan, 2007). In addition, students who use location-based AR have demonstrated increased initiative and concentration in analyzing, finding, sharing, and discussing what they have discovered. Portable location-based AR has the characteristics of mobility, location awareness, interoperability, seamlessness, situation awareness, social awareness, adaptability, and pervasiveness, thereby forming a ubiquitous context-aware learning environment in which students can undertake learning at any time or in any place (Yang, Okamoto, & Tseng, 2008). Therefore, many scholars believe that location-based AR has great potential in inquiry-based science education applications (Wu, Lee, Chang, & Liang, 2013).

In 1997, Ronald Azuma formulated a broad definition of AR that consists of three characteristics: (a) the integration of virtual objects and the real world; (b) users can interact with virtual objects in real time; and (c) it is registered in three dimensions. Azuma's is currently the most widely accepted definition of AR. The two major categories of AR are image-based AR and location-based AR. Location-based AR was used in this study and is more suitable for use in an outdoor environment because of the software and hardware requirements, using WiFi or GPS for determining user locations, and displaying virtual information on a mobile device, superimposed on the real environment.

Previously, desktop computers had the graphics processing power to support AR implementation, but they were not portable because of hardware limitations. In recent years, through the proliferation of mobile devices and continual breakthroughs in graphics processing power, as well as the advantages of mobile devices such as portability, high social interactivity, text relevance, and independent operability (Hwang, Tsai, Chu, Kinshuk, & Chen, 2012), mobile devices can now be used as learning centers that integrate learning tools, resources, and self-developed concepts, providing students with a continuous learning environment in multiple environments (Song, Wong, & Looi, 2012). Location-based AR on mobile devices exceeds the limitations of nonportable desktop computers, increasing the opportunities for widespread usage of AR technology, and bringing users more varied uses of such technology and experiences that differ from those in the past.

According to the spatial contiguity principle, the active learning hypothesis in the cognitive theory of multimedia learning states that learners not only store information in their memory but also understand course material by attempting to actively select words and pictures which they then organize into a coherent verbal and visual or pictorial mental representation. According to the temporal contiguity principle, student learning is more effective when pictures and the corresponding text are displayed simultaneously than when they are displayed separately (Mayer, 2001). That is, learning from scenarios that present relevant materials (e.g., images, text, videos) in a well-integrated and organized form can avoid creating incidental cognitive load, and hence benefits students in terms of improving their learning performance. Similar findings have been reported by Liu, Lin, Tsai, and Paas (2012) in web-based learning activities. When learning with the AR-based mobile learning system, the students learned from scenarios that presented real-world targets and supplementary digital materials in an integrated and organized way.

Because location-based AR delivered through mobile devices is not restricted by the limitations of indoor environments, and because virtual information can be integrated into the real environment and provides users with intuitive interaction, learners have even more opportunities to engage in outdoor learning in various areas and subjects (Cheng & Tsai, 2012). In the learning process, students can physically encounter and observe the objects they are learning about, then engage in face-to-face discussions with their peers. This can promote context awareness and learning outcomes, as well as result in cooperative learning among peers.

In numerous previous cases (Hou, 2012; Hwang et al., 2012), inquiry-based AR has been used in learning activities as a checkpoint that students must pass before they are given their next task. In this type of process, the students often overlook pertinent verbal information in their attempt to quickly discover a solution. The inquiry process is relatively shallow, and knowledge sharing occurs only in face-to-face situations, which makes it more difficult to encourage behaviors of cooperative inquiry-based learning. Therefore, future AR systems must be developed to provide a communication platform and environment that facilitates increased cooperative discussion among peers, encourages the production of multiphase inquiries, increases the frequency of cooperation and communication to collectively solve problems, and brings together the knowledge of all students for resolving problems together (Dunleavy et al., 2009).

The results of these studies demonstrate that the use of inquiry-based and location-based AR in the teaching of science subjects leads to positive learning experiences and students' high learning motivation (Rosenbaum, Klopfer, & Perry, 2007). While using GPS-enabled mobile devices to gather information in outdoor environments, students experience positive interdependence, communication, and interaction, which all lead to improved immersion in learning (O'Shea, Dede, & Cherian, 2011; Rosenbaum et al., 2007). Consequently, in this study, we have attempted to exploit the advantages of location-based AR to encourage students to fully engage in the exploring and learning process by actively seeking more questions, sharing, communicating, and focusing on analysis. During a "collaborative discussion" process, the need to answer peers' questions and discuss the questions/solutions provides an opportunity for members to both understand and internalize the knowledge relevant to the proposed questions. Furthermore, a member can propose solutions to other members in order to externalize his or her knowledge. Through the location-AR device, more questions and answers can be passed around in an efficient and timely manner via online discussions, resulting in a more efficient sharing of knowledge during the online inquiry process.

According to the temporal contiguity principle, student learning is more effective when pictures and the corresponding text are displayed simultaneously than when they are displayed separately (Mayer, 2001). Therefore, in this study, a location-based AR system is proposed to facilitate inquiry learning using mobile devices. Via the AR-based system, individual students are able to study the aquatic plants unit in the field with instant learning guidance and supports; moreover, it is expected that the system can stimulate group discussion and engage the students in higher-level thinking for gaining knowledge of aquatic plants. Moreover, the students' learning patterns and interactions were analyzed to answer the following research questions:

(1) What are the sequential patterns of peer interaction in the AR-based inquiry learning activities?
(2) Does cooperative discussion raise the comprehensive perspectives of observation when learners achieve high phases of knowledge construction through online group discussion using a location-based AR system? 当达到高级知识建构的水平是否可以达到更高的理解程度？
(3) What are the differences between the students' learning behaviors in the AR-based inquiry learning activities and the conventional inquiry-based mobile learning activities in terms of knowledge construction?
(4) Through empirical observations, explore the influences and limitations of the activity in terms of knowledge-sharing, then propose feasible suggestions for teacher educators who want to promote learners' knowledge-sharing.

3. Development of the AR-based learning system

To study the knowledge construction phases of learners during the discussions, we developed a location-based AR system for mobile devices that provides a platform for discussing questions and sharing knowledge among peers. The AR-based mobile learning system was developed using JAVA for the website, Oracle for the database, and Xcode for the iPad mini devices. The system consists of a location, a camera, image editing, a digital compass, a three-axis gyro, an accelerometer and an AR display module. The location module is able to detect the GPS location of the students, guide them to find the target ecology areas, and show them the corresponding learning tasks or related learning materials. The camera and image editing modules are able to capture images from the authentic environment and to annotate and comment on the images of the observed objects when students investigate different characteristics of learning objects. The edited images, comments, annotations, and GPS location data are uploaded to the media server by WIFI communication networks. The digital compass and the three-axis gyro are able to distinguish the direction and relative positions of the students and learning objects. The accelerometer module allows students to shake their iPad to catch authentic images through small micro electro-mechanical systems. Finally, the AR display module, according to the different locations of the learning objects, shows the integrated images consisting of the target learning objects, edited images and relevant information, on the screen of the mobile device.

Fig. 1 shows the system architecture, which is based on the design of the inquiry learning activity. The system includes a camera module, an image editing module (which allows notations and comments), a discussion board module, a picture-based commenting module, and a discovery history module. The camera module allows students to immediately capture the images of objects or phenomena that stimulate inquiry, and the image editing module is used to edit or add text to the photographs. These data are then published to a cloud database, enabling all students to click on a picture in the selection menu to enter the discussion board module and leave comments. Students can monitor their own participation in what their peers have shared or the status of what they themselves have shared by choosing the discovery history module in the main menu. The "My Discoveries" function of the discovery history module displays what the user has shared, and the "My Participation" function displays user participation in what their peers have shared. When learners wish to focus on a specific topic to engage in more in-depth online discussion with multiple participants, they use the discussion board module to do so. The process requires a digital gyroscope and GPS to obtain the relative distance and direction between a user and an activity checkpoint, and WiFi to transmit all the text and pictures to an Oracle Database in a cloud accessible to all the learners.

Fig. 2 illustrates the flowchart of the learning activities in this study. After students have logged into the system, they convey observed phenomena or questions to others through photographs, messages, or drawings. This results in knowledge sharing, and through frequent sharing with their peers, students can attain the critical "discussion" phase of inquiry learning. The main menu of the location-based AR displays all the pictures shared by the students. Each picture represents a question or phenomenon that someone has discovered. These can stimulate student curiosity and willingness to participate in the inquiry process, leading them to begin their own observations and to ask questions using the system platform. These questions produce peer discussion, eventually resulting in a solution to the question. This solution can form the basis of a new cycle of exploration and learning. These steps constitute the inquiry learning activity.

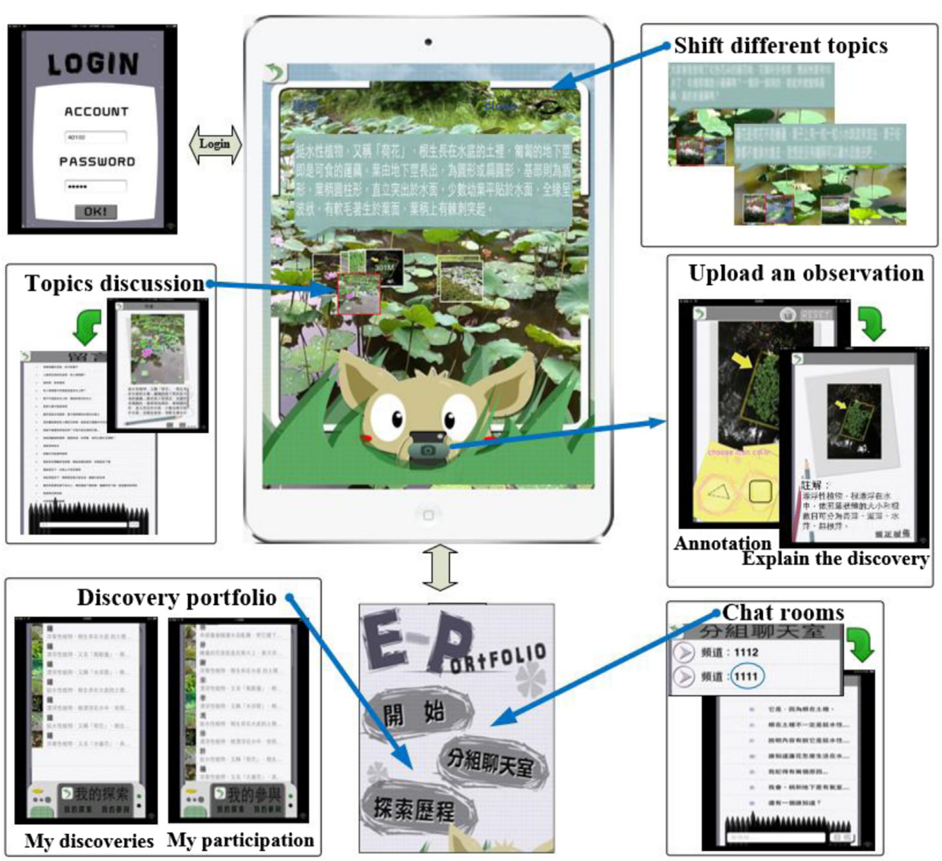

Fig. 1. System architecture of location-based AR.

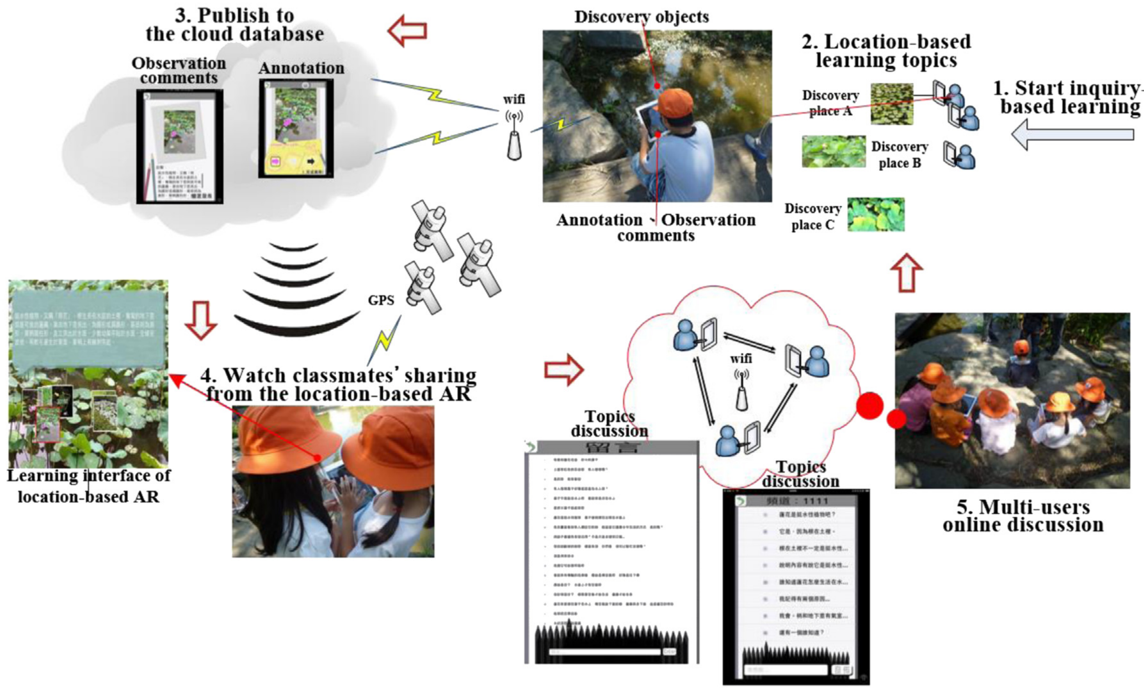

Fig. 2. A flowchart of inquiry learning activities using location-based AR on mobile devices.

4. Research design

4.1. Participants and environment

The participants in this study were fourth-grade elementary school students in Northern Taiwan. The students in the experimental group studied the ecological environment at a nearby pond in an outdoor inquiry-based teaching course. This course enabled the elementary students to physically observe the habitats and morphology of aquatic plants, which nurtured their knowledge inquiry process of learning about aquatic plants. In contrast, the students in the control group engaged in inquiry learning about aquatic plants inside the classroom. The experimental group comprised 28 students who used location-based AR in the learning process, and the control group comprised 29 students who used the "My Discoveries" function in the learning process.

Based on background knowledge of the fourth-grade students, the teaching goals of the course were for the students to learn the four major categories of aquatic plants, to learn how to categorize aquatic plants according to their morphology, and to learn the unique characteristics and structures of certain aquatic plants. The four major categories are emergent plants, such as lotuses; floating-leaf plants, such as water lilies; submerged plants, such as Brazilian waterweed; and free-floating plants, such as duckweeds or water lettuces.

4.2. Experimental process

Fig. 3 displays the flowchart of the experimental design of this study. The experimental group used mobile devices and location-based AR to engage in outdoor field inquiry learning; the control group used mobile devices and the "My Discoveries" function of the discovery history module to engage in indoor inquiry learning. The system used by the experimental group included location-based AR as well as the "My Discoveries" function of the discovery history module. The system used by the control group did not include location-based AR and the students were limited to using the "My Discoveries" function of the discovery history module to engage in indoor inquiry learning.

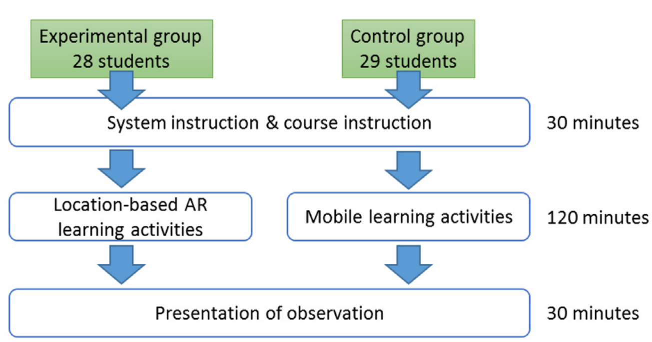

Fig. 3. The experimental process.

Before beginning the experimental activity, the teacher introduced aquatic plant knowledge to all the students, and described the learning goals and how to use the system for engaging in learning. The existing knowledge of both the experimental and control groups was then assessed. The teacher was given an account in order to access the location-AR system and posted questions/problems according to the true location of observed objects. Before the experiment concluded, we encouraged the students to participate in the inquiry activity of object-related knowledge via the system at home or at school. Once it was established that there was no considerable difference between the aquatic plant knowledge of the two groups, the students began the process of the experimental activity.

Access to the learning activities is shown in Fig. 4 (left), in which the subject of observation was the lotus. This illustrates the learning method encountered by the students in the experimental group when they engaged in outdoor field explorations of aquatic plants. The students used the location-based AR interface to quickly browse the knowledge and information shared by their peers. The icons and accompanying text that pop up in a 2D menu represent the knowledge and information gained by all students after their own inquiries. The subject of observation in Fig. 4 (right) was the hyacinth, and illustrates the learning method encountered by students in the control group when they engaged in classroom learning about aquatic plants. The students used the "My Discoveries" function of the discovery history module to record observed phenomena, and shared and allowed other students to browse these observations.

Fig. 5 shows the flow of the inquiry activities using the location-based AR system, which is implemented based on the 5-stage learning strategy proposed by Li et al. (2010). The 5-stage activities, "ask," "investigate," "create," "discuss" and "reflect", are described in detail below.

4.2.1. The "Ask" stage

After beginning the inquiry-based learning activities, students in both the experimental and control groups used the photography function of their devices to record their discoveries and observed phenomena. For example, they might be asked to observe aquatic plants and compare the growth pattern of its roots and leaves. They could also use various designs to label and emphasize what they wished to express concerning their observations or inquiries (Fig. 6). This enabled all the students browsing these articles to quickly discern the major points that the poster wished to convey.

After clicking "Finish" in the editing screen, the users were immediately taken to the text input section. Fig. 6 (right) shows how posters can use the notating function to add text describing what they want to communicate, enabling all learners to view a pictorial display supplemented by text, resulting in a clearer understanding of what the author is trying to communicate.

After completing their image and text editing, the users clicked "Post" to immediately post the image. Fig. 7 (left) shows that when the students in the experimental group shared pictures or text messages, this information was immediately displayed in the location-based AR. A pop-up icon or a text box integrated with the real environment was used to display the effect of intuitive information, and these could be quickly accessed using the location-based AR interface. Fig. 7 (right) shows that after students in the control group shared information, that information appeared in "My Discoveries." Users could clearly monitor the status of what they had shared, and this function conveniently allowed the users to organize and browse through their own discovery histories.

4.2.2. The "Investigate" and "Create" stage

The students in the experimental group used location-based AR to quickly browse information that they and their peers had shared. They could also click on the pictures that they were interested in learning more about to view detailed pictorial and verbal descriptions and to understand the knowledge that the sharer of this content wished to convey. They could then post textual questions concerning the information contained in the post, resulting in a discussion. The students in the control group used "My Discoveries" to review their own posts regarding observed phenomena and browse the questions their peers had regarding their posts. This resulted in a sequence of inquiry behaviors. If students wished to view the items that their peers had shared, they could click on their posts in the comments section to observe their sharing status.

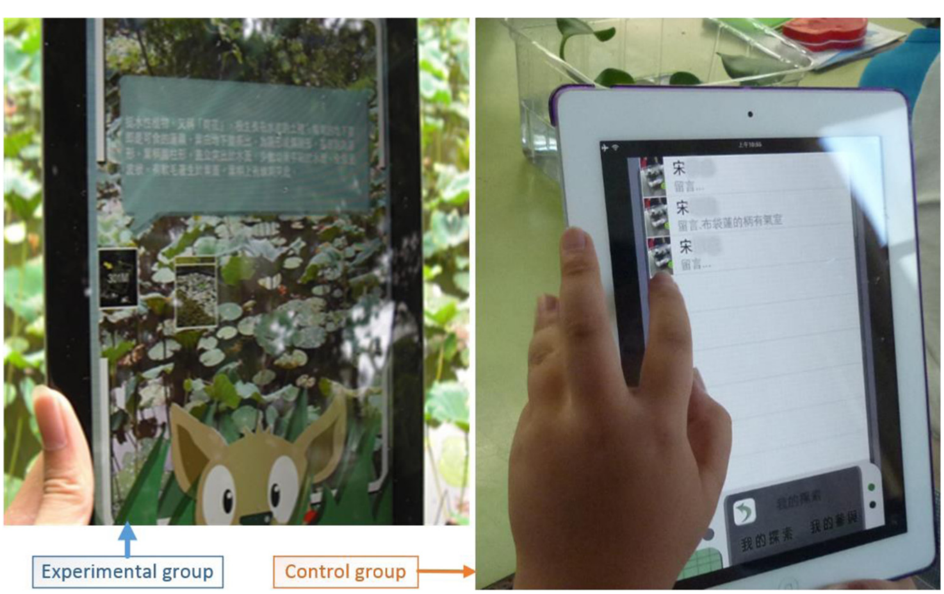

Fig. 4. Activity processes of the two groups.

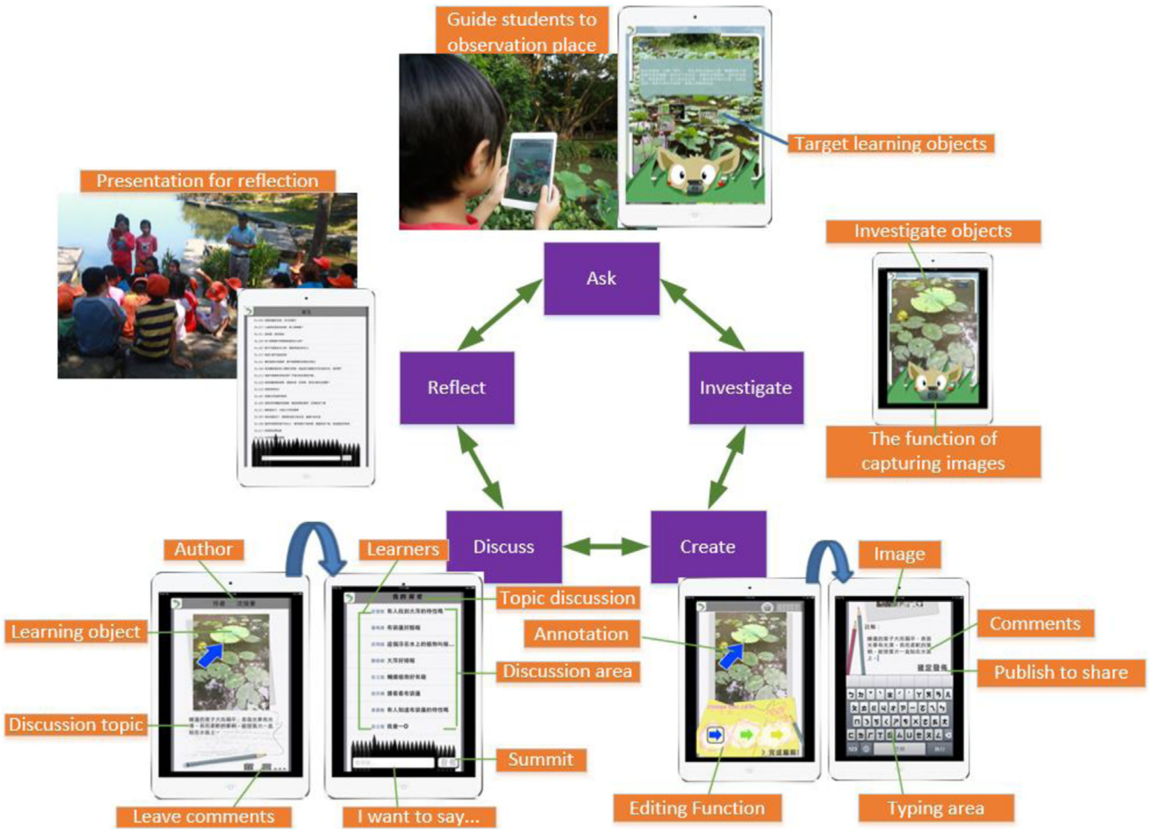

Fig. 5. Inquiry activities by location-based AR system.

4.2.3. The "Discuss" stage

In the process of discussing questions and answers, many students formed subgroups in chat rooms to focus on a particular topic and engaged in communication and discussion, producing text-only descriptions, opinions, and cognitions. Discussion of relevant knowledge regarding aquatic plants also expanded into more in-depth discussions in the chat rooms. During these discussions, all the students were able to freely express their viewpoints, and through discourse with their peers, they determined whether these viewpoints conformed to

Fig. 6. Upload an observation.

Fig. 7. How the experimental group (left) and the control group (right) viewed inquiries.

the natural phenomena. Students who knew the correct answers shared their knowledge with their peers. Students also discovered knowledge that they lacked and clarified concepts and knowledge that deviated from their cognition. This process allowed the students to actively ask questions, participate in discussions, and think cooperatively, which led to the discussion of additional questions. This aggregation of knowledge among peers provided all the involved students with a deeper understanding of the topic under discussion.

4.2.4. The "Reflect" stage

When a group in a chat room resolved a question on the discussion board, the students involved all gained a certain level of understanding regarding the topic. Some students then wished to make additional inquiries about a topic related to a concept they already understood. For example, some students wished to discover other examples of emergent plants besides lotuses. Based on existing concepts, the students formulated extension questions and inquired about the new topic, thus producing a new inquiry cycle.

When the experimental activity ended, all the students made an oral report based on their own observations and results. Lastly, we analyzed the sequence of interactions in both the experimental and control groups to understand what knowledge construction phases were achieved by the two groups. We expected that the experimental group, because of the location-based AR, would produce more active observations than the control group, leading to higher levels of thinking, and that closer observation and deeper thought processes would lead to more frequent discussions among the experimental group students than among the control group students. Compared with the students in the control group, the learners in the experimental group could attain higher levels of cognition based on the conclusion of their discussions, and achieve a higher knowledge construction phase in their cognition of aquatic plants.

4.3. Coding scheme

This study focused on analyzing the process of inquiry-based discussion. In the inquiry process, learners engage in inquiry learning methods through knowledge sharing to stimulate knowledge transference and innovation and to derive innovative ideas from organized information. Peer discussion and thinking resulting from knowledge sharing among multiple learners, the organization of questions from different phases, and the integration of all conclusions into a uniform cognition shared by all learners leads to the formation of multiphase knowledge construction. Among these methods, the most commonly used to delineate each phase of knowledge construction is an interaction analysis model (IAM). This coding method was jointly proposed by Gunawardena, Lowe, and Anderson in 1997 and has been recognized as being an effective way of analyzing quantitative content (Rourke & Anderson, 2004). The coding scheme used in this study is a modified IAM scheme proposed by Hou et al. (2009). It includes five phases, as shown in the following:

P1: Raising or defining a question or a problem.
P2: Proposing a solution to the question or offering information relevant to the question.
P3: Comparing or discussing the solutions proposed for the question.
P4: Reaching a conclusion regarding the various solutions proposed for the question.
P5: Sharing statements or comments unrelated to the discussion topic.

5. Results and discussion

Based on the coding scheme, the learning logs of this study were coded, and the lag-sequential analysis was performed to find the learning patterns from the coded behaviors. To test the reliability of the coded content, another researcher was asked to randomly select and code more than half of the comments of both groups. After both researchers finished coding the discussion comments of both the experimental and control groups, the results were compared and the number of consistent and inconsistent codes was tallied. The results showed that the inter-rater Kappa reliability of coding was 0.87 for the experimental group and 0.88 for the control group. A high Kappa score signifies high coding uniformity between two coders, and a score higher than 75% implies that the coding results are extremely reliable (Bakeman & Gottman, 1997).

In continuous discussions that exhibited sequential behavior, we calculated the frequency of phase transitions. The learning process of the experimental group yielded 164 inquiry topics and 1008 coded events; the learning process of the control group yielded 177 inquiry topics and 1059 coded events.

To further analyze whether the correlation between each knowledge construction phase in the student discussions reached statistical significance, lag-sequential analysis was performed, the results of which are listed in Table 1. The *z*-scores of each sequence obtained through sequential analysis for the experimental and control groups are listed in Table 2. A *z*-score higher than 1.96 represents a sequence that is statistically significant (Bakeman & Gottman, 1997). Finally, a behavioral transfer diagram of the statistically significant sequential relationships of the five phases based on the *z*-scores was produced.

Table 2 of the experimental group shows that nine sequences in the experimental group reached statistical significance: P1 → P1, P1 → P2, P2 → P2, P2 → P3, P2 → P4, P3 → P3, P3 → P4, P4 → P1, P4 → P3, and P5 → P5. Table 2 of the control group shows that six sequences in the control group reached statistical significance: P1 → P1, P1 → P2, P2 → P3, P3 → P4, P4 → P5, and P5 → P5.

Fig. 8 shows the behavioral transfer diagrams of the knowledge construction phases showing the sequences with significant *z*-scores in the experimental and control groups. All the sequences in the diagrams are statistically significant. The numbers above each arrow represent the *z*-scores for the sequence, and the thickness of the arrow indicates the relative significance. The direction of the arrow represents the direction of the knowledge phase transition.

The P1 → P1 sequence in Fig. 7 of the experimental group represents the behavior of the students after reaching the learning website; the students continuously raised questions and shared their observations. Based on these questions and shared information, they conducted discussions using different perspectives, represented by the P1 → P2 sequence. Numerous students offered answers to the questions and enthusiastically shared their opinions. They reflected on the questions, and actively tried to discover mistakes in others' opinions. Therefore, P2 → P2 was a crucial sequence. The P2 → P3 sequence represents the advancement from reflecting on questions and different viewpoints to analyzing and negotiating between opinions students agreed with and those they did not. Many students focused on the analysis and negotiation phase, represented by the P3 → P3 sequence. Students continued on to the resolution process of a higher phase when they formulated a meaningful conclusion negotiated by multiple participants, represented by the P3 → P4 sequence. The P2 → P4 sequence represents the process of bold assumptions, when participants jumped to conclusions or reached conclusions inconsistent with the facts. These assumptions were carefully tested, and the P4 → P3 sequence represents the process of determining the validity of these conclusions. In addition, the P4 → P1 sequence represents the behavior of the learners who produced additional inquiries based on discussion results, and P5 → P5 represents the behavior of the learners who continuously engaged in discussions unrelated to the topic.

Table 3 displays the probabilities of the phase transitions. According to the observations of the discussion process among both groups, after a student posted information or a question, the other students carefully read all of their peers' discoveries to understand the solutions proposed by others. After reading, they provided an analysis of the original post, offered clarification or confirmation of the validity of the concept, or stimulated an innovative perspective on the discourse. Lastly, the students provided a conclusion to the inquiry. This formed a cyclical learning process. Although P3 and P4 discussions comprised a small proportion of the control group discussions, both groups of students used the system to advance to progressively deeper inquiry learning. The P1 → P2, P2 → P3, and P3 → P4 sequences represented a sequential learning process without skipping phases. By following this sequence, the students were less likely to overlook crucial information or formulate conclusions without sufficient inquiry. Doing so can ensure that students in the discussion process achieve a certain knowledge phase. Therefore, learners who use online discussion learning methods based on inquiry learning to learn about a topic achieve higher knowledge construction phases.

Table 1
Frequency transition table of the two groups.

Experimental group						Control group					
	P1	P2	P3	P4	P5		P1	P2	P3	P4	P5
P1	488	193	0	0	9	P1	585	107	12	17	48
P2	2	51	52	13	4	P2	21	10	5	2	15
P3	6	4	103	18	5	P3	8	5	1	3	9
P4	33	0	14	0	0	P4	0	0	0	0	20
P5	5	0	4	1	3	P5	36	0	5	5	145

Table 2
Adjusted residuals table (*z*-scores) of the two groups.

Experimental group						Control group					
	P1	P2	P3	P4	P5		P1	P2	P3	P4	P5
P1	*16.63	*3.66	−21.29	−8.47	−2.55	P1	*15.99	*3.97	−2.22	−1.14	−20.52
P2	−12.12	*4.70	*7.96	*5.03	0.99	P2	−3.34	1.72	*3.72	0.58	1.06
P3	−12.20	−6.31	*19.48	*7.19	1.40	P3	−3.25	1.25	0.59	*2.94	1.52
P4	*2.42	−4.01	*2.35	−1.27	−1.02	P4	−5.69	−1.63	−0.67	−0.73	*8.41
P5	−1.06	−2.07	1.31	0.94	*5.33	P5	−13.33	−5.51	0.47	0.07	*19.61

*$p < .05$.

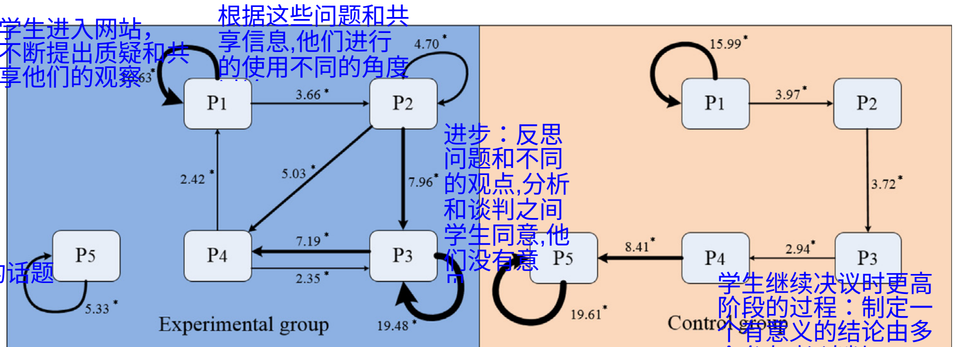

Fig. 8. Behavioral transfer diagram of the knowledge phase construction of the two groups.

Although the experimental and control groups both achieved a certain knowledge construction phase, the students in the experimental group attained a higher phase of knowledge construction because they had a higher probability of undergoing the P2 → P3 and the P3 → P4 phase transitions than those in the control group. The P2 → P3, P3 → P4 sequence is a crucial factor that indicates whether students can achieve a high knowledge construction phase. Comparing the P2 → P3 transfer probability of both groups revealed that the students in the experimental group strove to explicitly convey their opinions and solutions and to engage in in-depth comparisons and discussions. In contrast, the students in the control group had a higher probability of the P1 → P1 phase transition, demonstrating that their behavior remained in the “ask” phase, continually discovering and bringing up questions, which coincides with the previous findings of Jeong (2003) and Song (2014).

The probability of the P5 → P5 sequence is much higher in the control group than in the experimental group, signifying that the control group had a much higher chance of receiving interference from outside factors that resulted in deviation from the subject than the experimental group did.

Fig. 9 shows phase transfers that existed only in the experimental group. The P2 → P2 sequence shows that when the experimental group students used the location-based AR system to engage in inquiry learning activities, they continually and enthusiastically offered their own opposing ideas, questions, or different perspectives during discussions based on discoveries by other students, and frequently switched between these learning processes. The students explicitly conveyed their own ideas so that other students could understand them, or engaged in inquiries regarding different opinions. Doing this enabled the learners to increase their concentration, depth of discussion, and viewpoint diversity in the multiple-participant discussion learning process. It also increased the depth and persistence of students in the cognitive analysis phase. Furthermore, the P5 → P5 behavioral sequence transfer probability was much lower in the experimental group (23%) than in the control group (76%), signifying that the students in the experimental group were much more proactive about continuing the exploration of a subject or the analysis of knowledge than those in the control group.

Because using a location-based AR system can help students explore a subject from broader perspectives, the students in the control group exhibited less P2 discourse than the students in the experimental group did. The students in the control group exhibited a lack of organization regarding the integration of knowledge shared by their peers. Although the control group generated more P1 posts than the experimental group, they were unable to generate additional inquiry processes. Their responses remained in P1, asking questions and describing discoveries, and students in the control group were unable to effectively apply their knowledge to other concepts. In contrast, the experimental group students were able to break through to a higher level than the control group students; therefore, the P3 → P3 sequence represents the ability of students to focus on the subject and perform in-depth analyses of the inquiry.

The knowledge construction phases that occur sequentially after P2 include both P2 and P4. This signifies that the students in the experimental group attempted to summarize and consolidate the opinions conveyed by their peers to compile an interim conclusion. However, the conclusions reached after skipping the analysis phase (P3) often presented a discrepancy with the true answer. Therefore, after reaching a conclusion, the students revisited and analyzed the validity of their conclusions, which is represented by the P4 → P3 sequence. This encouraged student behaviors of rethinking and backtracking to derive a new deductive process and the solution. However, if the conclusion reached through the P2 → P4 and P3 → P4 sequences matched the true answer, students in the experimental group prompted new inquiries, developing a more in-depth topic of discussion than the previous topic. This is represented by the P4 → P1 sequence. This behavior allowed the inquiry learning process to cycle continuously (P1 → P2 → P3 → P4 → P1), and the students were able to achieve deeper phases of knowledge construction, which coincides with the previous findings of Hou et al. (2009).

The P4 → P5 sequence did not occur in the experimental group. This implies that the students in the control group encountered limitations and restrictions at higher phases of knowledge construction, primarily because fewer students concentrated on these higher phases of inquiry. Therefore, the students often ceased discourse in the middle of a discussion, resulting in knowledge that is overly fragmented in the discussion process, rendering it difficult for the control group students to effectively link discourse into summaries and consolidations.

Table 3
Probability of sequences that occurred in both groups.

Sequence	Experimental group	Control group
P1 → P1	71%	76%
P1 → P2	28%	14%
P2 → P3	43%	9%
P3 → P4	13%	12%
P5 → P5	23%	76%

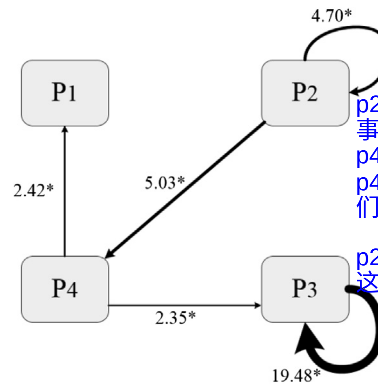

Fig. 9. Behavioral transfer diagram of sequences in the experimental group only.

p2:因为使用基于位置的AR系统可以从更广泛的角度帮助学生探索一个主题,学生们在控制组表现出更少的P2话语比实验组的学生。
p2-p4：大胆假设的过程,当达到参与者跃升至结论或结论与事实不符
p4-p3:确定结论的有效性
p4-p1:产生额外的调查，让探究性学习过程不断循环,和学生们能够实现更深的阶段知识的构建
p2-p4;p4-p3
这鼓励学生行为的反思和回溯得到新的演绎过程和解决方案
对照组的学生表现出的缺乏组织有关知识的集成共享的同行。尽管P1的帖子比生成的对照组与实验组,他们无法生成额外的调查过程。他们的反应仍在P1,提问和，对照组的描述发现,学生无法有效地将他们的知识应用到其他的概念。相比之下, 实验组的学生能够突破到更高水平比对照组学生;因此,P3 / P3序列代表学生的能力集中在主题和执行调查的深入分析

6. Conclusions and future work

This study integrated a quantitative analysis of the content and a sequential behavior analysis to determine whether learners can achieve high phases of knowledge construction through online group discussions using a location-based AR system. The two groups of students were engaged in a learning process using mobile devices. Their teacher did not interfere with the knowledge sharing in the group discussions but allowed the students to freely explore knowledge related to the topic. Both groups of students were able to take pictures and annotate, write descriptions, share, and leave comments regarding the pictures to record the knowledge they had gained. Students could share their knowledge and opinions. The difference between the groups is that one group of students used location-based AR to explore topics related to the subject. The other group did not use location-based AR, but used the "My Discoveries" function to access their peers' discoveries or questions. Based on this variable of whether or not students used location-based AR, we observed whether there was a difference in the knowledge construction phase achieved by the students in the two groups.

The results indicate that implementing inquiry learning methods can result in a sequential learning process (P1 → P2 → P3 → P4) for all learners, allowing them to experience each phase of knowledge construction. However, by calculating the probability of multiple sequence transitions, observing sequential behavior, and coding of the knowledge construction phases, it was found that the AR-based learning approach enabled the students to go beyond the guided sequential learning process, and resulted in a different learning pattern (P1 → P2 → P3 → P4 → P1). In addition, the peer interactions in the AR-based inquiry activity showed more knowledge construction behaviors (i.e., P3 or P4), which are usually difficult to achieve (Hou et al., 2009). In the meantime, the AR-based inquiry approach encouraged the students to generate creative conclusions by jumping from phase P2 to phase P4. If the conclusion is revealed to be inconsistent with the facts, the students can reexamine the validity of this conclusion (P4 → P3), which results in a series of organized, systematic analysis behaviors (P3 → P3) that culminate in the formulation of a unanimous, meaningful, and valid conclusion (P3 → P4).

From these findings, it is concluded that the location-based AR system enables learners to quickly and intuitively receive information, which facilitates seamless dissemination of information. Access to visual information supplemented with text guided the learners toward exploring topics related to the subject. This seamless knowledge presentation provided the learners with broad and comprehensive perspectives of observation and thought. It also enabled multiple learners with different perspectives to participate in online group discussion, thereby producing systematic and meaningful dialogue, and stimulating creative hypotheses, bold assumptions, and rigorous analyses. Therefore, the frequency of discussions that deviated from the topic because of external environmental factors or social interactions decreased considerably. The ratio of events coded P5 and the probability of the P5 → P5 sequence were considerably lower among the students who used location-based AR than among the students who did not. The challenge of ensuring that learners concentrate on the learning tasks at hand in outdoor inquiry learning activities can be resolved by integrating location-based AR with outdoor inquiry learning. This integration enables learners to become immersed in the learning process, and increases their concentration on learning; therefore, learners can achieve high phases of knowledge construction and high-level thinking and cognition.

It is also inferred that the integration of location-based AR on mobile devices and inquiry learning enables students to become immersed in the learning process. Therefore, it is suitable for teaching subjects that require high-level thinking, such as water quality or geology, and using it can provide learners with a more in-depth understanding and analysis. However, this type of mobile learning method is not suitable for long-term observations, and applying it in an indoor environment is not recommended.

Based on our findings, we will now provide some useful suggestions regarding how they can be used to intervene in and guide students' online inquiry discussions. First, avoid deviation. The probability of the P5 → P5 sequence is much higher in the control group than in the experimental group. Therefore, teachers can pay special attention to the discussion limitations that were commonly seen in our study, and remind students to return to the topic once they deviate to ensure that they remain on track. Second, encourage integrated conclusions. After a student has given a certain number of solutions or analyses for a certain question (P2, P3), the teacher should be guided to summarize and organize the solutions and discussions and draw a summarizing conclusion (i.e., facilitate the occurrence of P2 → P4, P3 → P4). Third, promote further analysis/discussion. Appropriate strategies can also be formulated to help students explore new solutions (P3 → P2, P2 → P2), continue in-depth analysis (P3 → P3), and arrive at new questions (P4 → P1). Teacher educators can post corresponding messages to guide the students since the above sequences rarely occur spontaneously in the discussion process. Lastly, apply technologies to assist knowledge-sharing. Many studies in recent years have used technologies to assist knowledge-sharing. An intelligent agent is capable of providing automatic timely guidance to learners. This kind of technology detects a learner's online operations and actively provides guidance. If we were able to integrate this technology in the existing inquiry forums, teachers would receive automatic prompts and supplementary information instantly, possibly assisting them in overcoming the bottlenecks in the discussion.

In this study, from students' online interactive patterns in augmented reality-based inquiry activities, cooperative discussion really can help students to achieve deeper phases of knowledge construction and inquiry abilities. However, small groups or teams of students working together may achieve greater efficacy in a manner that promotes the students' responsibility for their own learning as well as the learning of others. In terms of future studies, it is suggested that future research can focus on methods of cooperative learning, such as Student Learning Teams (SLT), Student Teams-Achievement Divisions (STAD) or Full Option Science Systems (FOSS), and provide students with an opportunity to practice skills or learn content presented by location-based AR systems.

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