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An Investigation of University Students' Collaborative Inquiry Learning Behaviors in an Augmented Reality Simulation and a Traditional Simulation

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Abstract The purpose of this study is to investigate and compare students' collaborative inquiry learning behaviors and their behavior patterns in an augmented reality (AR) simulation system and a traditional 2D simulation system. Their inquiry and discussion processes were analyzed by content analysis and lag sequential analysis (LSA). Forty university students were divided into dyads and then randomly assigned into AR group and traditional 2D group to collaboratively conduct an inquiry task about elastic collision. The results of the content analysis and LSA indicated that both systems supported students' collaborative inquiry learning. Particularly, students showed high frequencies on higher-level inquiry behaviors, such as interpreting experimental data or making conclusions, when using these two simulations. By comparing the behavioral patterns, similarities and differences between the two groups were revealed. The AR simulation engaged the students more thoroughly in the inquiry process. Moreover, students in both groups adopted the same approaches to design experiments. Due to the line of AR research is in its initial stage, suggestions for future studies were proposed.

Keywords Augmented reality · Lag sequential analysis · Collaborative inquiry learning · Simulation · Behavioral pattern

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Introduction

Students' Collaborative Inquiry Learning and Computer-Supported Simulation System(s)

In the last decade, collaborative inquiry learning, which combines the merits of practicing inquiry in science learning and peer collaboration, has been considered as a promising activity for fostering students' science learning in the literature (Bell et al. 2010; Mulder et al. 2012). Inquiry learning refers to a learning environment in which students can investigate the natural world as active agents (Gijlers and de Jong 2005). Students can carry out all the investigation activities by themselves in inquiry learning, such as formulating hypotheses, conducting experiments and observations, proposing explanations based on the evidence, and drawing conclusions.

Moreover, collaborative learning, which involves individuals as group members negotiating with and sharing learning tasks, has been widely discussed as a way of improving students' learning (Lou et al. 2001; Stahl et al. 2006) and for learning science in particular (Reiner 1998;

Harskamp and Ding 2006). As pure inquiry might create difficulties for the students (Klahr and Nigam 2004), various forms of guidance to address these problems have been developed, including collaborative learning (de Jong 2006; Gijlers et al. 2009; Reiser 2004). The processes of students arguing about decisions and explaining ideas are helpful when they conduct their inquiry tasks collaboratively (Gijlers et al. 2009). Thus, a combination of collaboration and inquiry learning is suggested as a possible way to scaffold students' science learning (Bell et al. 2010; Gijlers et al. 2009).

Also, learning technologies, such as computer simulation, have contributed more possibilities for enhancing students' science learning (Mulder et al. 2012; Rutten et al. 2012; Smetana and Bell 2012). In simulation environments, students can build their own models, generate and test hypotheses, and observe the results iteratively (Mulder et al. 2012). That is, the flexibility of computer simulations would encourage students to participate in their inquiry processes. Gijlers et al. (2009) have indicated that university students can actively construct knowledge within the collaborative inquiry learning environments supported by simulations.

The Affordances of Mobile AR Simulation

Recently, augmented reality (AR), a real-time technology that blends virtual objects or environments with the real world, has revealed great potential for enriching simulation with more authentic learning experiences (Klopfer 2008). Azuma (1997) indicated that AR could be defined as a system that offers three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects. In the notion of the reality–virtuality continuum proposed by Milgram and Kishino (1994), ranging from a completely real environment to a completely virtual one, mixed reality (MR) is regarded as a situation presenting the virtual world and the real world together. AR is one condition of the MR environment that contains more real-world objects than virtual materials. AR technology has been applied to support students' science learning and is recognized as a new technological trend in education (Chen and Tsai 2012; Martin et al. 2011; Wu et al. 2013).

As indicated in Cheng and Tsai's (2013) review, AR technology utilized in science education could be identified according to two major approaches, image-based AR and location-based AR. Image-based AR is supported by recognition of artificial labels (i.e., marker labels) or natural images, while GPS or a wireless network is used as the recognition technique to register users' locations for location-based AR. No matter which approach is used, augmented components (e.g., text, audio, video, and 3D objects) and physical-world images coexist on the user's display. Users or learners could interact with computer-generated multimedia components and the real world at the same time.

In the past, simulations with the 3D virtual world provided an engaging environment for learning (Dalgarno et al. 2009), but the departure from the real world would decrease the authentic learning experiences (Squire and Klopfer 2007). Chen and Tsai (2012) indicated that although virtual reality (VR) technology could provide an immersive learning environment for learners, AR technology allows learners to interact with the real-world and virtual objects together. Cheng and Tsai (2013) preliminarily concluded the affordances of AR technology for science learning as the fostering of students' spatial ability, practical skills, conceptual understanding, and scientific inquiry learning activities. Wu et al. (2013) indicated that the authentic experience provided by AR technology engages students in exploring real-world surroundings. When conducting inquiry learning with AR technology, students can manipulate virtual materials from a variety of perspectives and obtain plentiful supplementary information.

Meanwhile, Henrysson et al. (2005) recommended that mobile phones are an ideal platform for developing AR. Mobile technology allows students to have more physical contact with peers and consequently enhances their coordination and interactivity in computer-supported collaborative learning (CSCL) activities (Zurita and Nussbaum 2004a). The mobility helps students to interact with their peers in the most natural way (i.e., face to face). The ease of physical contact and interaction would be helpful to create a space that favors peer collaboration in order to achieve the creation of new knowledge (Zurita and Nussbaum 2004b). On the other hand, learners could be untethered from the desktop and be free to move through the world when using mobile devices (Squire and Klopfer 2007). More opportunities to expand their investigation of the real world are emerging along with the use of mobile devices (Hwang et al. 2008). With the affordances of mobile technology, mobile AR simulation systems might provide not only an applicable environment for augmenting students' authentic learning experiences, but also an appropriate channel for enhancing face-to-face interaction and collaboration (Wu et al. 2013).

Although a number of computer-aided simulations are available for supporting students' collaborative inquiry learning, Bell et al. (2010) suggested that the simulation environment should move forward to embrace advanced technology. While AR technology has created new opportunities in learning science (Cheng and Tsai 2013; Wu et al. 2013), there are, however, still relatively few studies investigating students' collaborative inquiry learning supported by mobile AR simulation.

Using Simulation to Learn the Concept of Elastic Collision

Researchers have indicated that momentum and kinetic energy are fundamental and crucial concepts in science learning (Bryce and MacMillan 2009; Singh and Rosegrant 2003). Singh and Rosegrant (2003) developed a multiple-choice test and surveyed university students' understanding of momentum and energy systems and found that most students have learning difficulties regarding these related concepts. In order to deal with such difficulties, Marshall and Young (2006) claimed that computer-aided simulation could provide a potential learning environment. By using simulations, the participants can manipulate parameters, obtain measures, and, most importantly, observe the physical phenomena that are unable to be directly observed in the real world, such as the elastic collision process. An interactive 2D simulation called Interactive Physics was used in their study to foster prospective teachers' understanding of collisions.

As mentioned above, AR technology can enhance simulation systems and foster students' learning of science. Lin et al. (2013) adopted an AR simulation, called AR physics, to investigate university students' learning of elastic collision. The results indicated that the students had better learning performance than those who used traditional simulations. Wu et al. (2013) have reviewed 54 studies and concluded five affordances of AR systems that may support students' science learning. Some of them may be regarded as beneficial to supporting students' learning of the elastic collision topic. For example, an AR system can show learning content in 3D perspective and help students visualize the invisible. The phenomenon of elastic collision, which is not easily observed by students in daily life, will be able to be manipulated and investigated via an AR system. Moreover, its immediate feedback and the immersive experience it creates may help learners to conduct investigations of the process of elastic collision situated in real-world surroundings.

Using Lag Sequential Analysis to Investigate Students' Learning Behaviors

The most commonly adopted methods for evaluating simulation systems for learning have tended to be undertaken at a surface level. That is, quantitative approaches comparing the students' learning achievements before and after using the system have frequently been used in previous studies (e.g., Jara et al. 2009; Kong et al. 2009). Chen (2010) has suggested that the focus should extend to students' reasoning ability and learning patterns when evaluating the effectiveness of a virtual learning environment. To obtain more detailed and deeper insights, some qualitative methods, such as content analysis of discussion processes, have also been employed (e.g., Lee and Tsai 2011). However, researchers have indicated that the results of the content analysis alone still lack the detail required to understand the behavior patterns and sequential progression of the entire discussion (Hou et al. 2009; Jeong and Davidson-Shivers 2006). As suggested by Cheng and Tsai (2013), applying a mixed method such as content analysis and lag sequential analysis (LSA) to identify and understand learners' behavioral patterns of using AR technology is required.

LSA is a method used to investigate the significance of the sequential correlation between behaviors (Bakeman and Gottman 1997). Kapur (2011) indicated that LSA not only takes into account the occurrence of each learning behavior, but also demonstrates the information of order and sequencing of the learning behavior. This method of examining users' online behavior patterns has been widely used by e-learning researchers (Hou et al. 2009; Jeong and Davidson-Shivers 2006).

Lin et al. (2013) adopted LSA to investigate students' processes of collaborative knowledge construction as using AR simulation. The students' behavioral patterns not only explained how students organized their activities of knowledge construction with the AR simulation, but also supported the evidence of improving students' learning performance. Moreover, more suggestions for educational researchers to advance the current status of AR research were also proposed. Lin et al. (2013) assumed that participants' learning behaviors when using AR simulation might differ from those of using traditional 2D simulation. Thus, this study followed up their assumption of using LSA to investigate and compare students' learning behaviors and processes in a 2D simulation group and an AR simulation group by analyzing the data collected in the study of Lin et al. (2013).

The insights revealed by LSA have enriched the quality of assessing learning environments (Hou et al. 2010). Through inferring their behavior patterns, researchers can understand how students experience learning systems. The findings could be helpful in uncovering the affordances and limitations of the current learning environments and could then provide educators or system designers with an important reference for improving their learning systems (Hou 2012). Thus, in this study, the result of LSA would reveal what kind of collaborative inquiry learning behavior often occurs following another certain kind of inquiry behavior.

Research Purposes

Based on the aforementioned literature, due to the fact that the research on AR technology is still in its initial stage

(Martin et al. 2011), how mobile AR simulation assists students' collaborative inquiry learning processes such as learning elastic collision needs to be investigated. Moreover, as previously mentioned, it has been suggested that future AR research should adopt mixed methods such as combining with LSA to obtain in-depth understanding of the learning process (Cheng and Tsai 2013). As previous findings have indicated that the participants' learning behaviors when using AR systems might differ from those when using 2D simulation (Lin et al. 2013), the main purpose of this follow-up study is therefore to investigate and compare students' collaborative inquiry learning behaviors and their behavior patterns when using different simulation systems. Comparing the distributions of behaviors and behavior patterns between these two systems can help us to understand what the similarities and differences are. Also, the affordances and limitations contributed by certain simulation systems in students' collaborative inquiry processes can be inferred. In sum, the research questions to be addressed in this study are as below:

1. What are the distributions of collaborative inquiry learning behaviors demonstrated by university students using the AR simulation and traditional simulation? And what is the difference, if any, between these two groups?
2. What are the behavior patterns of university students' collaborative inquiry learning when using AR simulation and traditional simulation? And what is the difference, if any, between these two groups?

Method

In order to answer the research questions, the details of how the students conducted their collaborative inquiry learning tasks are described below. As previously mentioned, this paper presents a follow-up study of Lin et al. (2013). Most of the research methods were the same as in the previous study, such as the participants, learning tasks, and procedures. It should be noted, however, that only the students' behavioral patterns of knowledge construction in the AR condition were analyzed in the previous study. This study aimed to analyze the learning behaviors of collaborative inquiry learning of the two conditions (i.e., AR simulation and 2D simulation) and compare the similarities and differences in the behavioral patterns in the two simulation conditions.

Participants

A total of 40 university students, including 15 males and 25 females, were invited to participate in the study. The participants took physics classes before the study, but there were no lessons related to elastic collision. Additionally, they had no prior experience of using the learning systems adopted in this study.

In order to explore the behavior patterns of using different simulation systems, they were divided into dyads (20 dyads in total), each of which was assigned to either one of the two experimental groups: the AR simulation group or the traditional simulation group. It should be noted that the students were randomly divided and assigned to eliminate the possible influences of their prior knowledge since they did not take a pretest.

Learning Environments

In this study, two mobile simulation learning environments, AR simulation and traditional simulation, were adopted in the two experimental conditions. In both groups, the students could use their own mobile devices to interact with peers and arrange their inquiry stages in any place at any time according to their preferences.

The AR group used an AR simulation, "AR physics," which was developed specifically for students to learn about elastic collision. AR physics runs on an Android OS mobile device with a software application of marker detection. When the marker is detected, the system will blend two virtual 3D cubes on the desk displayed on the screen of the mobile phone. Students can manipulate these virtual 3D cubes, visualize the process of elastic collision, and receive augmented information regarding kinetics and momentum. These system features of AR physics conform to the characteristics of AR systems suggested by researchers (Azuma 1997; Wu et al. 2013).

As shown in Fig. 1, the students had the in-time real-world images on the mobile device captured by the embedded camera. After the marker was detected, the

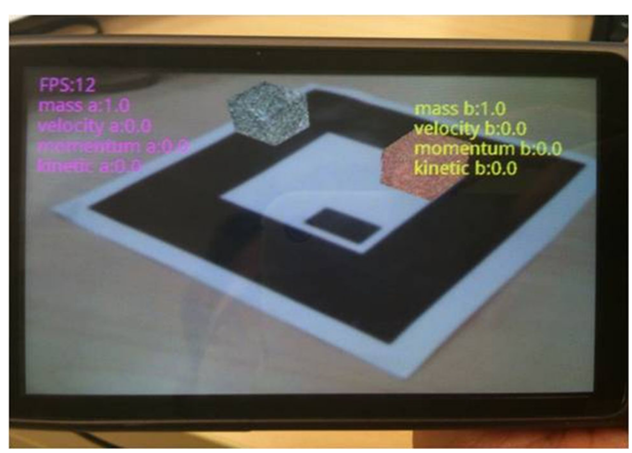

Fig. 1 Screenshot of the AR simulation system

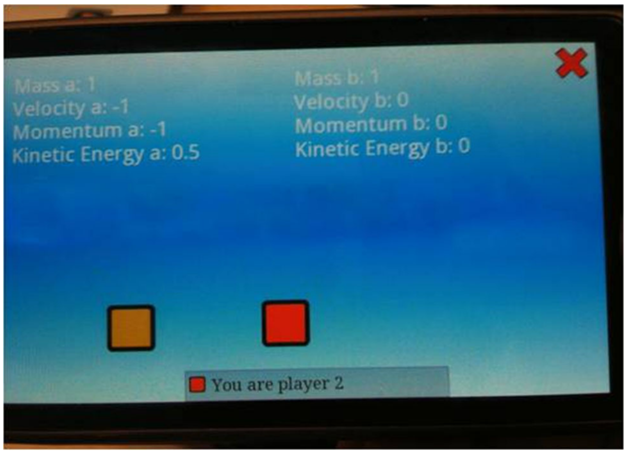

Fig. 2 Screenshot of the traditional simulation system

students could see two 3D virtual cubes blended on the mobile device. Each student controlled one cube. They could input the parameters (i.e., mass and initial velocity of the cube) into the mobile device. After receiving the parameters from both students, the system would start to simulate the process of the elastic collision. In particular, the students could observe the process of elastic collision from various perspectives by manipulating the marker.

In the traditional simulation group, as shown in Fig. 2, the students could see two cubes on the screen of the mobile device. The settings were similar to those of AR physics. Each student controlled one cube and could change the mass and initial velocity of the cube.

In brief, the settings of the traditional simulation environment were almost the same as those of the AR simulation environment in terms of the variables displayed on the screen and the cubes used as representation. The two simulations are able to simulate the process of elastic collision. Not only the process of how the cubes collided and moved is displayed on the screen, but also the real-time numerical data of the velocity, momentum, and kinetic energy of the two cubes are shown. The main differences between the two systems are the interface and the manipulation mechanism. The students in the AR group could manipulate the augmented 3D objects blended in the real environment. Those using the traditional simulation could only enter the parameters and watch the simulation of elastic collision via a 2D interface.

Procedures

First, all participants were asked to read a set of instructions regarding the basic concepts of elastic collision and inquiry process for 15 min. Next, each dyad in both groups was asked to carry out a scientific inquiry task with two open-ended questions related to elastic collision: (1) In the context that object B is stationary and object A moves toward B, how many kinds of subsequent motions can happen after the elastic collision? How does the relationship between the masses of the two objects influence the subsequent motions of the two objects after the collision? (2) How do you explain the change in motion of the two objects after the elastic collision?

The collaboration inquiry learning task was regarded as finished when each dyad reached agreement on the answers to the questions and submitted a discussion summary.

Table 1 Coding scheme of the collaborative inquiry learning behavior

Codes	Students' behaviors	Example
O	Identifying the variables (Orientation)	We can change the mass and velocity of this (cube A) and can only change the mass of this (cube B). So we can only change these three things (Student B, Dyad 2, AR group)
H	Specifying the relation between variables and proposing hypotheses (Hypothesis)	How about the heavier mass affects and changes the direction of motion? (Student B, Dyad 3, AR group)
E	Using simulation to conduct experiments and collect data (Experiment)	My velocity is 0. What mass did you put? (Student B, Dyad 3, AR group)
I	Making the interpretation based on the data (Interpretation)	When I am heavier than you, we both move in the same direction, but you move faster (Student B, Dyad 2, AR group)
C	Making conclusions (Conclusion)	So there are three ways in total (Student B, Dyad 2, AR group)

Data Collection and Analysis

In order to explore the patterns of the students' collaborative inquiry learning behaviors, both quantitative content analysis and sequential analysis were employed in this study. First, the complete learning processes of the students' inquiry steps were videoed and transcribed verbatim for analysis. For segmenting the transcripts of the students' learning processes, a framework consisting of five activities to describe the process of generating new knowledge within collaborative inquiry learning proposed by Njoo and de Jong (1993) was adopted as a coding scheme: (1) Orientation: students can search for information about learning tasks and identify the objects, variables, and parameters; (2) Hypothesis: students will propose hypotheses to specify the relations between variables; (3) Experiment: all activities for dealing with the experiment design and testing hypothesis are included in this stage; (4) Interpretation: the results of the experiments become the resources for discussion in this stage. Students' activities related to dealing with the interpretation of the results and data are categorized in this stage; (5) Conclusion: this stage refers to the activities of extracting the interpretations, making conclusions, reflecting on their experiment design, and putting the results in a broader context. The codes used, the corresponding students' behaviors, and examples are presented in Table 1.

Two researchers who were familiar with the framework discussed and divided the students' utterances into segments that are defined as representing one student's single learning behavior. A total of 20 sets of code strings consisting of 1,108 behavioral codes were obtained. In order to examine the reliability of the behavioral codes, because there were more than 1,000 codes, we selected 10 % of the data and trained another coder to work independently with the coding system. The reliability coefficient between the two coders reached .83 (Cohen's kappa).

The 1,108 behavioral codes were analyzed to investigate the distributions of collaborative inquiry learning behaviors. Then, the 20 code strings which were coded based on their temporal order were analyzed to calculate the frequency of each behavioral code immediately following another one. According to the formula provided by Bakeman and Gottman (1997), the sequences among the students' learning behaviors in the two learning environments were calculated. Z-scores greater than +1.96 indicate that the continuity between two behavioral codes has reached statistical significance.

Results

Analysis of Collaborative Inquiry Learning Behaviors in the Two Groups

In order to explore the distributions of the students' collaborative inquiry learning behavior, a content analysis was conducted. The distribution and frequency of the coded behaviors are shown in Table 2.

Table 2 The descriptive data of coded behaviors in the two groups

Learning process	AR simulation		Traditional simulation	
	Frequency	Percentage	Frequency	Percentage
Orientation	75	13	61	11
Hypothesis	49	9	46	9
Experiment	90	16	78	14
Interpretation	274	48	269	50
Conclusion	78	14	88	16
Total	566	100	542	100

Table 2 indicates that in the AR simulation group, the most frequent behavior was "Interpretation" ($n = 274$, 48 %), followed by "Experiment" ($n = 90$, 16 %), "Conclusion" ($n = 78$, 14 %), "Orientation" ($n = 75$, 13 %), and "Hypothesis" ($n = 49$, 9 %). In the traditional 2D simulation group, the most frequent behavior was "Interpretation" ($n = 269$, 50 %), followed by "Conclusion" ($n = 88$, 16 %), "Experiment" ($n = 78$, 14 %), "Orientation" ($n = 61$, 11 %), and "Hypothesis" ($n = 46$, 9 %).

Then, a chi-square test was conducted to determine the significant differences in the distributions between the two groups. The result ($\chi^2 = 2.52$, $p > .05$) showed no significance. Thus, the distributions of the students' collaborative learning behaviors were similar in these two groups.

"Interpretation" was the most frequent behavior in both systems. Almost 50 % of behaviors were included in this category. The students put a great deal of effort into interpreting the experiment results with their peers when using these simulation systems. After conducting the experiments, the students' mutual discussions and data interpretation appeared frequently for reaching agreement or confirming the hypotheses. In contrast, it should be noted that "Hypothesis" was the least frequent behavior in both groups. The students made 49 and 46 hypotheses in total in the AR group and the traditional 2D group, respectively. In other words, each dyad only made around 4 hypotheses in their inquiry process in both groups.

Behavior Patterns from the Lag Sequential Analysis

In order to examine the students' behavioral patterns of collaborative inquiry learning in each group in depth and to compare the differences so as to answer our second research question, a series of lag sequential analyses were conducted. The significant sequences are illustrated in Figs. 3, 4, representing the "AR simulation group" and the "traditional simulation group," respectively. In the diagrams, the values in the figure represent the Z-value of each sequence. The arrow indicates the direction of transfer for each sequence, while the thickness of the arrow shows the level of significance and the strength of transition probability.

In all, nine significant behavioral patterns demonstrated by the students in the AR group are shown in Fig. 3. The four significantly looped patterns H → H (Hypothesis),

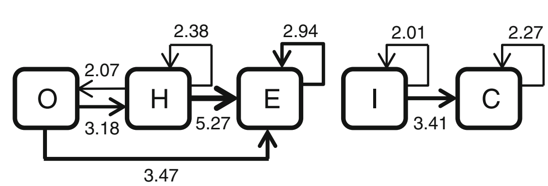

Fig. 3 Sequential pattern of behaviors in the AR simulation. *Note* *O* Orientation, *H* Hypothesis, *E* Experiment, *I* Interpretation, *C* Conclusion

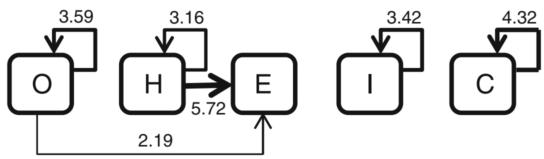

Fig. 4 Sequential pattern of behaviors in the traditional simulation. *Note O* Orientation, *H* Hypothesis, *E* Experiment, *I* Interpretation, *C* Conclusion

E → E (Experiment), I → I (Interpretation), and C → C (Conclusion) indicate that the students were continually involved in the individual inquiry activities such as making hypotheses, conducting experiments, interpreting results with peers, and making conclusions. Furthermore, the patterns O (Orientation) → H, H → O, and H → E indicate that when using AR simulation, the students can analyze inquiry tasks and generate hypotheses iteratively and then test their hypotheses by using AR simulation. Then, the pattern I → C indicates that the students made conclusions after they interpreted the results. In addition, the pattern O → E reveals that some students used the AR simulation directly after identifying the variables.

Figure 4 indicates six significant behavioral patterns obtained from the students in the traditional simulation group: O → O, H → H, H → E, I → I, C → C, and O → E. Four looped behavioral patterns O → O, H → H, I → I, and C → C indicate that the students were involved in these inquiry stages when using traditional 2D simulation, including identifying their tasks and variables, generating hypotheses, interpreting experiment data, and making their conclusions iteratively. The behavioral pattern H → E indicates that the students conducted experiments after proposing a hypothesis. The behavioral pattern O → E, which was also found in the AR group, represents that the students often conducted an experiment immediately after the variables were identified.

After comparing the two diagrams, the similarities and differences in the learning behavior patterns of the two groups were unraveled. First of all, five learning behavior patterns were found in both environments, including three looped patterns (H → H, I → I, and C → C) and two patterns (H → E and O → E) related to the process of "Experiment." In terms of looped patterns, the behavioral pattern O → O only existed in the traditional 2D group, while the behavioral pattern E → E only existed in the AR group. Each simulation contained four looped patterns, meaning that the students' collaborative inquiry learning was supported when they used the simulations.

Furthermore, the two behavioral patterns O → E and H → E indicate how the students designed their experiments. Namely, when the students in both groups went through the experimentation process, they adopted two approaches: following the proposed hypothesis (i.e., H → E) and conducting the experiment after identifying the variables (i.e., O → E).

The similarities also revealed that most of the significant behavioral sequences in the traditional 2D group were also found in the AR group. There were six significant behavioral sequences in the traditional group, five of which were shared with the AR group. Moreover, there were four more distinctive behavior patterns in the AR simulation: O → H, H → O, E → E, and I → C. The behavioral patterns O → H, H → O, and I → C indicate that the students' inquiry processes were tightly connected in the AR group. The behavioral pattern E → E shows that the students iteratively used the AR simulation to conduct experiments. In sum, these results indicate that the AR simulation can not only support students' collaborative inquiry learning activities as well as the traditional 2D simulation can, but also engage them more thoroughly in the inquiry process.

Researchers have indicated that there is a sequential order when conducting these five inquiry steps (van Joolingen et al. 2005). In addition to the significant behavioral patterns, it should be noted that an expected behavioral pattern E → I did not reach significance in either group.

Discussion

In order to answer the first research question, the distributions of students' collaborative inquiry learning behaviors in the AR group and traditional 2D group were revealed through content analysis. The chi-square results indicated that there was no significant difference in the frequencies of the five inquiry behaviors between the two groups. Although the "Interpretation" predominated over other behaviors, other behaviors could still be regularly observed in both simulations from the distributions. These preliminary findings imply that the students could conduct the inquiry of elastic collision when they used either of the simulations.

"Interpretation" was the most frequent behavior of students' collaborative inquiry processes in both groups. This result indicates that the students put a lot of effort into interpreting the results of the experiments. Students are required to interpret data for two reasons. One is to confirm a hypothesis, and the other is to find evidence for building consensus with peers (Gijlers et al. 2009). Bell et al. (2010) have indicated that students who use computer tools (i.e., simulation) for conducting experiments tend to focus on higher-order processes of inquiry, such as interpretation and conclusion. The result of this study shows a similarity with the literature. Using computer-supported simulation, either traditional 2D or afforded by AR technology, students can concentrate on organizing and interpreting the data from the experiment and build their own knowledge during the inquiry process.

On the other hand, the students in both groups showed comparatively less frequency of the "Hypothesis" behavior. Each dyad proposed 4 hypotheses on average. In the literature, hypothesis generation has been determined as one of the more difficult processes in inquiry learning (de Jong and van Joolingen 1998); thus, the result of small numbers of hypotheses indicates that the students seemed to encounter this problem.

The second purpose of this study was to investigate and compare the students' behavioral patterns of collaborative inquiry learning when using the AR simulation and traditional 2D simulation. By using LSA, there were six and nine significant behavioral patterns in the traditional 2D group and the AR group, respectively. Although the aforementioned distributions had no significant differences between the two groups, the comparison between the two groups' behavioral patterns provided more insights. The two groups shared five behavioral patterns. In terms of diversity, four were found only in the AR group, while the traditional 2D group had one unique behavioral pattern.

First, students' collaborative inquiry learning can be supported by using computer-aided simulation (Bell et al. 2010; Rutten et al. 2012), either traditional 2D simulation or AR simulation. The three looped patterns which existed in both groups (i.e., H → H, I → I, and C → C) indicate that the two simulations can support the students' collaborative inquiry behaviors, such as generating hypotheses, interpreting experiment data, and concluding inquiry results. A previous finding is also confirmed here. That is, when using the two simulations, the students can involve the interpretation and conclusion steps that are considered as high-order inquiry learning behaviors (Bell et al. 2010).

Second, the behavioral patterns O → E and H → E also existed in both groups. This represents two approaches that the students in both group adopted to design their experiments. One followed the proposed hypothesis, and the other was just based on the variables identified in the orientation stage. The first approach is normally found in the literature (Bell et al. 2010), while the second approach can be explained by two reasons. First, de Jong and van Joolingen (1998) indicated that students who fail to make a formal hypothesis might design their experiment based on their heuristic. A number of heuristic experiment designs were found in a previous study (Klahr et al. 1993). Second, researchers have indicated that students show high interest in using computer simulations (Rutten et al. 2012). Some dyads were attracted to using the simulations for experiments directly after specifying the variables. Nevertheless, hypothesis generation is a central process in inquiry learning (de Jong and van Joolingen 1998). Thus, scaffolds or guidance for supporting students to generate proper hypotheses should be given.

In addition, the results of the comparison also reveal that the AR simulation plays a more supportive role in the students' collaborative inquiry learning than traditional 2D simulation. Among the six significant behavioral patterns found in the traditional 2D group, five can be found in the AR group. Furthermore, there were four more significant behavioral patterns in the AR group. These plentiful behavioral patterns enrich the connections between inquiry steps. The learning behavior patterns of using AR simulation are similar to the ideal collaborative inquiry learning processes. Bell et al. (2010) suggested that inquiry processes should be orientation and questioning in the beginning, processes of investigation such as experimenting in the middle, and finalizing activities such as conclusion and evaluation at the end. In addition, the behavioral pattern E → E indicates that when using the AR simulation, students iteratively conducted experiments. Wu et al. (2013) have stated that AR simulation is capable of providing immersion and manipulation for enhancing learning environments. Thus, students are motivated to be involved in the experimentation process. In sum, the AR simulation would be more suitable for students to conduct inquiry tasks collaboratively according to these empirical findings.

Besides, one behavioral pattern, O → O, only reached significance in the traditional 2D simulation. This looped pattern shows that the students identified the variables of the inquiry task repetitively before proposing their research questions in this stage. Moreover, after this stage, the behavioral pattern O → E indicates that the students adopted a heuristic approach to conduct their experiments. It is supposed that the students put much effort into identifying the variables. For this reason, they tended to prefer the experimentation-driven strategy.

Notably, the expected behavioral pattern between "Experiment" and "Interpretation" did not reach significance in either group. In fact, the behavioral pattern of E → I did exist in the transcriptions of the students' discussions, but the transition probability was not sufficient compared with other sequences. It may be that the output of the computer simulations was consistent. The experiment data never changed. The students were accustomed to accepting the results directly. In fact, conducting an inquiry task in the real world, students very likely need to repeat the experiment and interpretation stages due to the possibility of some errors. The convenience afforded by computer simulation can help students to pay more attention to higher learning processes; however, the error-free and oversimplified environment may harm science education in terms of fostering the ability to conduct authentic scientific inquiry (Chen 2010).

Conclusion

The purpose of this study is to understand university students' collaborative inquiry learning behaviors when using simulations to conduct inquiry tasks related to elastic collision. The results indicate that students are engaged in either traditional 2D simulation or AR simulation. In particular, students are able to concentrate on the high-order inquiry activities. Moreover, after comparing the behavioral patterns of the two simulation groups, it was found that AR simulation can be more supportive than traditional 2D simulation. Therefore, computer-aided simulation should be considered when educators design collaborative inquiry learning activities for students. In addition, the new rising AR technology is more strongly recommended to build more authentic environments.

In this study, the students made only a small number of hypotheses when they conducted the inquiry tasks. As collaboration is one useful support, more guidance or scaffolds should be offered to help students generate hypotheses. Researchers concluded a variety of suggestions (de Jong and van Joolingen 1998). For example, an add-on tool called the "hypothesis menu" can be provided with the simulation. Variables, relations, and conditions are predefined in the menu. Students can assemble those elements of the hypothesis by themselves. Smetana and Bell (2012) suggested that simulations are most effective when they are used properly. Such add-on tools would scaffold students to interact more effectively with the simulation. Thus, it is recommended that educators or designers pay more attention to the support structures of simulations and provide suitable guidance for students when designing educational simulation systems for collaborative inquiry learning.

Also, the simple and direct experiment results given by the powerful computing simulations should be reconsidered. In this study, the transition probability from "Experiment" to "Interpretation" did not reach significance. The students did not frequently repeat the experiments to confirm the results when interpreting the data. Chen (2010) has suggested that simulation-based learning environments should include some features of conducting experiments in reality, such as random errors, which could foster students' critical thinking. By integrating these features, students need to re-conduct experiments and reconsider whether the result is believable or not. On the one hand, these authentic features might be able to build a more natural experience that is advocated by the notions of inquiry learning. On the other hand, students can realize that unpredictable system errors are natural and are an essential part of experiments. This is helpful in terms of fostering students' scientific inquiry ability and promoting their scientific literacy.

Contemporary science environments should foster "hands-on" inquiry-based experience and investigation (Pyatt and Sims 2012). Combining real physical laboratory activities and simulation activities has been widely adopted to facilitate students' learning of science (e.g., Zacharia and Olympiou 2011). In previous studies, the simulation systems were attributed to traditional 2D environments. Future studies may be able to blend AR and physical experimentations to investigate the influences on students' learning.

As the frequency from the content analysis provides an initial understanding, it should be noted that the results of LSA provided further details illustrating the users' behaviors. As previously mentioned, the results can provide designers or educators with a reference for fine-tuning their learning systems (Sung et al. 2010). Thus, designers or educators could use LSA to analyze learners' learning behavioral patterns for measuring the efficiency of learning systems.

Moreover, the mixed method of investigating AR research is recommended to attain understanding of students' learning processes and learning experiences (Cheng and Tsai 2013). Interviews, observations, and videotaping analysis could be adopted. Besides, students' eye movement collected by the eye-tracking technique should be analyzed as well for determining their attention to AR information.

Lastly, the two simulations adopted in this study were an AR system and a traditional 2D system. As indicated, the AR technology presented the learning environment from a 3D perspective. The 3D feature is a key factor when comparing the differences between the AR system and the traditional 2D system. In order to precisely investigate the effectiveness of AR technology, future works could further compare users' behavior between a 3D (VR) system and an AR system.

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