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Effects of a contextualised reflective mechanism-based augmented reality learning model on students' scientific inquiry learning performances, behavioural patterns, and higher order thinking

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ABSTRACT

Augmented reality (AR) can represent a contextualised scientific inquiry environment in which students may explore the real world and develop science process skills via interacting with rich information from virtual systems, such as visualised scientific models, guidance, and feedback. Although AR environments have offered opportunities for facilitating students' inquiry learning, it remains a challenge for most students to complete scientific inquiry tasks without proper support. Research evidence has suggested the potential of engaging students in deep conceptual understanding and construction with reflective scaffolding when applying scientific inquiry. Accordingly, we designed a contextualised reflective mechanism-based AR learning model to assist students in completing scientific inquiry tasks. Guided by the proposed model, we designed four stages of scientific inquiry learning: conceptual understanding, reflective cognition, in-depth inquiry, and knowledge building. A quasi-experiment and lag sequential analysis were conducted by recruiting 81 sixth-grade students to examine the effects of the proposed model on their scientific inquiry learning performances, higher order thinking, and behavioural patterns. The experimental results reveal that the proposed approach improved students' inquiry learning performances and higher order thinking tendency (problem-solving tendency and metacognitive awareness). Moreover, the evidence from this study also suggests that the students who learned with the proposed approach exhibited more observation, comparison, exploration, and reflection behavioural patterns in the field trip than those who learned without the contextualised reflective mechanism. This implies that such an approach could be a good reference for future instructional designs of AR-based scientific inquiry activities.

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Introduction

The science education paradigm has shown a tendency of change from being knowledge-oriented to inquiry-oriented. The importance of scientific inquiry in science education is self-evident and consensual since scientific inquiry has been shown to be highly beneficial in enhancing students' understanding of scientific phenomena, scientific reasoning, investigation, and experimental skills (Mueller et al., 2020; Peten, 2021). Scientific inquiry activities are the closest to real scientists' scientific hands-on doing processes and knowledge construction, which differs from knowledge-oriented scientific learning (Chen, 2020b). However, scholars have addressed the problems in implementing inquiry learning, such as the lack of in-time guidance and feedback in less-structured inquiry, and students' lack of motivation and engagement when they encounter problems (Hwang et al., 2019; Lin et al., 2020). Furthermore, students may be limited by the traditional inquiry activities with clear reproductive steps because they have less opportunity to understand how to solve problems by themselves when conducting scientific practices (Li et al., 2020; Yeh et al., 2019).

Many studies have shown that augmented reality (AR) has the potential to guide students to deal with real-world inquiry learning via interacting with supports and feedback from virtual systems, thus enabling them to promote knowledge understanding, engagement, and motivation when conducting real-world science learning and inquiry activities (Chen, 2020a; Fuchsova & Korenova, 2019; Lo et al., 2021). Furthermore, AR has been applied to assist with abstraction, micro-levelling, modelling, spatial cognition, or complex scientific concept learning, for instance, elastic collision in physics (Crăciun & Bunoiu, 2017; Wang et al., 2014), chemical bonding (Chen & Liu, 2020; Habig, 2020), molecular biology (Fuchsova & Korenova, 2019), and other concepts related to science. To support learners' understanding, the AR-based 3D system could be applied to visualise complex difficult-to-observe natural or scientific phenomena (Chen, 2020b). Lo et al. (2021) created an augmented reality application to engage students in visual, auditory, and tactile experiences for natural science inquiry learning outcomes and motivation. Moreover, it is useful to employ AR in setting up different parameters of the variables to assist the process of testing scientific experimental hypotheses, which can facilitate learners' scientific hands-on doing and in-depth conceptual knowledge in science inquiry activities (Lin et al., 2020; Wu & Wu, 2020). Therefore, these studies have indicated that developing an AR environment could become a favourable way of scientific inquiry to help students understand the nature of scientific concepts by integrating the digital learning content with the contextualised real-world environment. It could also enhance their motivation and engagement by combining human senses with virtual objects to promote active interactions when conducting inquiry practices.

However, without appropriate designs of AR-based scientific inquiry activities, most students might feel frustrated when facing difficulties in AR-embedded science inquiry (Lin et al., 2020; Wu et al., 2018). If there is a lack of thinking scaffolding, students may encounter challenges regarding attention, concentration, overload, and evidence-based explanation building to solve complex tasks in AR-based science inquiry (ChanLin, 2021; Kyza & Georgiou, 2019; Wu et al., 2018). For instance, due to the lack of adequate investigation scaffoldings and weak concentration in understanding narrative texts when inquiry with the AR apps, young students are unable to practise scientific inquiry deeply in order to achieve the expected learning goals (Kyza & Georgiou, 2019). Chen (2020b) argued that if the design is not appropriate, the advantage of using AR technology in scientific learning might be reduced. Accordingly, it is necessary to incorporate appropriate support scaffoldings into the design of how to use AR to reduce the difficulties in scientific inquiry.

Reflective thinking-promoting scaffolding, which could be defined as a reasoning process, has the potential to help learners obtain new understandings in the process of problem-solving with a positive learning experience (Chen et al., 2019). The reflective scaffolding could enhance students' in-depth conceptual understanding and help them overcome difficulties in learning by actively checking their exploration processes, hence helping them to make progress (Chen et al., 2020; Hsia & Hwang, 2020). Furthermore, research evidence has suggested the potential of engaging students in deep conceptual understanding and knowledge construction with reflective scaffoldings when applying scientific learning with AR (Chen, 2020b; Lin et al., 2020). Rohana (2015) employed the context-experience-reflection-action-evaluation reflective reasoning framework in students' practising process to help them connect conceptual understanding with the context, experience, and reflection through guided discussion and interaction, increase their reflection in action to promote action, and evaluate their learning outcomes. Thus, it is reasonable to integrate reflective scaffolding into AR-based scientific inquiry so that students can examine their knowledge gaps and identify their lack of ideas, knowledge, or ability with the aim of broadening their knowledge levels and strengthening their thinking capabilities. The present study refers to the reflective theories (e.g. Rohana (2015) and Lei and Chan's (2018) reflective framework) and strategies proposed by previous researchers to investigate students' scientific inquiry because it combines theories that describe the factors which address the challenges mentioned above and the conditions needed to generate the optimum inquiry. Since the design of how reflective scaffolding integrates into AR-based science learning and its impact on scientific inquiry are still unclear, this study proposes a contextualised reflective mechanism-based AR learning model (i.e. conceptual understanding, reflective cognition, in-depth inquiry, and knowledge building) and assesses its effectiveness in terms of students' scientific inquiry outcomes.

Literature review

Scientific inquiry

Scientific inquiry refers to an active process which supports students' comprehension of the nature of science (i.e. understanding the value of science) and which develops their science process skills like a scientist (Ekici & Erdem, 2020; Wu & Wu, 2020). Science process skills refer to the skills of using scientific methods to design experiments, investigate, collect, and analyse data related to doing science (Sandoval, 2005). The comprehension of the nature of science is to understand the nature of science from the perspectives of scientific characteristics, such as its temporary, creative, and empirical nature, and the role of the scientific community. Scientific inquiry activities emphasise student-centred scientific learning activities (Lin et al., 2020). Learners construct their knowledge concepts related to science after they experience these related scientific inquiry activities, and then establish their understanding of the nature of scientific knowledge (Peten, 2021). These studies indicated that students benefit highly from scientific inquiry, which underlies the production and exploration process of scientific knowledge. Such a process also reflects the common nature of the scientific inquiry, which focuses on helping students grasp evidence-driven reasons to back up their claims in science.

However, studies have pointed out the challenges of carrying out a scientific inquiry in real-world environments (Ekici & Erdem, 2020; Li et al., 2020; Wu & Wu, 2020), including the lack of in-time guidance and feedback in less-structured inquiry, the reproductive inquiry, the inquiry environment's separation from the real world, and students' lack of motivation when applying scientific inquiry (Hwang et al., 2019; Leblebicioglu et al., 2020; Li et al., 2020; Lin et al., 2020). Lin et al. (2020) reported that most students had trouble transforming their preliminary knowledge to solve problems in scientific inquiry field practice. This happened because students might not have had enough in-time guidance and feedback before their problems could be solved. Thus, students tend to suspend the inquiry when they face difficulties in scientific inquiry activities. Researchers have indicated that, without proper support, it could be too complicated for students to complete scientific inquiry tasks, as they require high-order thinking competencies such as making scientific hypotheses, argumentation, and demonstration (e.g. Chang et al., 2015; Lai et al., 2018).

AR-based scientific inquiry and learning

There is an expanding body of literature detailing technology-assisted environments for offering suitable learning supports to overcome the difficulties in scientific inquiry (Antink-Meyer et al., 2016; Mesci et al., 2020). Previous studies have introduced technology-enhanced teacher support for reflection (Land & Zembal-Saul, 2003), computer-supported collaborative argumentation for online synchronisation (Oh & Jonassen, 2007), and the technology acceptance model of AR-based learning according to rational action theory (Lo et al., 2021), and have integrated spherical video-based virtual reality into inquiry-based scientific activities (Wu et al., 2021). Among the various technologies that assist scientific and learning environments, AR could be regarded as an artificial vision technique to present digital information in the physical world for scientific inquiry in real time (Lin et al., 2020). It is helpful to enhance students' understanding of complex phenomena with AR by providing the retention of information (Veretekhina et al., 2020). Therefore, these studies indicate that the AR environment could become a favourable way to help students understand the complex phenomena in scientific inquiry by integrating the digital and interactive learning content with the real-world environment.

It is widely considered that teachers could apply AR to promote learners' scientific inquiry by affording them an authentic context (Lin et al., 2019; Lin et al., 2020). Lo et al. (2021) proposed an effective behavioural model to explain users' new technology acceptance in AR-based scientific inquiry for enhancing students' learning performance, class participation, and motivation with travel tour systems and 3D scenes. Their results revealed that AR is a real-time tool used to combine virtual digital information in the real world for helping users understand abstract concepts and constructing knowledge with the interactive experience. Considering the important role of experiencing these related scientific inquiry activities, researchers use AR to provide an immersive experience for the students, which promotes their deep thinking, thus fostering understanding of the scientific concepts in the learning process (Lin et al., 2020). Elaish et al. (2019) showed that using AR technology could create a virtual AR learning scene and provide a more convenient contextualised teaching environment. The contextualised AR mechanisms can provide a knowledge construction process related to the learning contexts and assist with an in-depth understanding of the nature of scientific knowledge (Lin et al., 2022). Therefore, contextualised AR mechanisms may be embedded in scientific inquiry for solving the scientific inquiry difficulties regarding lacking motivation and the separation between the inquiry environment and the real world.

However, some challenges which hinder the effectiveness of AR-based scientific inquiry for thinking actively and deeply still exist. First, if students do not perceive enough thinking scaffolding, they might feel frustrated and overloaded when facing difficulties in AR-embedded science inquiry (Lin et al., 2020). For instance, Wu et al. (2018) identified the challenges of cognitive overload faced by learners in a conventional AR environment since they should process too much information from both the real world and digital systems to solve complex science tasks. Students were frequently confused due to the superabundant amount of learning materials and tasks while using an AR simulation. Second, students may be unfamiliar with AR-based learning materials and application rules when they lack adequate scaffolding to present AR learning materials for scientific learning (Turan & Atila, 2021). Due to the lack of adequate scaffolding, students might not actively participate in critical reflection during scientific inquiry learning (He et al., 2021), which may reduce the benefits of using AR. However, through critical reflection, students can expand their learning and improve their learning performance (Li et al., 2018). Wu et al. (2018) reported that contextualised AR learning based on mindtool-based thinking scaffoldings could effectively promote students' academic performance, as compared to that of a conventional AR learning system, without increasing their learning burden. Therefore, particularly in the context of AR inquiry for educational purposes, issues related to sufficient pedagogical support for scientific inquiry should be considered more carefully to potentially understand learners' cognitive load (Ibáñez et al., 2020; Wei et al., 2015). Therefore, in this study, reflective scaffolding was proposed as adequate scaffolding to engage students in actively participating in reflective thinking during the scientific inquiry processes.

Reflective mechanism

Reflection refers to the process of evaluating one's performances or behaviours for making a change toward a better direction (Dewey, 1933), which is helpful for in-depth learning activities (Chen et al., 2019; Hsia & Hwang, 2020). Dewey (1933) proposed that reflection is a process of transforming thinking actively into practice to re-examine assumptions, which means a reflective, repeated, serious, and continuous reflection on a problem. Through reflection, students can examine their knowledge gaps and identify their lack of ideas, knowledge, or ability with the aim of broadening their knowledge levels and strengthening their thinking capabilities. More recent evidence shows that the function of reflection could enable learners to build up a new concept from experience (Chen et al., 2019; Lei & Chan, 2018). It has now been suggested from their study that reflection could enrich learners' motivation for in-depth learning, for instance, increasing valuable experience, generating new ideas, changing behaviour, generating new applications, and fulfilling commitments for future activities.

To facilitate students' inquiry and learning, researchers have reported many methods and models of using the reflective mechanism, for instance, the philosophical reflective model (Demissie, 2015); the ecological model with reflection (Leijen et al., 2020); the reflective reasoning framework (Rohan, 2015); the iterative model (Quinton & Smallbone, 2010; Runnel et al., 2013); the 4E × 2 instructional models (Marshall et al., 2009); and the reflective learning model in practice contexts (Davys & Beddoe, 2009). Demissie (2015) indicated that, in the inquiry stimulus of reflective thinking, an approach that prioritises the skills and dispositions for reflection could be vital scaffolding to understand and re-evaluate the expectations and approaches to teaching reflection. He proposed a philosophical reflective mode to promote students' reflective thinking which consists of four approaches: stimulus, question development/voting, discussion, and reflection. Moreover, Rohana (2015) employed the context-experience-reflection-action-evaluation reflective reasoning framework in students' practising process. Context refers to connecting the conceptual understanding process with the real-world context or authentic simulation. Experience and reflection can be regarded as affording more responsibility and autonomy for students through discussion and interaction, which needs teachers' in-time feedback or promoting questions to guide the students. Action refers to students' practice and the growth of reflection in action based on their learning experience. Evaluation means a conclusion about what they have learned and what they would do better through knowledge building. These findings can serve as a reference for the proposed approach of the current study.

Based on these reflection theories, Lei and Chan (2018) further proposed a modified reflective framework by replacing the "evaluation" step with "knowledge building" to emphasise the importance of constructing knowledge when promoting reflection. With the modified reflective framework, the students cooperate to achieve deeper and more types of knowledge building through meta-discourse e-archives, which foster the students' reflective skills and learning outcomes. Drawing on reflection theories and the above-mentioned literature, the current study developed an approach more suitable for AR-scientific inquiry, which may be concluded into similar steps, including contextualised connection for conceptual understanding, experience and reflection for cognition, reflection in action for in-depth inquiry, and evaluation for knowledge building. Accordingly, it has become an essential issue to apply a reflective mechanism-based learning model consisting of four stages (i.e. conceptual understanding, reflective cognition, in-depth inquiry, and knowledge building) as a cycle to address the challenges of conventional AR-based scientific inquiry learning which lacks effective scaffolding for thinking deeply and actively.

Research purposes and questions

Despite the advantages of reflective mechanisms for solving the challenges in AR-based scientific inquiry, to the best of our knowledge, studies about the effects of incorporating reflective mechanisms into AR-based scientific learning are quite rare. For example, although Lin et al. (2020) revealed the important factors in the relationship between perceived technology-assisted teacher support and technology-embedded (e.g. AR and mobile) scientific inquiry, they did not consider reflective scaffolding as a crucial mechanism or test its effects on the AR-based scientific inquiry. In contrast to their findings, this study focused on examining the effects of using a reflective mechanism to address challenges in AR-based scientific inquiry, and provides some recommendations for advancing students' scientific inquiry effect. In addition, unlike Bidarra and Rusman (2017), who just noted AR and reflection as one possible technology and pedagogy among various choices without conducting a practical application, this study incorporated a reflective activity into AR-based activities to further explore the effects of a contextualised reflective mechanism-based augmented reality learning model for promoting a more complex level of inquiry.

To test the students' scientific inquiry learning outcomes, it is important to measure students' learning performances, behavioural patterns, and perceptions of higher order thinking tendencies. In addition to learning performances, if students do not have enough thinking scaffoldings, they may encounter cognitive overload during the AR-based learning process (Wu et al., 2018). Measuring cognitive load is important for assessing whether the design of AR-based inquiry protects students from being overwhelmed and confused in an AR environment due to being overloaded by the AR learning materials (Akayr & Akayr, 2017; Ibáñez et al., 2020). Furthermore, the educational objectives of the scientific inquiry include fostering students' higher order thinking competencies, such as scientific problem solving, proposing hypotheses, and engaging in argumentation and demonstration (e.g. Chang et al., 2015; Wu et al., 2021). Measuring higher order thinking provides a good indicator that reflects the changes in students' higher order cognition after incorporating the reflective mechanism into the AR-based inquiry environment. Furthermore, learners' behavioural patterns of using AR technology are required to help designers know how to adjust their AR-based learning mechanisms (Hou & Keng, 2021). Consequently, the students' scientific inquiry learning performances, cognitive load, behavioural patterns, and higher order thinking were measured to evaluate the effects of a contextualised reflective mechanism-based scientific inquiry learning approach in comparison with the conventional AR-based inquiry approach. This study may provide considerable insights into scientific inquiry supported by AR technology to improve students' scientific inquiry learning effectiveness, which calls into question the following aspects:

(1) Does the contextualised reflective mechanism-based scientific inquiry learning approach enhance students' learning performances?
(2) Do the students learning with the contextualised reflective mechanism-based scientific inquiry learning approach have a lower cognitive load than those learning with the conventional AR scientific inquiry learning approach?
(3) Does the contextualised reflective mechanism-based scientific inquiry learning approach boost the students' higher-order thinking tendency?
(4) What are the differences in behavioural patterns between the contextualised reflective mechanism-based scientific inquiry learning approach and the conventional AR scientific inquiry learning approach?

Development of a contextualised reflective mechanism-based AR scientific inquiry learning environment

This study proposes a contextualised reflective mechanism to promote students' reflective thinking as well as their learning performance and higher order thinking tendency in AR scientific inquiry learning contexts. In this model, learners' inquiry learning process cycles through a contextualised reflective mechanism, which is divided into four stages: conceptual understanding, reflective cognition, in-depth inquiry, and knowledge building (Figure 1). The proposed model aims to promote learners' learning performances, interactions, and tendencies to engage in higher order thinking.

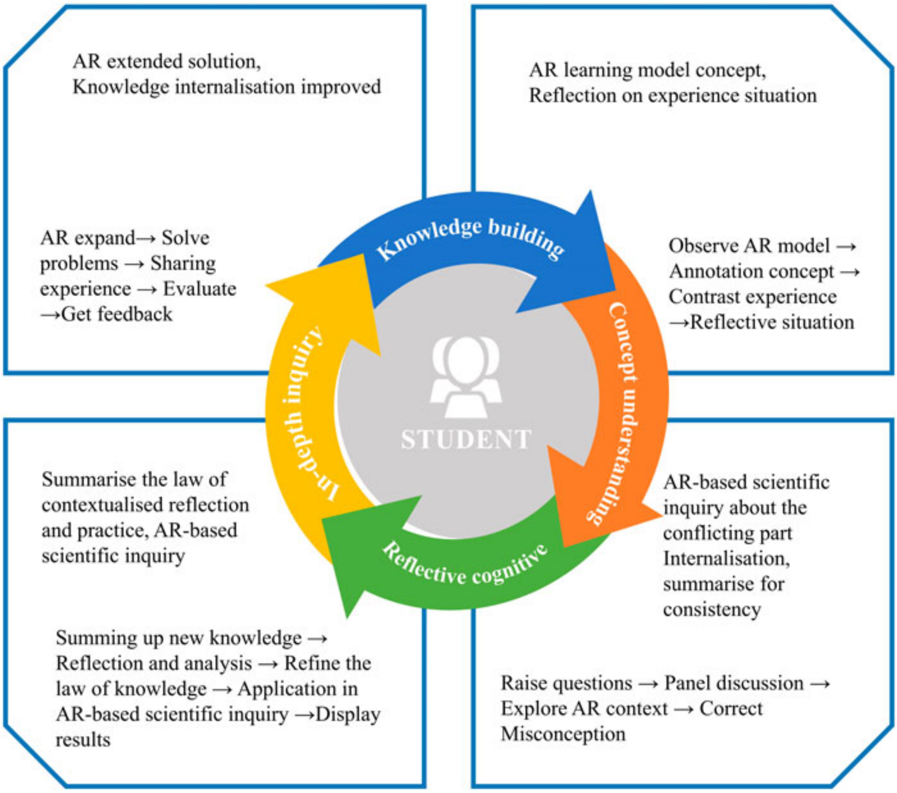

Figure 1. Learning cycle in the contextualised reflective mechanism-based inquiry learning.

(1) Conceptual understanding stage: This stage involves understanding a new concept through the AR model and reflecting upon the experienced situation. In this process, learners first enter the context created by the teacher to acquire the desire to explore knowledge, and then explore the new concept by observing the AR model. They compare this new concept with their own experience to find similarities and differences to understand it.

(2) Reflective cognition stage: Comparing the new and old concepts gives rise to questions, and the AR exploration eliminates contradictions. After comparing the differences, the learners come up with their own doubts. In this phase, the teachers design discussion and exploration activities, and first, let the learners interact through group discussions. Then, when they are situated in the context being explored, they make scientific inquiries using the AR model and integrate opinions of the different groups to understand any errors and misconceptions in their life experience.

(3) In-depth inquiry stage: The learners assimilate the new knowledge acquired in the last stage and rethink the inquiry process. They also analyse the questions raised and solutions found in the inquiry process, and they extract and refine the new knowledge. The teachers guide the students to perform scientific experiments in small groups by setting up a collaborative inquiry context. Teachers not only instruct students to use the newly learned scientific concepts, but also attempt to explain the experimental phenomena using what the students have learned. Ultimately, they explain and reveal their experimental outcomes.

(4) Knowledge building stage: Students improve through continuous problem-solving and internalisation of knowledge. In this stage, teachers use the AR system to let learners understand the knowledge acquired in a real-life context and create contexts to guide students to confront challenges by adopting what they have learned. After learners complete study tasks, the

teachers engage them in a rethinking process via focusing on the entire study process and acquired knowledge and on what they have learned during the learning activity. To achieve satisfaction and promote knowledge building, teachers organise reflection and sharing of the students' summaries to let them express themselves and evaluate their learning performances to provide them with positive learning feedback.

Based on the model, an AR-based inquiry environment named "AR class" was developed. As indicated in Figure 2, it is a system and visualisation technique that mainly offers reflective and inquiry tasks in real-time interactions to achieve accurate 3D objects as well as multimedia controlling modules, and combines test and feedback transferring modules. Therefore, the "AR class" system is equipped with a reflective contextualised AR mechanism and learners' individual learning system. The "AR class" system was implemented throughout the entire scientific inquiry process, including learning observation, investigated verification, and experience comparison.

Figure 3 shows the interface based on pattern markers of AR technology. Students can form a sense of scientific knowledge or problems, and watch 3D or multimedia via the "AR class" system using smartphones. Then, they conduct individual extracurricular authentic inquiry learning and collaborative learning activities. Students also need to explore scientific knowledge or problems in the real world. They are encouraged to take part in inquiry activities, take photos of and take notes on the activities, and upload files that contain photos and words of every scientific inquiry activity to share with the class.

For instance, in the inquiry activity of flower anatomy in the field, students inquired and completed a comparison table supported by reflective scaffolding. The table outlines scaffolding to help students compare the difference in the structures of the flowers in the orchard and those in the field. Through smartphones, students comment on and modify the words that their classmates post in the system. Then teachers may choose topics to enhance students' scientific knowledge building. Students talk about them together in class, developing new ideas or solutions to the problems as they go.

Figure 4 illustrates the procedures adopted, as shown below. The learners first log into the "AR class" system. Thereafter, they gain access to the corresponding AR learning content (i.e. 3D

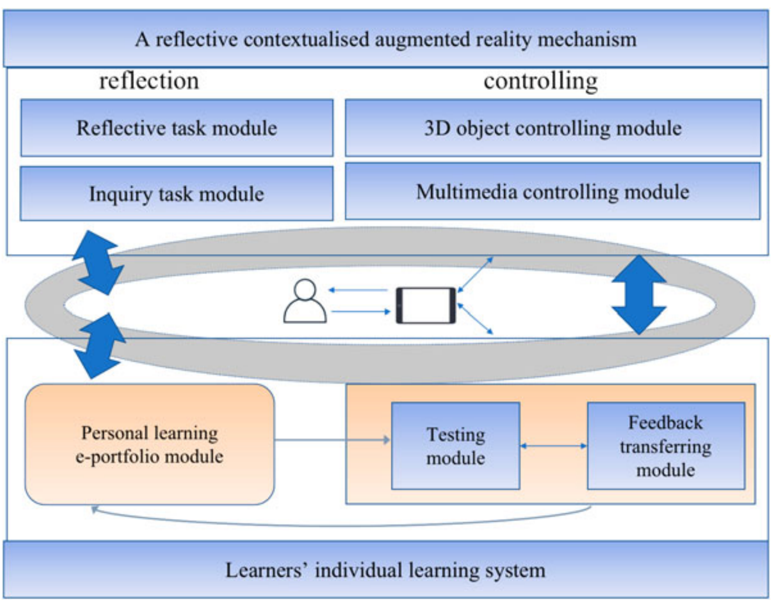

Figure 2. The structure of the "AR class" system.

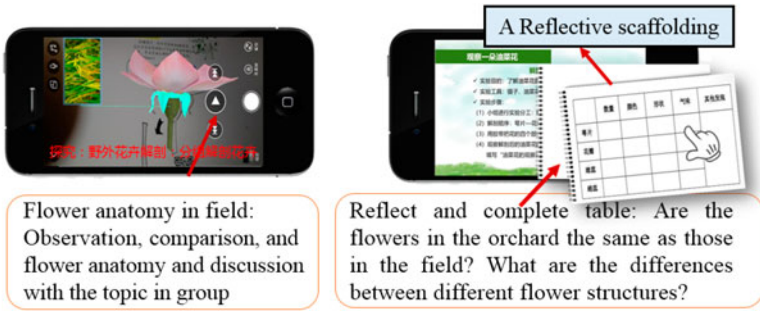

Figure 3. The interface of the contextualised reflective mechanism in the "AR class" system.

controlling objects, video, audio, animation, etc.) on the mobile terminal by scanning the AR marker on the interface. The learners can use the AR learning content to learn new scientific concepts (Figure 4a), explore in-field through the reflective and inquiry task module (Figure 4b), and argue or ask for help through the feedback transferring module (Figure 4b). The learning prompts, such as the mode, time, and guidance of each inquiry activity, are clearly presented in the "AR class" interface, which can be used as auxiliary learning material for scientific inquiry (Figure 3). Learners can also scan the QR code of the expanded reading module after class to obtain online learning resources for expanded reading, reviewing, and consolidation of knowledge (Figure 4c).

Methodology

Participants

This study recruited 81 sixth-grade students from two classes of a primary school in southern China. None of the participants had any prior experience of using AR technology. One class was randomly selected as the experimental group using the proposed approach, and the other class was the control group using the conventional AR-based inquiry approach. The experimental group consisted of 41 students (mean age = 11.25 years, standard deviation = 1.60). The control group consisted of 40 students (mean age = 11.70 years, standard deviation = 0.98). The students in both groups were randomly divided into subgroups, each of which consisted of four to five students. To ensure that all participants had the same AR learning experience, they were required to complete AR-based science courses to be qualified for a series of more advanced courses. Therefore, all participants had previous exposure to AR learning projects, in which mobile devices were used for teaching and learning (i.e. the projects occupying more than one-third of the class time).

Experimental procedure

The primary school science curriculum, "the structure of flowers", was adopted in this study to understand the structure of a plant's flower and the processes from pollination to fruit development. The AR-based scientific inquiry resources with an authentic context provide students with observation tools to help them solve the new scientific problems encountered in learning.

Figure 5 illustrates the experimental procedure. In the first week, all students were trained in the AR-based instruction before the pre-test to use the AR resources to familiarise them with the AR equipment and AR learning resources needed later in the classroom. In the second week, the students had to complete a pre-test and pre-questionnaire. All students were taught by the same teacher, who in turn was guided by an expert science teacher with 16 years of teaching experience and had undergone skills training (20 lessons over 80 h) in the use of AR for science learning.

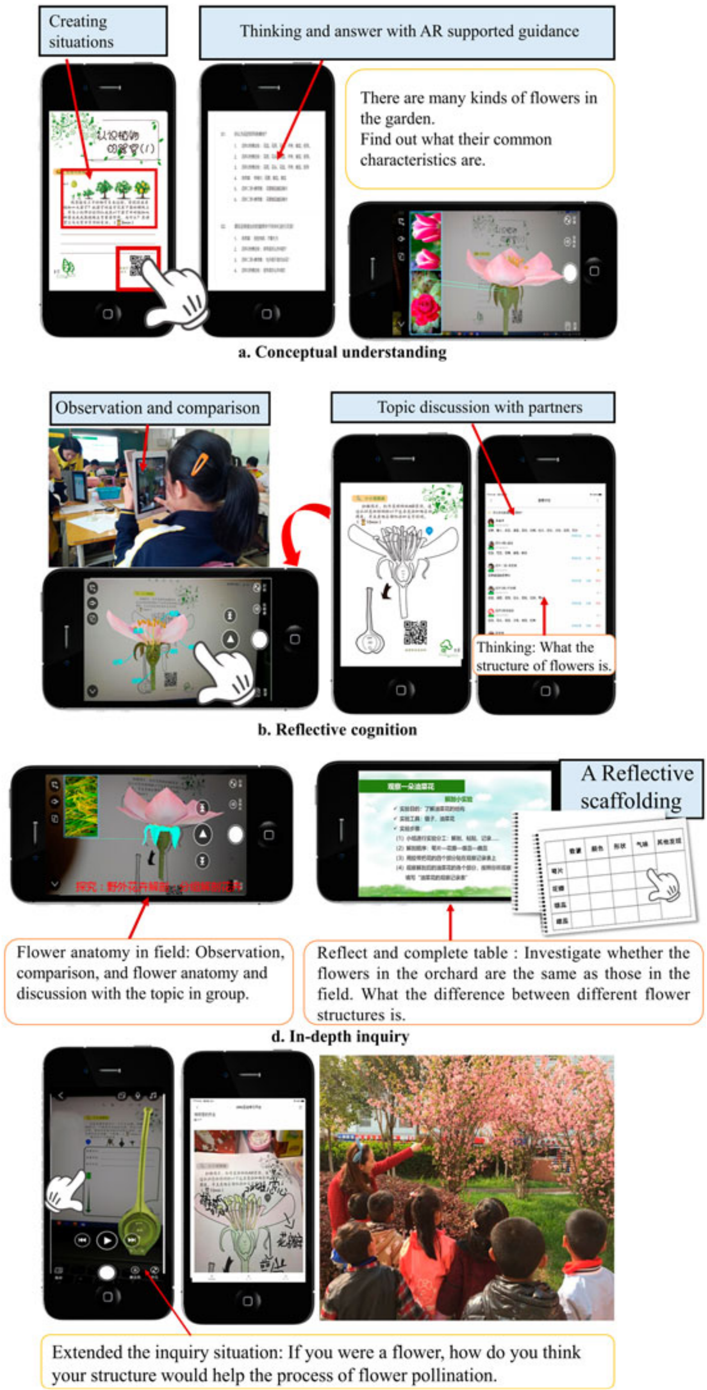

Figure 4. Example and process of the contextualised reflective mechanism "AR class" system.

During face-to-face learning in class, the teacher mainly taught the AR learning materials, learning objects, and key learning content to help the students learn through the "AR class" system. After learning in class, students were assigned to different learning groups to collaborate on the group assignments in a field trip inquiry activity. The two groups of students could communicate freely with the

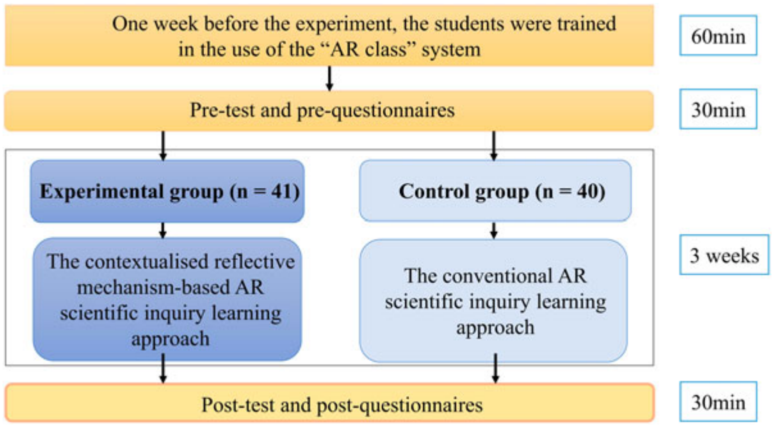

Figure 5. Experimental procedure.

other group and share their findings during the inquiry process. All participants were arranged in the same "AR class" learning system on their smartphone or laptop (as shown in Figure 3).

During the learning stage, all of the students participated in the conceptual understanding class. Compared with the control group, students in the experimental group learned using the contextualised reflective mechanism-based AR scientific inquiry learning approach, while the control group learned using a conventional AR scientific inquiry learning approach. The students in the experimental group inquired in teams and completed a comparison table supported by reflective scaffolding. The teachers provide students with reflective hints about the connection between life situations and conceptual knowledge. Besides, the teachers guided them to find solutions when they had questions. On the other hand, students in the control group participated on a more individual basis in the related inquiry learning. Teachers tended to give them more direct guidance about the inquiry steps. In the classroom, the teacher mainly explained the concept knowledge which appeared in the textbook, following which the teacher instructed the students to use the AR resources to gain a more in-depth understanding and to engage in conceptual learning. The "AR class" system suggested orientations for hands-on activities in the field trip inquiry activities to the control group students.

After the AR learning procedure, the students in both groups were required to complete the post-test and post-questionnaires.

Measurement tools

Pre- and post-test questions

This study used knowledge test performances and questionnaires to examine students' learning performance. The pre- and post-tests contained questions that were validated by three science experts. Both pre- and post-tests included 10 choice items (5 single-choice items and 5 double-choice items). The pre-test aimed to measure the students' prior knowledge of conceptual understanding and common life mistakes. Basically, none of the students had previous scientific concepts or related knowledge. The post-tests were designed to evaluate the students' ultimate learning levels of knowledge, which included three subscales: knowledge conversion, error correction, and life application. The difficulty analysis result showed that the average difficulty mean value for both groups was 0.86. Sample questions appearing in each test are shown below:

(1) Pre-test sample question: What is a flower with both stamens and pistils called?
(2) Post-test sample question: What is the reason for the disappearance of the pale green sepals of the newly opened lilies?

Higher order thinking tendency questionnaire

The questionnaire was modelled after the original students' higher order thinking tendency scale (Lai & Hwang, 2014), which includes three subscales: complex problem-solving tendency (6 items), meta-cognitive awareness (10 items), and creativity tendency (6 items). The questionnaire comprised 22 items that were rated on a 5-point Likert-type scale.

Cognitive load questionnaire

To further explore whether the introduction of AR learning resources in classroom teaching activities would affect students' cognitive loads, cognitive load questionnaires developed by Wang et al. (2018) and Chang et al. (2018) were modelled in this study. This questionnaire comprised 10 items rated on a 5-point Likert-type scale. It was designed to measure students' cognitive load after engaging in AR scientific inquiry learning activities from two dimensions: mental load (5 items) and mental effort (5 items). The pre-test of the cognitive load meant the load that learners experienced when learning the basic science knowledge in the AR-based instruction in the first week.

Coding scheme

The coding scheme of the AR-based scientific inquiry learning behavioural pattern was developed based on the AR class system and the AR features. Hwang et al. (2018) modified the findings of Lin et al.'s (2013) study, which was adopted in this study to obtain a reasonable coding scheme for behavioural pattern analysis. Lag sequential analysis (LSA), which is a method used to understand learners' behavioural patterns in an AR environment (Cheng & Tsai, 2013; Lin et al., 2013; Wang et al., 2014), was conducted to clarify the changes in students' behaviour after incorporating the contextualised reflective mechanism into the AR-based scientific inquiry. To evaluate the effects of the contextualised reflective mechanism-based AR learning model with LSA, all students' learning actions recorded in the portfolio were categorised based on the coding scheme. The final behavioural pattern coding scheme was obtained on the basis of this coding scheme. Both experimental and control groups used the same coding scheme of the AR-based scientific inquiry learning behaviours, learning behaviour codes, and reflection on the procedure. As shown in Table 1, the behavioural pattern coding scheme is divided into 13 dimensions.

Results

Learning performances

Levene's test for equality of variances was conducted, and no violation was observed ($F = 2.54$, $p > .05$). Moreover, the homogeneity of regression slopes between groups was confirmed, indicating

Table 1. Coding scheme.

Behavioural pattern	*code*
Read the learning content	R1
Take personal notes in the system	R2
Scan the AR marker to access more materials	R3
Set inquiry goals	E1
Observe the key phenomena or characteristics in the field	E2
Compare the characteristic	E3
Explore problems in the inquiry task	E4
Give explanations of the phenomenon	E5
Answer the test in the system	Q1
Read the feedback of the test	Q2
Ask a question for learning help	C1
Discuss with peers	C2
Reflect on the procedure	C3

Table 2. The result of the ANCOVA on students' learning performances.

Group	*N*	Mean	*SD*	Adjusted mean	*SE*	*F*	η^2
Experimental group	40	90.79	8.60	89.77	2.39	4.27*	0.360
Control group	41	81.62	8.98	81.00	2.43		

* $p < .05$.

that it was appropriate to employ the analysis of covariance with $F = 2.36$ ($p > .05$). Thus, a one-way analysis of covariance (ANCOVA) was conducted on the post-test by considering the pre-test scores as the covariance. The ANCOVA result is shown in Table 2, in which the adjusted means of the post-test scores were 89.77 for the experimental group and 81 for the control group. In other words, the students in the experimental group showed significantly better performance compared to those in the control group ($F = 4.27$, $p < .05$, $\eta 2 = 0.36$). This implies that the students who learned with the contextualised reflective mechanism-based AR scientific inquiry learning approach showed significantly better learning performances than those learning with the conventional AR scientific inquiry learning approach.

Cognitive load

Before ANCOVA, the homogeneity of variance assumption and the homogeneity of regression coefficients were tested. The Levene's test for equality of variances was not significant ($F = 0.36$, $p > 0.05$). Hence, the homogeneity of variance assumption was not violated. Also, the homogeneity of regression coefficients showed no significance in the homogeneity test result within groups, indicating that ANCOVA analysis could be continued to compare the post-test data of the two groups by excluding the impacts of the pre-test data. As seen in Table 3, the adjusted means and standard error were 90.20 and 9.69 for the experimental group, and 80.50 and 7.16 for the control group. There was a non-significant difference between the two groups ($F = 0.23$, $p > 0.05$, $\eta^2 = 0.002$).

Higher order thinking tendency

Table 4 lists the ANCOVA results of higher order thinking tendency. The Levene' s test for equality of variances and test of homogeneity of regression revealed no significant difference (i.e. $F = 4.09$, $p > 0.05$; $F = 3.59$, $p > 0.05$ respectively). The assumption of homogeneity of regression shows that an ANCOVA analysis could be performed. In the pre-test, the differences of all variables between the experimental and the control groups were not significant. The adjusted means and standard error were 4.03 and 0.47 for the experimental group, and 3.78 and 0.68 for the control group. It was found that the experimental group had better post-test scores of higher order thinking tendency than the control group ($p < 0.05$). Furthermore, the effect size ($\eta 2$) of higher order thinking tendency was 0.068, indicating a medium effect size.

Learning behavioural patterns

By using the coding scheme summarised in Table 1, we coded the teaching process following the principle of recording the behavioural patterns transition once. To investigate the behavioural patterns of the two groups, a series of lag sequential analyses (LSAs) were conducted. As shown in Figure 6, the LSAs revealed several important behavioural patterns which accounted for the learning procedures of the students in the experimental group: E2, E3, E4, and C3. Under the contextualised reflective mechanism-based AR scientific inquiry learning approach, the students tended to observe the key phenomena or characteristics in the field, which would lead to two dominant behavioural patterns: compare the characteristics or give explanations of the phenomenon (E2→E3 and E2→E4). Similarly, the students may compare the characteristic, then explore problems in the

Table 3. The ANCOVA results of cognitive load.

Group	*N*	Mean	*SD*	Adjusted mean	Standard error	*F*	η^2
Experimental group	40	3.66	0.78	3.66	0.75	0.23	0.002
Control group	41	3.49	0.92	3.49	0.89		

inquiry task (E3→ E4), give explanations of the phenomenon (E3→ E5), think and reflect (E3→C3), or ask a question for learning help, which can all lead to discussions with peers.

Compared to the behavioural pattern transition diagrams of the experimental group, those in the control group indicated that the dominant behavioural patterns consisted of answering the test in the system and reading the feedback of the test (Figure 7). The students in the control group could learn via a linear process, which involved reading the learning content, subsequently taking notes in the system, and observing in-field, which may lead to explanations (R1↔R2→E2→E5). Thereafter, they would focus on the test module and ask questions if required (Q1↔Q2→C1→C2↔C3). The thinking and reflection behavioural patterns (C3) are at the end of the behavioural patterns transition diagrams, which revealed that the students in the control group tended to regard thinking and reflection as a task, instead of an approach that could facilitate their inquiry and discussion.

Discussion and conclusions

A contextualised reflective mechanism-based AR scientific inquiry learning approach was employed to incorporate the reflective scaffolding and learning contexts into scientific inquiry. The experimental finding revealed that the contextualised reflective mechanism-based AR scientific inquiry learning approach not only enhanced the students' learning performances but also facilitated their perceptions of problem-solving tendency and meta-cognitive awareness.

Cognitive load

The findings regarding cognitive load are consistent with Crăciun and Bunoiu's (2017) study. Crăciun and Bunoiu (2017) used AR mobile games to study students' interactive behavioural patterns for scientific learning. They found that students actively touched models in the AR learning tools, then explained them to others, and understood the learning content in the software. This could explain why these factors together can effectively reduce the cognitive load and learning burnout in both groups.

Higher order thinking tendency

The findings of higher order thinking tendency in this study confirm the previous findings of Bursali and Yilmaz (2019). They developed an AR Turkish reading application using the Aurasma software, and their findings demonstrated that an experimental group of fifth-grade students showed better persistence and academic scores than a control group. This finding is similar to Chiang et al.'s (2014) study, which showed that an AR-supported learning process could contribute to students' critical thinking inclination and group self-efficacy. Obviously, the students can develop higher order skills as well as improve science performances when they have enough opportunities to situate themselves in and reflect upon the scientific inquiry activities.

Table 4. The ANCOVA results of higher order thinking tendency.

Group	*N*	Mean	*SD*	Adjusted mean	Standard error	*F*	η^2
Experimental group	40	4.11	0.48	4.03	0.47	4.91*	0.068
Control group	41	3.76	0.71	3.78	0.68		

* $p < .05$.

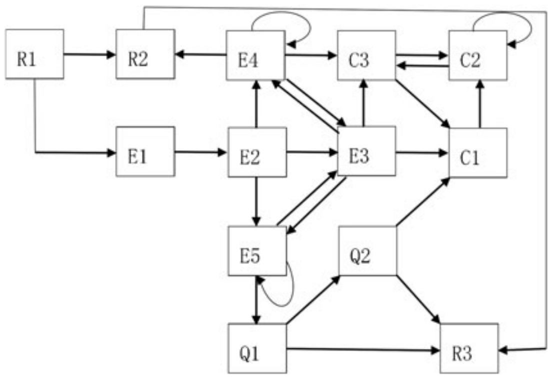

Figure 6. Behavioural patterns transition diagrams of the experimental group.

Behavioural patterns with regard to the contextualised reflective mechanism

Students' behavioural patterns in the two AR-based learning groups were explored through LSAs. The results indicated that under the contextualised reflective mechanism-based AR learning approach, students from the experimental group showed more occurrences of the "observation in the field (E2)", "comparison (E3)", "exploration (E4)", and "reflection (C3)" behavioural patterns. There were two reasons for these diverse frequent behavioural patterns. First, in the reflective cognition stage of the contextualised reflective mechanism-based AR learning approach, students were required to observe different phenomena in the learning materials in the "AR class" system and in real-life contexts. This is consistent with Chiang et al.'s (2014) study, which noted that the AR-enhanced inquiry-based guiding approach could promote students' participation in scientific inquiry. Second, when the students used the "AR class" system as guidance for practice and conducting the scientific inquiry, they tended to observe the phenomena. They then found the differences and mistakes between their previous conceptual learning and the observation, which led to the mistakes being corrected. In addition, the students in the experimental group portrayed the "communicating" behavioural pattern (C1, C2) more frequently than those in the control group. The findings indicated that students in the experimental group focused on field observation and comparison, and paid more attention to asking questions and discussing than those in the control group. In the control group, students were waiting for the answer from their team members instead of actively participating in communication activities.

Further, the results from the LSAs revealed that the proposed contextualised reflective mechanism-based AR scientific inquiry learning approach makes a positive contribution to the students' reflection, meta-cognitive awareness, and problem-solving tendency. The behavioural pattern transitions, C3→R2 and C3→R3 indicated a reflection occurring before students' new knowledge was built. This is in good agreement with Wang et al.'s (2014) finding. They suggested using an AR system to persuade learners to rapidly react to the presented results and facilitate the effectiveness of inquiry learning to engender favourable thinking and meta-cognition. Overall, these findings suggest that the proposed contextualised reflective mechanism-based AR learning model could help improve students' tendency to perform favourable reflection and self-regulated learning during inquiry activities.

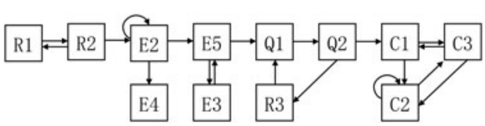

Figure 7. Behavioural patterns transition diagrams of the control group.

In addition to the above similarities, these findings are inconsistent with previous evidence. On the one hand, although Hwang et al. (2018) tested students' behavioural patterns to reveal the effect of an AR-based mobile learning system for helping them learn deeply with positive attitudes, they highlighted the greater importance of teachers' questions, supplementary materials, and hints for promoting active learning in an AR-based mobile learning system. Contradicting Hwang et al. (2018), this study noted that students benefited greatly from the guidance of non-intrusive reflection and AR-based in-time feedback to identify their inquiry gaps for solving difficult scientific inquiry challenges. Furthermore, this study indicated that teachers could provide collaborative interactions with the AR-enhanced inquiry-based guiding approach to creating a cycle of students' behavioural patterns consisting of observation in the field, comparison, exploration, and reflection. Therefore, the students' behavioural patterns could be improved from the single form of surface reflection to the deep reflection regarding the advanced cognitive or problem-solving activities. On the other hand, in contrast to Wang et al.'s (2014) finding that visualising 3D models with AR simulation is more helpful for collaborative scientific inquiry by investigating the students' behavioural patterns, this study found much higher values for comparing the 3D scientific model and supplementary materials with AR and reflective hints to help students find the answers on their own in the AR-based scientific inquiry. Moreover, although the existing research evidence has revealed that the use of AR technology in education could help students be more active in class (Fuchsova & Korenova, 2019), this study found that students benefited greatly from the contextualised reflective mechanism-based AR learning model in terms of improving their positive reflective behaviour in inquiry activities. This study has added value to science education, given the lack of studies discussing the design of how reflective scaffolding integrates into AR-based science inquiry learning by clarifying the most important behavioural patterns with regard to the contextualised reflective mechanism and how the behavioural integration contributes to the development of AR-based science inquiry learning. To solve students' learning difficulties in AR-based science learning, an iterative behavioural sequence should be considered to facilitate students' observation, comparison, exploration, and reflection in AR-based science inquiry learning. However, previous researchers paid more attention to revealing the most important behaviour patterns (e.g. of participating in reflection or peer commenting) for improving students' performance in the AR-based scientific inquiry activities (Chiang et al., 2014). Unlike Chiang et al. (2014), this study highlights the importance of following the integration of behavioural patterns among the three phases of examining knowledge gaps, reflecting in action, and discussing iteration with peers in order. For example, in the first behavioural phase of examining knowledge gaps, students were encouraged to identify their scientific inquiry gap between the existing circumstance and the learning objective with the support of the AR model and reflective guidance. Then, the students could move on to the next phase of reflecting in action to practice their plan for actively addressing their learning gap. After re-checking the reflection gap in action, the students could engage in discussing iteration with peers to eliminate their present contradictions of the scientific inquiries with the support of the AR exploration, and identify new gaps with the help of group interaction. The three phases may help teachers create an iterative cycle of students' behavioural improvement regarding contextualised reflection to address difficulties in AR-based science inquiry learning.

A four-stage model with regard to reflective behavioural patterns

The contextualised reflective mechanism model is more integrated than existing research frameworks. For instance, previous studies have indicated that reflection is hierarchical in that it ranges from the surface level to the deep level in terms of the approaches and depth of reflection (Kember et al., 2000; Looi et al., 2014). Surface reflection refers to a process of a single form of reflection, which is limited to the face-to-face classroom or the internal metacognition of an individual. As suggested by Spector (2017), deep reflection represents an advanced cognitive activity or a set of problem-solving activities, including reflection-in-action, reflection-on-action, and reflection in collaboration and communication. Another framework proposed by Hsia and Hwang (2021) accords with the reflective thinking-promoting approach, which is divided into watch-annotate, summarise-question, discuss-give peer assessment, and reflect-project. The model proposed in this study combines the works of Kember et al. (2000), Looi et al. (2014), and Chen et al. (2019). Based on the findings of the lag sequential analysis and a quasi-experiment, this study updates the four-stage model with diverse reflection behavioural patterns changing from a surface level to a deep level. In terms of the conceptual understanding stage, students might experience individual-oriented learning and reflection for a long period of time. Learners who were engaged in reflective cognition and in-depth inquiry probably explored inquiry tasks, gave explanations, and reflected on their practice with peers. Comparatively, the students might reflect in action and construct new concepts in the knowledge-building stage.

Implications and limitations

The major contribution of this study is that it integrated the contextualised reflective mechanism-based scientific inquiry learning approach with the help of AR technologies, and allowed students to interact with them. Experimental results showed that the proposed approach improved the students' inquiry learning performances and higher order thinking tendency (i.e. complex problem-solving tendency, meta-cognitive awareness, and creativity tendency) with a reduction in cognitive load compared to the control group learning with the conventional AR scientific inquiry learning approach. Compared with traditional science education in a classroom setting, the proposed approach provides the following two crucial reflective stages for conducting a well-designed AR-based scientific inquiry activity. First, combining AR and the guidance of non-intrusive contextualised reflection has great potential for helping students face the difficulties in understanding abstract scientific concepts by associating the 3D supplementary materials with practical tasks rather than merely making imagination with 2D materials. To apply this approach effectively, teachers need to provide non-intrusive guidance and hints, and AR-based 3D scientific models for enabling students to identify the inquiry gaps and to explore the answers on their own. Second, the contextualised reflective mechanism-based AR scientific inquiry learning approach can help students deeply engage in the scientific inquiry activities with positive attitudes by guiding them to participate in reflective cognition. Therefore, teachers should not only encourage students to interact and develop their learning knowledge, but also enable them to learn how to identify and analyse problems, manage their learning plans, and make reflections in the scientific inquiry process. More insight into forming a positive cycle regarding contextualised reflective mechanism-based AR scientific inquiry learning can help students think deeply to identify their knowledge gaps, as well as think actively to find appropriate solutions for overcoming challenges in scientific inquiry practice.

The present study may have some limitations. First, self-reported questionnaires were used to investigate students' meta-cognitive awareness and problem-solving tendency, which referred to students' tendency and conception of the two factors rather than their ability. Second, it is essential to track the proposed approach for a longer period and to conduct relevant experiments to clarify the influence of the approach on higher order skills such as creativity and critical thinking, which are more difficult to acquire in scientific inquiries.

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