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Implementation mechanisms for AR-based inquiry learning through the Lens of motivational design

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Abstract
The application of Augmented Reality (AR) in science learning has gained widespread recognition for its potential benefits. Existing studies highlight the role of teachers as cognitive and emotional facilitators in AR-enhanced learning environments. However, limited research has explored the specific teaching mechanisms that support the effective implementation of AR-based learning activities. This mixed-methods quasi-experimental study examined the use of a self-developed AR-supported inquiry learning app in primary science classrooms, analysed teachers' instructional events in terms of the ARCS model and identified four key implementation mechanisms for optimizing AR-supported inquiry learning through case comparisons. The study provides practical recommendations for AR instructional designers and educators to enhance the integration of AR into teaching practices.

Keywords Augmented reality · ARCS · Motivation · Primary school · Science learning

1 Introduction

Over the past decades, the use of Augmented Reality (AR) applications in education has grown significantly (Arici et al., 2019). Research suggests that AR-based learning environments can improve students' engagement, conceptual understanding, and learning motivation (Fan et al., 2020; Li et al., 2023; Wen et al., 2023). While research highlights the benefits of AR for student learning (Chang et al., 2023), its

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successful implementation in classrooms presents challenges that educators need to carefully consider. Effective AR integration requires not only technological usability and stability but also the appropriation of pedagogical approaches and teaching strategies (Garzón et al., 2020; López-Belmonte et al., 2020; Wen & Looi, 2019). Inquiry-based learning has proven highly effective in enhancing students' learning motivation and outcomes when integrated into AR learning activity design (e.g., Lo et al., 2021; Lin et al., 2023). Also, pedagogical models that provide practical strategies for designing teaching processes and resources, such as Keller's (1987) ARCS model (Attention, Relevance, Confidence, Satisfaction), have been employed to promote learners' motivation and learning outcomes in AR-supported learning environments (e.g., Hao, 2023; Li et al., 2023).

While the design of AR learning environments is essential, teachers often lack the necessary competencies to effectively implement AR activities in their classrooms (Alalwan et al., 2020; Nikou et al., 2023). Prior research indicates that teachers act as both cognitive and emotional facilitators in AR-enhanced learning environments, helping students manage and reduce the extraneous cognitive load introduced by AR's multimodal nature (Chang et al., 2013; Sakiz, 2017). However, little research has examined the prerequisites for teachers or specific instructional mechanisms that support the effective implementation of AR in classrooms.

To address this gap, the present mixed-methods quasi-experimental study investigates the effectiveness of a self-designed AR-based science inquiry learning app in Primary 4 science classrooms. Beyond that, the study aims to identify the real-time instructional mechanisms teachers employed when implementing AR-supported learning activities, and how these mechanisms may affect students' motivation and learning outcomes. Motivation is not static during a learning process. In this approach, not only can the effectiveness of design be assessed, but also its implementation context can be described in detail to better interpret design and implementation mechanisms. The study seeks to provides insights for AR instructional designers and educators, helping to bridge the gap between learning design and classroom implementation. The research questions guiding this investigation are as follows:

1. What are the effects of AR-based inquiry learning activities, guided by ARCS design, on students' academic performance and learning motivation?
2. What implementation mechanisms employed by teachers influence students' learning motivation and academic performance in AR-based inquiry learning?

2 Theoretical farmwork

This study is grounded in Keller's ARCS model (1987). It has been effectively applied to technology-enhanced learning environments, serving the needs of educational research and practice (Ma & Lee, 2021). Motivation has been identified as a crucial factor in learning that affects students' academic achievement and emotion (Shapiro et al., 2017). Thus, motivation is a key element for informing instructional design (Huett et al., 2008). There are also other motivational design models; however, earlier models often concentrate on specific motivational characteristics, such as achievement motivation. In contrast, the ARCS model takes a more holistic approach to designing motivating learning environments.

Keller's model (1987), comprising four components of *attention*, *relevance*, *confidence*, *and satisfaction*, demonstrates a motivational design strategy by first capturing and sustaining learners' attention, while triggering their curiosity. Next, relevance requires learning activities to be aligned with the individual goals and needs of learners for it to be perceived as meaningful. The model also emphasised that learners' confidence can be fostered by their sense of control and their expectations of success, as it impacts the effort they are willing to invest in the activities. Lastly, learners' completion of learning goals will impact their level of satisfaction and cultivate a sense of reward and pride (Li & Keller, 2018). Keller outlined these four major components that need to be present for learners to feel motivated and sustain that motivation.

Studies have shown that the use of AR technology in educational settings can help enhance motivation (e.g. Silva et al., 2023). For instance, as reported in the systematic review by Garzón et al. (2019), motivation was the second most frequently reported benefit of AR use in classrooms. The overlay of 3D virtual elements in a real-world setting provides an immersive quality that captures learners' attention, creating a learning environment that can enhance motivation (Xu et al., 2022). Moreover, the contextualised scenarios provided by AR technology can bridge the gap between the theoretical content and real-world application (Lin et al., 2023). The AR elements can provide authentic learning scenarios which help students see the relevance of their learning. This can engage students further, motivating them through a sense of purpose and meaning. Although a growing number of studies have examined AR learning environments guided by ARCS model (e.g., Hao & Lee, 2021; Laurens-Arredondo, 2022), there is a scarcity of research on teachers' implementation mechanisms or strategies that reflect the ARCS model in AR environments to ensure the effectiveness of design.

3 Methods

3.1 Participants

This study was conducted in three Singapore primary schools on the topic of digestion. It involved Grade 4 students (10–12 years) from 10 classes, along with their science teachers (see Table 1). The duration for the study was for a period of over three weeks. The learning objectives for all the classes were similar, based on the

Table 1 Participants from 3 schools

Schools	AR Class	Non-AR Class
School A	School A_AR1	School A_Con1
	School A_AR2	School A_Con2
School B	School B_AR3	School B_Con3
	School B_AR4	School B_Con3
School C	School C_AR5	Nil
	School C_AR6	Nil

curriculum. However, 6 classes from the 3 schools used the AR app "The Doctor's Digest" to learn about digestion, while 4 control classes from the same schools were taught the same topic using conventional approach without the AR app.

Two case classes were selected for further analysis based on their learning performance. The first class, School A_AR2, was taught by a female teacher with 25 years of teaching experience, while the second class, School B_AR 4 was taught by a male teacher with 10 years of teaching experience. School A_AR2 comprised 35 students (22 girls and 13 boys), and School B_AR4 comprised 33 students (16 girls and 17 boys).

3.2 AR-based learning guided by ARCS design on the topic of digestive system

The app's storyline is designed for students to take on the role of a doctor, tasked with diagnosing and treating patients experiencing various digestive issues. This interactive approach aims to introduce students about the digestive system and related health issues in authentic, real-life scenarios. All the AR learning activities are aligned with their science syllabus. The design of the app activities encourages collaborative problem solving and critical thinking as they attempt the questions and activities in the app. We recommended that teachers assign students to small groups (3 or 4 students per group) to complete tasks collaboratively in class.

The app comprises four activities– "Training simulation", "What happens?", "Case Files" and "Create an alien". Figure 1a shows the interface of the "training simulation" activity, and Fig. 1b shows the students posing with the AR alien that they created in the last activity. "Training simulation" gives an overview of the digestive system, where students have to position the different digestive organs (mouth, gullet, stomach, small intestine, large intestine, anus) correctly, in order to activate a simulation of how digestion occurs. This activity also serves to familiarise students with the AR functions for use in subsequent tasks.

In the "What happens?" activity, students are presented with scenarios such as "*What do you think will happen to the digestive system if the small intestine is too short?*" Students need to apply what they have learnt and give reasons for their expla-

Fig. 1 Students working on the "Training Simulation" and "Create an Alien" activity in groups (**a**) Students exploring the functions of the digestive organs, (**b**) Students posing with the alien they created

nations. The aim is to encourage students to apply their understanding and scientific reasoning skills and to communicate their claims. Teachers can assess these explanations to identify potential misconceptions.

In "Case Files", students diagnose digestive problems based on symptoms presented in fictional patient profiles. They observe simulations of the digestive issues, apply their knowledge, and select the appropriate remedy from a set of options aligned to specific conditions.

The final activity, "Create an Alien", aims to consolidate and provide a synthesis of the digestion concepts. Students are given hypothetical planetary scenarios (e.g., environments with minimal rainfall and restricted diets such as only vegetables) and are asked to design a digestive system suited to the alien's context (e.g., sharp teeth, elongated gullet). This activity encourages the transfer of their knowledge of digestion to imaginative and practical design tasks.

In our design, the *Attention*dimension of the ARCS model is naturally addressed, as the use of AR can spark students' curiosity, enthusiasm, and interest at first instance (Laurens-Arredondo, 2022). Beyond providing 3D animation, we also embedded prediction questions to stimulate students' attention and cognitive engagement. The *Relevance* dimension of the ARCS model is embodied by fostering students' sense of connection with the innovative elements of AR-based content and their own experiences, needs, and preferences. For instance, students have the authority to choose different case files and take on the role of a doctor, solving the problems by linking digestion-related concepts to their real-life experiences. The *Confidence* dimension is supported by providing students with opportunities to collaboratively complete interactive learning tasks within the AR environment. By providing opportunities for students to actively engage in hands-on exploration, and scientific elaborations, the design instils a sense of competence in them. Additionally, a teacher's dashboard, developed alongside the AR app, facilitates real-time monitoring of students'group work progress and performance. This feature not only enables teachers to provide timely guidance and feedback but also empowers students to track and reflect on their group's progress. As such, the dashboard plays a critical role in reinforcing both confidence and satisfaction by providing students with a clearer sense of achievement and areas for improvement. Additionally, the *Satisfaction* dimension is also supported by features such as immediate feedback on multiple-choice questions and options to replay simulation animations when needed. These elements enhance students' sense of accomplishment and promote sustained motivation throughout the learning process.

3.3 Procedure

In the experimental classes, teachers used the AR Doctor's digest app together with the designed worksheets. They also incorporated the worksheets from the Textbook. Each lesson began with a brief introduction to the Digestive system and a demonstration of how to use the AR app. Students then used the iPads to complete the AR activities and worked in groups of three or four. Each AR class took two to three weeks to complete 4 one-hour AR lessons. Figure 2 summarizes the main tasks to be covered in these four lessons.

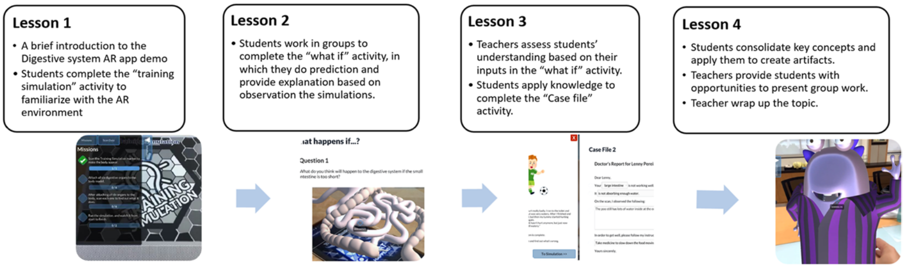

Fig. 2 Learning with the AR Doctor's Digest App

In the control classes, students were taught using traditional teaching methods without the use of AR. Lessons included teacher-led lectures and teacher-led class discussions. Teachers presented the concepts using visual aids such as PowerPoint slides and showed videos to complement their lectures. Both the experimental and control classes completed the same worksheets.

3.4 Data collection

To investigate students' learning performance, pre-and post-tests were administered before and after the intervention. There were three multiple-choice questions (6 marks) and two open-ended questions (6 marks) for the pre-test, with a total score of 12 marks. The two open-ended questions were designed to test students' application of knowledge, rather than fact-recalling questions. They were meant to assess students' ability to transfer and apply what they had learnt to new problems. For the post-test, the questions were different but of a similar difficulty level. Similarly, there were three multiple-choice questions (6 marks) and two open-ended questions (6 marks), with a total score of 12 marks.

To explore students' learning motivation, a motivation survey questionnaire was adapted and rewritten to fit the learning content of this study, based on the measurement scale used by Hao and Lee (2021). The questionnaire consisted of 18 items in total. All the students from the 10 classes were invited to complete both the pre- and post-surveys, as well as the pre- and post-tests. After cleaning the raw data, 287 valid responses were keyed into the SPSS. Some students were absent from either pre- or post-test or survey, so these incomplete cases were excluded.

The reliability of the questionnaire was tested and showed that the questionnaire and its four subscales of attention (Cronbach's $\alpha = 0.91$), relevance (Cronbach's $\alpha = 0.83$), confidence (Cronbach's $\alpha = 0.84$), and satisfaction (Cronbach's $\alpha = 0.91$) were reliable in terms of internal consistency. Then, the data were subjected to a confirmatory factor analysis (CFA) to test the construct validity of responses to the questionnaire. The values of composite reliability (CR) for the four subscales of the questionnaire were acceptable with values greater than 0.7 (Fornell & Larcker, 1981), and the convergent validity (AVE) was acceptable with values greater than 0.5 (Peterson, 2000). A satisfactory model fit was obtained ($\chi 2$ (126) $=256.6$, $p<.001$, CFI $=0.968$, RMSEA $=0.059$, SRMR $=0.032$) (Hair et al., 2010).

To analyse how teachers conducted the AR lessons, we video-recorded all AR classes. During the classroom interventions, the research team set up two video cameras to capture classroom interactions and instructional practices. After the completion of all AR lessons, we conducted post-lesson interviews with teachers and focus-group discussions with students. For the student focus groups, we randomly selected two small groups from each AR class to participate in the discussions.

3.5 Data analysis

The data was analysed in three phases. In the first phase statistical analysis was done to investigate the effect of the AR-based learning approach. In the next phase, the case classes were chosen based on their learning performance, and content analysis was conducted to investigate teachers' instructional events. In the third phase, teachers' and students' post-interviews were analysed to triangulate the findings drawn from the content analysis.

A one-way factorial ANCOVA analysis was conducted to examine the academic differences between the AR and non-AR groups by taking the students' pre-test results as a covariate variable. To understand students' perceptions towards motivational design upon using different teaching approaches, MANCOVA was conducted to examine motivations from four aspects. The pre-survey results served as the covariant to eliminate the differences in students' motivation.

Content analysis was conducted to analyse the instructional events by systematically categorizing code and identification of themes (Hsieh & Shannon, 2005). Content analysis was conducted in the order of (1) identifying all class-level instructional events, (2) finalizing coding categories based on ARCS model and observed instructional events that reflected instructional motivation, (3) coding the class-level instructional events. The coding was done with the Behavioural Observation Research Interactive Software (Boris).

Based on students' learning performance, two case classes were selected to investigate how the teachers implemented the AR lessons. The teacher's class level instructions were first segmented by themes for further analysis. Teachers' discourse within small groups were excluded. The class-level instructions were segmented in terms of different themes, for instance, the instructional events for introducing learning objective, providing feedback etc. The unit of analysis of this study refers to every meaningful teacher-to-class instructional event. The ARCS model was used as a theoretical starting point to guide the development of coding categories. The final categorisation was based on observed instructional events (as shown in Table 2).

According to ARCS model (Keller, 1987), motivating students required that teachers or instructional materials "catch and sustain students' attention". Hence, initiating the topic and introducing the AR-related instructional events were categorised under "attention". Secondly, teachers or instructional materials need to "state why the students need to learn the content", so introducing learning objectives and linkage between the AR app-based activities and the worksheet were included in "relevance". Thirdly, to foster confidence, teachers or instructional materials should "make students believe that they are able to succeed if they exert effort". This category of confidence includes providing details on expectations of activities and role assign-

Table 2 Coding book for observed instructional events

ARCS dimensions	Sub-categories
Attention	A1. Initiating the topic by asking questions
	A2. Introducing AR functions
	A3. Introducing AR activities
Relevance	R1. Introducing learning objectives
	R2. Explaining the linkage between AR tasks and worksheets
Confidence	C1. Providing details on expectations of activities and role assignment
Satisfaction	S1. Providing feedback at task level
	S2. Providing feedback at process level
	S3. Providing feedback at self-regulation level
	S4. Providing feedback at self-level

ment. The final category, satisfaction, emphasised the importance to "help students feel a sense of reward and pride". All feedback-related instructional events were grouped under this category, with feedback messages coded according to Hattie and Timperly's (2007) four levels of feedback. These levels include task feedback, to assess whether the learner has completed the task correctly or has met the required standards; process feedback, to address the steps, methods, or strategies the learner is using, in the process of completing the task; self-regulation feedback, to encourage learners to take control of their own learning process, including monitoring and adjusting their approach; and self-level feedback, to provide feedback on the learner as person.

Although we categorised the detected implementation mechanisms in this manner, it is important to note, as Keller emphasised when proposing the ARCS model, that it is essentially a macro model with interrelated dimensions. Therefore, in our coding book, there was no strict one-to-one correspondence between these sub-categories and the four ARCS categories. Particularly, the dimensions of confidence and satisfaction were closely related, so the feedback-related mechanisms under satisfaction influence students' confidence as well, rather than solely linked to satisfaction. This classification was used primarily to aid in understanding and facilitate coding. After finalising the coding book, the second author helped code the video data in terms of the coding book. To check coding reliability, the first author coded the data separately, and the interrater reliability was over 0.89 (Cohen's kappa). Additionally, students' post-interview data were cited to triangulate the findings of content analysis.

4 Findings

4.1 The effects of the designed AR-based learning environment on students' academic performance

As shown in Table 3, the ANCOVA result showed a nonsignificant result F (2, 280) $=2.53$, $p=.111$, $\eta 2=0.009$, indicating that no differences on academic performance were found between the AR and non-AR approaches. Nevertheless, when we paid attention to the pre-test and post-test performance of each AR class, we found the

Table 3 The one-way ANCOVA result of the academic performance of the two conditions

Group	*N*	Adjusted Mean	Adjusted SD	F	*P*	η2
AR Classes	154	7.35	0.24	2.53	0.112	0.009
Non-AR Classes	133	6.79	0.26			

Table 4 Students' academic performance in each AR class

Class	*N*	Pre-test		Post-test		t	*p*
		Mean	SD	Mean	SD		
School A_AR1	31	4.60	2.01	8.73	1.78	8.33	< 0.001
School A_AR2	34	6.79	3.30	9.79	1.67	5.40	< 0.001
School B_AR3	37	3.27	2.06	6.10	2.91	5.85	< 0.001
School B_AR4	20	2.30	1.45	3.40	2.67	2.05	0.055
School C_AR5	21	4.85	2.48	8.29	2.10	5.93	< 0.001
School C_AR6	26	4.62	1.92	6.27	2.82	2.66	0.014

Table 5 Descriptive findings of students' learning motivation

Motivation Subscales	AR (*n*= 154)		Non-AR (*n*= 133)	
	Mean	SD	Mean	SD
Attention	3.92	0.94	3.67	0.92
Relevance	3.96	0.85	3.93	0.77
Confidence	3.85	0.94	3.73	0.94
Satisfaction	4.13	0.87	4.02	0.82

Table 6 MANCOVA summary of students' motivation

Motivation Subscales	F(1, 281)	*P* Value	Partial η2
Attention	5.38	0.021	0.019
Relevance	0.07	0.79	0.000
Confidence	0.56	0.46	0.002
Satisfaction	0.73	0.38	0.003

class's performance were diverse (see Table 4). In this study, we selected AR2 and AR4 classes as case classes as their post-test scores were the highest and lowest respectively after the intervention.

4.2 The effects of the designed AR-based learning environment on students' learning motivation

The group means on attention, relevance, confidence, and satisfaction are shown in Table 5. The Levene's tests of equality of error variances were not significant, indicating that the assumption of equal error variance of the dependent variables across groups was met. The multivariate result for the effect of the AR approach showed statistical significance, $F(4, 278) = 2.94$, $p = .021$, $\eta 2 = 0.041$, indicating that students from the AR classes showed higher learning motivation compared to those from the non-AR classes. Univariate tests showed an effect of the AR approach on students' attention perception, $F(1, 281) = 5.38$, $p = .021$, $\eta 2 = 0.019$ (see Table 6). Students in the AR classes reported to have higher attention perception than those in the non-AR classes (p<.05). However, the AR approach did not impact on students' perceptions of relevance, confidence, and satisfaction significantly.

In the post-interview, students from the AR groups all shared that they were particularly drawn to the realistic simulations and interactive elements in the AR app. These features likely captured their attention more effectively than traditional teaching methods due to their immersive and hands-on qualities, allowing students to explore and manipulate the content independently rather than merely observing a teacher's demonstration.

We further examined the learning motivation data from the two case classes and observed improvements across all three motivation subscales, except for "relevance", in the AR2 class (see Table 7). However, no improvements were detected in the AR4 class, in which students' pre- and post-test scores had no significant improvement.

4.3 Observed implementation mechanisms in the case classes

Based on the results of the content analysis, we compared the teachers' instructional events during the enactment of AR lessons (see Table 8). A notable difference was observed in the approach taken by the teacher of the AR2 class, who engaged students in the digestive system topic at the beginning of all activities by asking questions (14 min 42 s). Aligned with inquiry-based learning, this strategy effectively sparked students' interest and prompted them to generate their own set of questions related to the topic. As the teacher of AR2 class mentioned in the post interview, "we will still need to have questioning, we will still need to have worksheets, we will still need to have questions based on it to see whether they're assimilated what they have learnt." Teacher AR2 also highlighted the importance of providing students' opportunities to question. She said,

> They (students) will also have to make sure that they question enough. Because the AR itself, they learn, but it's the question that brings out whether they actually understand.

Regarding attracting students' attention, another key difference was that the AR2 teacher spent time thoroughly explaining the AR app features, including the user interface and the function of buttons (8 min 26 s), rather than only explaining the design of AR activities (6 min).

Table 7 Descriptive findings of students' learning motivation about the two cases

Motivation Subscales	School A_AR2		School B_AR4	
	Pre	Post	Pre	Post
Attention	4.04 (0.68)	4.35 (0.62)	3.75 (0.67)	3.48 (1.10)
Relevance	4.46 (0.45)	4.44 (0.53)	3.78 (0.62)	3.53(0.87)
Confidence	3.93 (0.80)	4.23 (0.73)	3.73 (0.67)	3.45 (1.03)
Satisfaction	4.51 (0.43)	4.65 (0.47)	4.03(0.65)	3.68(0.83)

Table 8 A comparison of used strategies for promoting students' learning motivation in the two case classes

ARCS dimensions	Observed Strategies of Enactment	School A_AR2		School B_AR4	
		f	Length (mm: ss)	*f*	Length (mm: ss)
Attention	A1. Initiating the topic by asking questions	1	14:42	0	0
	A2. Introducing AR functions	4	8:26	5	5:16
	A3. Introducing AR activities	4	6:00	8	13:51
Relevance	R1. Introducing learning objectives	2	1:28	3	6:26
	R2. Explaining the link between AR tasks and worksheets	6	4:19	2	3:32
Confidence	C1. Providing details on expectations of activities and role assignment	2	0:18	0	0
Satisfaction	S1. Providing feedback at task level	30	19:25	35	29:58
	S2. Providing feedback at process level	24	26:32	8	06:00
	S3. Providing feedback at self-regulation level	8	05:00	3	01:40
	S4. Providing feedback at self-level	7	00:51	6	02:12

Regarding relevance, the AR2 teacher did not repeatedly highlight learning objectives, (1 min 28 s), as compared to the AR4 teacher (6 min 26 s). However, both teachers reminded students of the connection between AR app activities and the worksheet.

During the activities, the AR2 teacher occasionally encouraged students to collaborate with one another (18 s). There was a notable difference between AR2 and AR4 teachers in terms of their feedback-related instructions. The AR2 teacher spent much more time providing process level feedback, guiding students to deepen their understanding. She organised and projected each group's responses and commented on the completeness of their answers, thereby promoting a better understanding and application of the targeted concepts. However, because such summarisation took time, she did not provide this feedback at the end of each lesson, but at the beginning of the following AR lesson, to address issues identified based on students' inputs.

In contrast, this approach was less observed in the AR4 class. The AR4 teacher tended to provide process level feedback at the end of each activity. As he mentioned in the post-review, due to "the lack of time, you do not see me consolidating their learning, because I just wanted them to explore. To find out things on their own." Meanwhile, the AR4 teacher used the dashboard more frequently to monitor the progress of groups during the activities and provided task level feedback (29 min 58 s). He occasionally praised faster groups and reminded slower groups to catch up, helping them when necessary. In the post interview, he also said "The dashboard overview, I thought it was good. It allows me to track their progress. It allows me to know where they are, and at the same time I also get to see. I won't say in detail, but I know which part they're stuck in, and it allows me to go to them personally to see what is wrong."

The AR2 teacher, however, did not intentionally praise specific groups for their progress, but praised the performance of the whole class. Instead, as compared to the AR4 teacher, she spent more time on providing feedback that helped students to develop self-evaluation skills. For example, she said "Yes, very good. You have got the exact definition, it's complete. Those of you who are still not sure about digestion, please make sure you know. Not only does it consist of breaking down food, but absorption is needed as well". In addition, during AR activities, the AR2 teacher chose not to project her teacher dashboard onto the screen for students, contrary to our suggestion. She explained that her students were typically highly engaged in learning activities, and projecting group progress might increase their competitiveness unnecessarily.

The interview data from the two classes also highlighted obvious differences in their experiences during the AR lessons. These differences were mainly reflected in two aspects: (1) familiarity with the AR app and (2) students' reflection on their group collaboration. However, students from both classes were highly consistent in their responses regarding whether the AR activities were engaging compared to teacher-led lessons. They all agreed that the visualisation and hands-on approach were more interesting.

Students in the AR4 class mentioned that they sometimes struggled with operating the app and expressed dissatisfaction with their group's performance during the activities. For instance, students from AR4 Group 7 shared that they faced challenges during the first AR lesson. Although the teacher showed them how to use the AR app, they still did not fully understand it until the second AR lesson, when the teacher used the PowerPoint slides to guide them and explain the functions. AR4 Group 2 students noted that while the teacher's explanation helped them understand how to carry out the AR activities, their bigger challenge was not knowing how to collaborate. This hindered the smooth progress of their activities, making the experience less enjoyable. AR4_G2S3 said, "The first activity was quite fun until everyone started to get angry and didn't get along with each other." AR4_G2S1 added, "in our training simulation (the first activity), everyone started going out of control. We have no teamwork." AR4_G2S3 further explained, "Everyone got different answers. We don't know who has the correct answer, the problem is still a problem and then we don't know what to do, how are we supposed to know."

Regarding the usefulness of the dashboard, AR4 Group 2 mentioned that, initially, they paid attention to the progress as indicated by the dashboard and noticed that their team was working somewhat slowly. After a few AR lessons, they noticed that other groups had improved while their own performance stagnated, which left them feeling frustrated.

In contrast, when asked their feedback on group work. AR2_G3S1 commented, it was "quite good, we build team bonding. It was quite difficult to handle the iPad and the pieces of paper together so in a group it would be easier". When asked how they resolved differences in opinions, they responded, "… just try out both ways and see which one is more correct." AR2 Group 4 students also agreed that working in a group helped them learn better.

These differing responses were largely shaped by students' familiarity with collaborative learning and self-directed exploration. As the AR 4 teacher reflected in the post-interview, this AR-based inquiry approach was significantly different from his usual approach. After the intervention, he reflected on the need for substantial adjustments in instruction in the AR class. He said:

> "Because it's not something that I'm used to. And at the same time, I have never done that, so there were a lot of adjustments made along the way—like the way I gave my instructions, the way I got their attention. I paused and tried to insert learning moments here and there. I definitely changed how I structured my lessons and the kind of routine we had. To be honest, they (students) were also not very familiar with that routine. It was something new, so it took time. We spent a lot more time in the beginning, but later, we benefited once everything was in place. So, the greatest change—the greatest impact on my teaching—was in the way I gave my instructions, how I structured my lessons, and how I guided my students."

5 Discussion

There was no significant difference in academic performance between AR and non-AR classes across the 10 classes analysed. However, from the perspective of learning motivation, AR classes showed significant improvement in the attention dimension. In some AR classes, both students' learning motivation and academic performance showed significant improvement, attributed to the effective use of AR. Our data suggest that these outcomes are closely related to how teachers implemented AR activities. Based on the results from the comparative cases, we identified four implementation mechanisms that support students' learning motivation and academic performance in the AR-supported inquiry learning class: (1) explicitly introducing AR functions at the start of lessons, rather than letting students discover them during task completion; (2) tailoring feedback on regulation based on students' readiness to pedagogical approaches; (3) providing process-level feedback beyond task-level feedback; (4) leveraging AR learning data to drive a new cycle of inquiry.

5.1 Explicitly introduce AR functions at the start of lessons

When introducing AR apps into the class, especially for the first time, it is essential to allocate sufficient time to explain their features comprehensively. The findings of this study suggest that AR with 3D simulations can naturally capture students' attention and boost their motivation. However, the novelty effect may diminish when students encounter challenges in continuing the activities. Classroom implementation data from AR4 Class and corresponding student feedback indicate that when the teacher did not spend sufficient time introducing the AR app functions at the beginning, it can lead to a certain level of frustration among students. The unfamiliar learning environment can result in increased cognitive load, which may reduce engagement and interaction (Nadolny, 2017). As Wu et al. (2018) also pointed out, students often face cognitive overload in AR environments, because they need to process information from both the real world and digital system to solve complex science tasks. Therefore, unlike other technology-supported learning environments, where teachers may choose to let students self-explore to maintain a high level of engagement, AR-based learning requires teachers to prioritise explaining AR functions before students begin the learning activities.

5.2 Tailor feedback on regulation based on students' readiness to pedagogical approaches

Feedback during AR activities should consider students' readiness for the pedagogical approach. In our study, classes that showed less academic improvement also demonstrated deficiencies in collaborative learning skills. Projecting dashboards to students may help them to monitor and reflect on their group work progress. Nevertheless, teachers should clearly articulate their expectations and support students accordingly, if it is unfamiliar to their students. Socially shared regulation of learning is critical for students' collaborative learning engagement (Järvelä et al., 2020), and affects their cognitive, motivational, and emotional states (Edwards et al., 2024). Furthermore, as Panadero and Lipnevich (2022) asserted in their study, feedback on the self-level was not as beneficial for learning and motivation as feedback on self-regulation. Teachers' feedback should be provided beyond parsing individual group's progress or reminding students to keep monitoring their group progress. Teachers should spend additional time guiding students to self-reflect on their own learning. More importantly, they should spend time coordinating group progress, guiding students to negotiate with one another and reach a consensus, especially if their students are not yet ready for collaborative learning.

5.3 Provide process level feedback beyond task-level feedback

Panadero and Lipnevich's study (2022) emphasise the importance of task-level feedback and process-level feedback for students' learning and motivation. However, the findings of this study suggest that greater emphasis should be placed on process-level feedback in AR-supported lessons. Task-level feedback focuses on correctness and may include guidance on obtaining additional or accurate knowledge (Hattie & Timperly, 2007). In AR environments, such feedback is often automated through system responses. Once students become familiar with the system and develop collaboration skills, they may not necessarily need to obtain additional information from teachers. In contrast, process-level feedback is arguably more effective for promoting deeper learning (Hattie & Gan, 2011). It focuses on guiding students in improving their understanding and approach and serves as a cue to detect errors (Hattie & Timperly, 2007). Teachers should place greater emphasis on this type of feedback in the AR learning environment.

5.4 Leverage AR learning data to drive inquiry cycles

In AR-supported classes, teachers need to use students' cognitive learning data from AR activities to identify students' knowledge gaps, misconceptions, or emerging ideas to foster a new cycle of inquiry, so as to improve student' satisfaction with learning effectively. This finding aligns with the motivational AR-based learning approach proposed in Li et al.'s study (2023), which highlights the importance of discussion between teachers and students in fostering students a sense of accomplishment and satisfaction. Carless and Winstone (2023) also underscore the importance of avoiding delays in providing post-task feedback. However, this does not imply that such feedback must be provided within the same lesson. As ICT tools often record students' inputs, teachers can provide tailored feedback in subsequent sessions based on individual and group performance.

It is worth noticing that the AR system mentioned in this paper includes a corresponding dashboard for teachers to monitor group activity progress and record students' learning data. However, integrating a teachers' dashboard is not common in the AR environment. In other similar AR cases, teachers can place emphasis on the use of paper worksheets which also serve a purpose for recording students' inputs based on their AR environment observation and interaction. No matter the means used to collect students' understanding of knowledge or their misunderstandings, integrating AR apps into classroom teaching requires teachers to allocate sufficient time for students to complete activities and deepen discussion to ensure its effectiveness.

6 Conclusion

This study confirmed the positive impact of the AR-based learning approach, guided by the ARCS design, on students' academic performance and learning motivation in primary science classes. Beyond the design, this study highlighted the pivotal role of teachers in the implementation process and identified four key mechanisms to enhance student motivation and conceptual understandings. It is worth noting that though these implementation mechanisms were proposed specifically based on AR-supported inquiry learning, they may have a certain level of generality. These mechanisms provide guidance not only for AR classes but also for the integration of other emerging technologies into classrooms more broadly. Additionally, regarding to the research methods, the coding book for teacher instructional events, derived from the ARCS model, offers insights for assessing the effectiveness of ARCS-based classroom activity implementation.

The study also has limitations. The most significant limitation lies in the need to account for differences in class contexts. The mechanisms we identified are based on two comparative cases. However, the students of these classes differed notably in their academic performance levels and familiarity with collaborative learning before the intervention. The intent of this comparison is not to evaluate teachers' enactment but uncover potentially effective approaches and shed light on challenges that can be addressed. Future research could take class contexts into account to further validate and refine these mechanisms.

Also, all discussions related to implementation should be based on the affordances of tools. The discussion on implementation, in this paper, is grounded in the technological, pedagogical, and social affordances of the AR system we designed. For instance, features such as teacher dashboards, embedded prediction questions to trigger inquiry, and case files for scenario-based problem solving were central to the effectiveness of our design. However, not all available AR tools provide such features. When applying other AR tools in classrooms or using AR tools in different subject teaching, the implementation mechanisms that need to be emphasised may vary.

In addition, large-scale or long-term implementations may face further challenges. Variations in teachers' technological readiness, school infrastructure, and curriculum alignment could affect fidelity of implementation as well. These factors present potential challenges to scalability or sustainability of AR-based inquiry learning and should be further examined across diverse educational settings and over extended periods in future research.

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Data availability The data that support the findings of this study are not publicly available due to privacy or ethical restrictions. NTU Research Data Policy requires to retain research data for a minimum of 10 years. The data will be retained and/or shared for reuse by others after the completion of the research project in https://researchdata.nie.edu.sg.

Declarations

Consent to participate Written informed consent was obtained from all individual participants/their parents.

Consent to publish The project has research ethics approval from the Institutional Review Board of Nanyang Technological University. The NTU IRB reference number for this study is IRB-2022-849. The author affirms that all participants provided informed consent for the publication of the images.

Conflict of interest The author declares that she has no conflict of interest.

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