Journal of Research in Science Teaching

WILEY

RESEARCH ARTICLE

Teacher Support in Augmented Reality-Enhanced Science Inquiry Learning in Primary Classrooms

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Received: 7 April 2025 | **Revised:** 25 March 2026 | **Accepted:** 6 April 2026

Keywords: augmented reality | inquiry-based learning | primary school | science self-efficacy | teacher support

ABSTRACT

Augmented reality (AR) is increasingly integrated into science education, yet the role of teacher support in fostering students' self-efficacy within AR-based inquiry learning remains underexplored. This mixed-methods study investigated the effects of the AR-based inquiry learning activities on students' science self-efficacy in various dimensions, as well as the impact of teacher support and students' attitudes toward the features of the designed AR learning environment on students' science self-efficacy. The study involved 114 Grade 5 students from four classes of a primary school in Singapore. The results showed that the use of AR significantly improved students' conceptual understanding and science communication self-efficacy. Teachers' emotional support played a key role in conceptual understanding and practical work self-efficacy, while instrumental support was particularly influential in everyday application. Both forms of teacher support significantly contributed to science communication self-efficacy. Additionally, students' attitudes toward the AR features partially mediated the effect of emotional support on conceptual understanding self-efficacy. These findings provide insights for both researchers and practitioners into the importance of and design consideration for adaptive teacher support in optimizing AR-based science learning in primary school classrooms.

1 | Introduction

In recent decades, augmented reality (AR) has become increasingly integrated into educational settings, offering new opportunities to improve students' engagement, conceptual understanding (CU), and motivation (Wen et al. 2023; Fan et al. 2020). AR is defined as the blending of reality and virtuality, offering interactive and immersive educational experiences (Akçayır and Akçayır 2017). In science education, for example, AR allows students to virtually simulate plant reproduction mechanisms and construct 3D hybrid plants to explore biological processes in a more visual and interactive manner (Wen et al. 2023). Although AR technology can provide immersive learning experiences, it does not guarantee student learning success. The importance of integration of AR and well-structured pedagogical approaches has been widely acknowledged (Garzón et al. 2020; Manna 2023). Meanwhile, prior research suggests that teachers act as cognitive and emotional facilitators in AR-enhanced learning environments. Teachers can help students manage extraneous cognitive load by providing instructional guidance in scientific inquiry and facilitating problem-solving within AR-based activities (Sakiz 2017; Cai et al. 2021).

Scientific inquiry is understood as a process engaging learners in designing investigations, collecting and analyzing data, and drawing evidence-based conclusions (Lin et al. 2023). When integrated with AR, these inquiry processes form an AR-supported inquiry learning environment where students engage in scientific exploration supported by AR's dynamic visualizations, interactive simulations, and contextualized feedback (Wen et al. 2024). In AR-based learning, teacher guidance strategies such as encouraging active exploration of virtual content (AlNajdi 2022), providing scaffolded explanations, clarifying misconceptions (Aldeeb et al. 2024), fostering reflection, and offering structured instructional facilitation (Manna 2023) have been found to significantly impact student learning outcomes.

Despite these insights, the mechanisms by which teacher support impacts self-efficacy in AR-based science learning remain unclear. Self-efficacy is defined as an individual's belief in their ability to successfully complete a task (Bandura 1977). It is a critical factor that influences students' motivation, persistence, and academic achievement (Schunk and DiBenedetto 2021). Existing studies have highlighted the potential of AR environments to enhance self-efficacy by providing immersive, interactive, and scaffolded learning experiences that reduce cognitive load and increase engagement. Studies also found that AR fosters self-efficacy by enabling students to visualize abstract concepts in 3D, manipulate virtual models, and receive real-time feedback, all of which contribute to a greater sense of competence and confidence in their learning abilities (Aldeeb et al. 2024; Lin et al. 2023).

Previous studies have proved that AR's immersive and interactive features benefit students' self-efficacy across different learning activities and instructional contexts (Vanneste et al. 2024). However, less attention has been given to the instructional factors that shape these effects. Specifically, how teacher support interacts with AR learning environment features (e.g., system's visual, interface design, and interaction elements) to influence self-efficacy in science education remains underexplored (Hao and Lee 2021). Therefore, this study aims to examine the effect of teacher support on primary school students' self-efficacy in AR-based science learning and further explore whether the AR features moderate the effect. The study provides insights into optimizing AR-based instructional strategies and classroom implementation in science education.

2 | Literature Review

This section reviews research on self-efficacy in science learning to provide concept foundations for assessing students' beliefs and confidence in performing science-related tasks. It also examines the role of teacher support, highlighting how different forms of support influence students' confidence and engagement. Additionally, it discusses the impact of AR features, such as 3D simulations, interface design, and operational affordances, on students' self-efficacy by shaping their perceptions of learning capabilities. By integrating these perspectives, this review offers a comprehensive framework for investigating the interplay among teacher support, AR features, and students' science self-efficacy.

2.1 | Self-Efficacy in Science Learning

Self-efficacy, originally conceptualized within Bandura's (1977) social cognitive theory, refers to an individual's belief in their ability to successfully perform a specific task. Within educational contexts, self-efficacy plays a fundamental role in influencing students' motivation, engagement, and academic performance (Chong et al. 2018; Martin et al. 2019). Researchers have emphasized that self-efficacy should be assessed as a multidimensional construct, as students' confidence varies depending on the nature of the task and the learning environment (Bandura 2006; Zimmerman 2000). In science education, self-efficacy has been extensively studied across various disciplines, such as chemistry, biology, and mathematics (Uzuntiryaki and Capa Aydin 2009; Aldeeb et al. 2024). Several existing frameworks have been developed to measure self-efficacy in specific scientific domains. For instance, Uzuntiryaki and Capa Aydin (2009) developed the chemistry self-efficacy scale. Martin et al. (2019) classified science self-efficacy into two primary dimensions: students' understanding of science concepts and their ability to perform well in science-related tasks. Britner and Pajares' (2006) framework examined the sources of science self-efficacy in four factors: mastery experiences, vicarious experiences, social persuasions, and physiological states (Britner and Pajares 2006). Yet these frameworks are limited in that they primarily focus on either subject-specific self-efficacy or the sources of self-efficacy beliefs rather than measuring self-efficacy across different dimensions of science learning itself.

A robust framework for assessing science learning self-efficacy must encompass multiple dimensions that reflect students' confidence in engaging with science in diverse contexts. Lin et al. (2013) identified four key dimensions that collectively capture the science learning self-efficacy as *CU*, *practical work (PW)*, *everyday application (EA)*, and *science communication (SC)* and higher-order cognitive skills (Lin et al. 2013). It is a more holistic and contextually relevant framework that captures science self-efficacy. However, distinguishing between CU and higher-order cognitive skills can be challenging for some students. Prior research suggested that these two factors function as a unified cognitive construct that supports self-efficacy in knowledge development, problem-solving, and reasoning (Wang et al. 2018).

Given this overlap, the present study adopts four dimensions, excluding higher-order cognitive skills, to ensure conceptual and measurement clarity. CU represents students' confidence in grasping abstract scientific concepts and employing higher-order cognitive skills such as analysis, evaluation, and synthesis. This dimension is fundamental to science learning, as a strong conceptual foundation enables students to construct meaning and integrate new information with prior knowledge. PW reflects students' self-efficacy in conducting experiments, manipulating scientific tools, making empirical observations, and engaging in scientific reasoning. EA captures students' belief in their ability to apply scientific knowledge to real-world contexts. SC measures students' self-efficacy in articulating, debating, and presenting scientific ideas. Effective science learning necessitates the ability to communicate findings, engage in scientific discourse, and justify arguments based on evidence. Given that AR enhances conceptual visualization, interactive experimentation, real-world application, and communication with others, measuring self-efficacy across these four domains provides a comprehensive perspective on understanding how students perceive their competence in science learning (Chang et al. 2023; Lin et al. 2023).

2.2 | Teacher Support and Its Impact on Self-Efficacy

Teacher support refers to the extent to which students perceive their teachers as valuing them and actively fostering personal relationships to enhance both their academic success and overall well-being (Patrick et al. 2007; Lin et al. 2020; Shao et al. 2025). It reflects a nurturing relationship characterized by care, assistance, affirmation, and encouragement, all of which contribute to students' engagement and persistence in learning (Wang et al. 2024). Teacher support includes professional skill guidance and practical assistance grounded in pedagogical expertise, aiming to facilitate students' holistic development. This dimension of teacher support highlights the role of teachers not only as knowledge providers but also as facilitators who equip students with the necessary cognitive and practical skills to navigate complex learning tasks. Beyond providing academic guidance, teacher support extends to emotional reassurance, creating a psychologically safe and conducive learning environment that promotes students' confidence and willingness to take intellectual risks (Shen et al. 2024).

Teacher support plays a pivotal role in shaping students' self-efficacy, fostering both academic motivation and engagement. Various forms of teacher support have been extensively studied in different educational contexts, demonstrating significant effects on students' confidence and ability to navigate complex learning environments, particularly those integrating technology-enhanced learning tools (Wang et al. 2022). Self-efficacy may also serve as a critical variable in the relationship between teacher support and academic performance. Researchers have reinforced the idea that students who feel supported by their teachers are more likely to persist in challenging tasks and obtain academic success (Affuso et al. 2023). This finding aligns with Chong et al. (2018), who emphasized that teacher-led instructional strategies, including cognitive rehearsal and direct instruction, contribute to enhancing students' self-efficacy and learning engagement (Chong et al. 2018). Furthermore, Wang et al. (2024) identified a positive correlation between teacher support, engagement, exploration, and autonomy in technology use, which in turn enhances students' self-efficacy. This relationship underscores the importance of providing students with structured opportunities to engage with technology while maintaining a balance between guidance and independent exploration (Wang et al. 2024).

Moreover, several studies focused on the specific types of teacher support that impact students' self-efficacy. Sakiz (2017) defined affective teacher support as fostering a sense of belonging, motivation, and engagement, reducing externalizing behaviors and encouraging students to take academic risks. This form of support plays a particularly significant role in boosting academic self-efficacy, academic emotions, and behavioral engagement, as positive teacher-student relationships contribute to students' confidence in their abilities.

Liu et al. (2021) extended Sakiz's (2017) study by identifying three primary dimensions of teacher support, namely academic, emotional, and competence support. Academic support is defined as students' perception that their teachers provide the necessary resources and guidance to help them with CU and problem-solving. Research suggests that students who perceive strong academic support from teachers exhibit higher levels of confidence in their academic abilities, leading to increased engagement and persistence in learning tasks (Liu et al. 2021). Emotional support, similar to affective support (Sakiz 2017), is characterized by encouragement, trust, and warmth, reduces anxiety and fosters a sense of belonging, thereby increasing motivation. Competence support refers to the structured guidance and facilitation that teachers provide to help students stay engaged, organized, and on task during learning activities.

Lai (2015) categorized teacher support into affection support, capacity support, and behavior support, each playing a distinct role in influencing students' self-directed learning and technology use. *Affection support* enhances students' motivation and reduces anxiety in digital learning environments. *Capacity support* aims to strengthen technological competence. *Behavior support* refers to the ways teachers structure students' learning processes, establish expectations, and foster engagement through instructional scaffolding. Research suggests that students who perceive strong behavioral support from teachers exhibit higher levels of engagement and persistence in learning tasks (Hoi and Mu 2021; Lai 2015). Hoi and Mu (2021) expanded on Lai (2015) by examining the role of teacher support in mobile-assisted language learning, emphasizing that students' independent learning practices with mobile technologies are significantly influenced by teacher guidance. Their findings suggest that teacher support extends beyond direct classroom instruction, reinforcing the broader impact of teacher encouragement on the learning process and technology use (Federici and Skaalvik 2013; Hoi and Mu 2021).

2.3 | The Mediation Role of AR Features

The effectiveness of AR in students' self-efficacy in science learning stems from its ability to provide immersive, interactive, and adaptive science learning experiences (Cai et al. 2021). Recent studies have explored how specific AR features, such as 3D or 4D visualizations, and interactive operations shape students' perceptions and learning outcomes. Research indicates that usability factors, including navigation clarity, intuitive controls, and real-time feedback, impact students' engagement and confidence in using AR tools for science learning. The ability of AR 3D visualization to present scientific models from multiple perspectives, zoom into microscopic structures, and overlay theoretical representations onto real-world phenomena helps bridge the gap between abstract scientific concepts and concrete learning experiences (Lin et al. 2023). For instance, in physics and chemistry education, AR has been utilized to visualize motion dynamics and electromagnetic fields, enabling students to interact with abstract scientific concepts in tangible and immersive ways. This interactive engagement fosters deeper CU, enhances student motivation, and strengthens self-efficacy (Essmiller et al. 2020).

Moreover, studies suggest that AR systems offering flexible interactions and clear affordances for user input can enhance students' self-efficacy by reinforcing their belief in their ability to effectively engage with and regulate their own learning process (Adnan and Osman 2024). When students can manipulate AR environments with ease, they experience reduced anxiety and increased confidence, particularly, in exploratory STEM tasks that require problem-solving and experimentation (Garzón et al. 2019). Therefore, a well-designed AR environment should integrate interactive interfaces, 3D simulations, and intuitive operational controls. These features foster a sense of control, a key factor in the development of self-efficacy. When students can navigate AR environments smoothly and without frustration, they are more likely to develop positive attitudes toward the technology. Such attitudes can, in turn, influence their confidence in their ability to learn effectively within AR-enhanced settings. Therefore, students' attitudes toward AR features were measured by focusing on the system's visual, interface design, and interaction elements. These three dimensions of AR features were also highlighted in Hao and Lee's (2021) study when they developed and evaluated their education game integrating AR. While AR technology can provide students with engaging, multimodal learning experiences, the extent to which these experiences translate into increased confidence and independent problem-solving abilities also depends on the type and quality of instructional support provided (Wen and He 2025; Chen 2020).

2.4 | Summary

Teacher support plays a critical role in fostering students' confidence in learning with technology (Patrick et al. 2007; Wentzel et al. 2010). However, limited attention has been paid to how teacher support interacts with AR features to shape scientific self-efficacy for primary school students. It remains unclear whether and how students' attitudes (e.g., students' perceptions and affective responses) toward AR features mediate the relationship between teacher support and self-efficacy in AR-based science learning (Hao and Lee 2021). To address this gap, the present study is guided by the following research questions:

1. What is the effect of the designed AR-based inquiry learning environment on students' science self-efficacy?
2. How do different forms of teacher support contribute to the development of students' science self-efficacy in AR-based science inquiry learning?
3. Does students' attitudes toward AR features mediate the relationship between teacher support and science self-efficacy?

3 | Methods

This study adopted an explanatory mixed-methods design, in which quantitative data were collected and analyzed to examine the relationships among teacher support, AR features, and students' science self-efficacy. Meanwhile, the qualitative data from teacher and student interviews were thematically analyzed to explain and contextualize the quantitative findings. This mixed methods approach allowed for a comprehensive understanding of how instructional and technological factors interact in AR-based science education, explaining and deepening statistical results by exploring participants' perspectives and experiences (Creswell and Clark 2017). It should be noted that the study did not include a control group due to school-level implementation constraints. All participating classes engaged to examine students' self-efficacy and received teacher support within an authentic AR-integrated classroom implementation. Therefore, the study complemented with teacher and student interviews to triangulate and explain observed effects.

3.1 | Participants and Procedure

This study was conducted in a Primary school in Singapore, which is a government-aided school. Such schools receive financial support from the government but also have their own sources of funding, and they follow the national curriculum. Four Grade 5 classes taught by four science teachers participated in the study. Due to some students being absent for the pre- or post-survey, the final sample consisted of 114 students (aged 11–12 years old; 50 boys and 64 girls).

The students used the AR app "Celery Lab" to learn how plants transport water and food through their roots and stems during their science lessons on the topic of the plant transport system. Before implementation, the research team conducted a professional development session with the teachers, introducing the pedagogical design and the AR app functions. The lessons on the plant transport system were conducted over 2 weeks. At the beginning of the first lesson, the teachers provided instructions on how to use the AR app and explained the lesson objectives to their students. Students then worked in groups of three or four students to explore the AR app, completing both the AR activities and an accompanying worksheet (see Figure 1). Celery Lab comprises three activities, each taking approximately 20–25 min to complete collaboratively. Students were encouraged to observe the simulation together, make predictions, and provide explanations to address the embedded question after discussing and reaching consensus as a group. By using AR markers, different group members had the opportunity to interact with the AR environment.

3.2 | The Designed AR App

The Celery Lab app was developed to help students explore the plant transport system through AR. Using an AR model of a celery stem, students could conduct virtual experiments and observe how water and nutrient molecules moved after the food- or water-carrying tubes are cut. The topic of the plant transport system was selected by the school's teachers due to the difficulties in visualizing the internal processes of plant transport, which are often invisible, abstract, or delayed in traditional classroom experiments. The AR-based Celery Lab was therefore designed to make these invisible processes immediately visible through real-time animations and manipulable visualizations, allowing students to observe causal mechanisms that would otherwise remain abstract or delayed in real-life settings. This design aligns with prior research suggesting that AR is particularly effective when used to visualize hidden, microscopic, or temporally extended scientific phenomena, rather than simply replicating or replacing hands-on manipulation alone.

Our research team then collaborated closely with the teachers to design the AR-based activity, ensuring alignment with the syllabus. Meanwhile, students also completed other textbook and workbook exercises as part of the official school science curriculum. Using the Celery Lab app, they engaged in three plant transport learning activities, namely (i) Single Stem, (ii) Dyed Celery, and (iii) Two Colors.

In the first activity, *Single Stem*, students scanned the AR marker to activate a virtual celery plant. They then “cut” the celery with a virtual knife to remove either the food or food-and-water carrying tubes (see Figure 2a). The AR simulation showed immediate swelling of the celery stem when the food-carrying tubes were cut. This activity was designed to help students observe the almost immediate swelling in the celery stem, allowing them to relate to the function of food-carrying tubes by highlighting the accumulation of nutrients at the cut areas. The swelling highlights the accumulation of nutrients at the cut site due to the impeded flow. Such an observation may not be possible in a real-life specimen, or even if it is, the swelling may not occur immediately.

For the second activity, *Dyed Celery*, students applied either blue or red dye to a virtual celery and observed corresponding changes in the stem and leaves (see Figure 2b). The AR environment also enabled a close-up view of the celery stem's cross-section after cutting, illustrating the internal movement of particles. These visual details offered a deeper understanding of the internal mechanisms of the stem, which would not have been visible in a physical specimen.

For the third activity, *Two Colors*, students observed the changes to the leaves and stems of the celery when two different dye colors were added into two different beakers containing red and blue dyed water (see Figure 2c). Before beginning this activity, teachers usually guided students in generating a hypothesis about the expected leaf color when a split-stem celery was placed into both blue and red dyes. Once again, the effects were immediate, enabling teachers to address students' misconceptions on the spot.

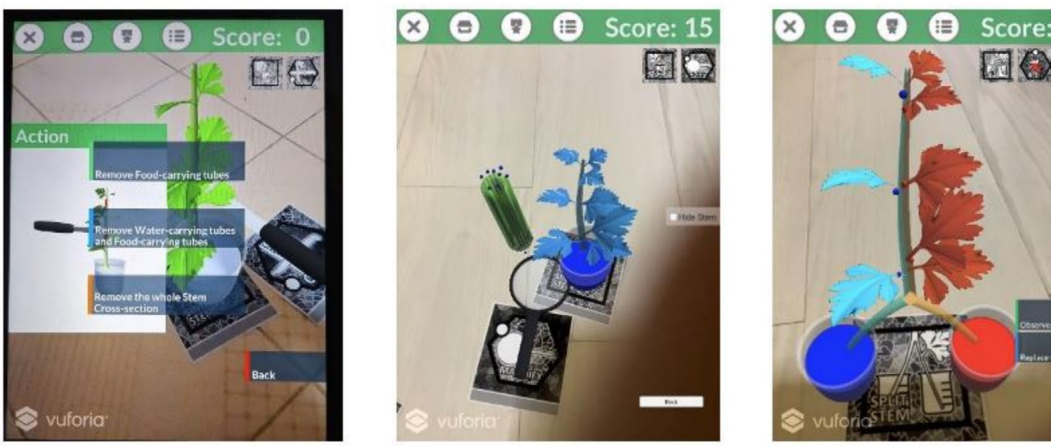
3.3 | Data Sources

3.3.1 | Survey

The pre- and postsurveys were used to assess students' science learning self-efficacy. In addition to the same self-efficacy items, the post-survey also included scales measuring

(a) (b)

FIGURE 1 | students working on AR activities in the classroom environment. (a) Classroom setting and (b) students working in groups.



(a) (b) (c)

FIGURE 2 | Interfaces of the CeleryLab App. (a) Interface of the single-stem activity, (b) interface of the dyed celery activity, and (c) interface of the two colors activity.

perceived teacher support in AR-based science learning and students' attitudes toward the features of the AR app. All items were rated on a 5-point Likert scale (1 = *strongly disagree*; 5 = *strongly agree*).

Science self-efficacy was measured using 22 items adapted from Lin et al. (2013), capturing students' self-efficacy in four dimensions: CU, PW, EA, and SC. Sample items include: "I can explain scientific laws and theories to others" (CU), "I know how to set up equipment for science experiments." (PW) "I am able to propose solutions to everyday problems using science" (EA), and "I feel comfortable discussing science content with my classmates" (SC).

Perceived teacher support was assessed using nine items adapted from Lai's (2015) study, encompassing three dimensions: Affective Support, Capacity Support, and Behavioral Support. The items were modified to reflect the AR-based inquiry learning context. For example, the original item "My language teacher encourages us to use technology for language learning outside the classroom," was adapted to "My science teacher encouraged us to use AR for science learning." Affective support refers to teachers' encouragement, interpersonal relationships, and emotional reinforcement, which contribute to students' confidence and motivation, with sample items such as "My science teacher encouraged us to use AR for science learning." Capacity support highlights the role of teacher guidance in helping students navigate AR tools, troubleshoot technical challenges, and develop digital competence, with sample items such as "My science teacher demonstrated how to use the different functions of the AR app." Behavioral support encompasses teachers' efforts in structuring learning processes, setting expectations, and fostering student engagement through instructional scaffolding. A sample item is "My science teacher reminded us to observe the AR completing the worksheet."

In the postsurvey, students' attitudes toward AR app features were measured in nine additional items adapted from Hao and Lee (2021), covering three dimensions: 3D Graphics, Interface Design, and Operation Interface. Sample items include: "I like the quizzes in 3D format" and "This material features easy-to-understand operation interface that enables users to engage in repeated operations with ease."

3.3.2 | Interview

Semistructured interviews were conducted by a researcher (the second author) with four teachers, and separate focus group discussions were held by the same researcher with two students from each of four classes (A, B, C, and D). Students were selected through convenience sampling, with priority given to those who were more outspoken to encourage active participation and richer discourse during the discussions. All the interviews were audio recorded and transcribed verbatim. Each student focus group discussion was conducted in person for about 20–30 min per group, and each teacher interview was about 40 min. The purpose of the student interview was to gain insights into their AR-supported learning experiences. Questions explored how AR affected their learning compared to non-AR lessons, challenges they encountered, their favorite feature of the app, and any perceived shortcomings of the app.

The teacher interviews aimed to understand their instructional experience with AR-based learning and identify strategies used to support students. Teachers were asked about their perceptions of AR implementation, how they facilitated students' learning with AR, their observations of students' engagement, and the challenges they faced in integrating AR into inquiry-based science learning.

3.4 | Instrument Validation

An exploratory factor analysis (EFA) was conducted to examine the underlying structure of science learning self-efficacy and perceived teacher support. The KMO value was 0.84, indicating that the sample was highly suitable for factor analysis (Kaiser 1974). Bartlett's test of Sphericity was statistically significant (χ^2 (21) = 663.29, $p < 0.001$), confirming that the correlations among variables were sufficient for conducting factor analysis. The EFA results for science learning self-efficacy showed that some items did not load adequately onto their intended factors, leading to the modifications of 22 items to 17 items ($\alpha = 0.96$). The internal reliability for the four subscales was: CU (6 items, $\alpha = 0.90$), PW (3 items, $\alpha = 0.89$), EA (4 items, $\alpha = 0.84$), and SC (4 items, $\alpha = 0.89$).

For students' attitudes toward AR features, the EFA revealed a KMO value of 0.89, which was suitable for factor analysis. Bartlett's Test of Sphericity was statistically significant (χ^2 (36) = 1083.84, $p < 0.001$). All nine items were loaded onto a single factor, with strong loadings ranging from 0.80 to 0.88, suggesting that students perceive AR3D visualization, interactive interface, and operational interface as a unified construct rather than separate dimensions. Accordingly, 9 items of AR features ($\alpha = 0.95$) were treated as a single variable in subsequent analyses.

The EFA results for the teacher support scale indicated that the original three-factor model did not hold. Items related to behavioral and capacity support loaded onto a single factor, suggesting that students did not perceive these as distinct types of support. This finding is consistent with previous studies by Federici and Skaalvik (2013) and Wang et al. (2022), which conceptualized instrumental support as a combination of practical, skill-based assistance and behavioral structuring. Additionally, one item from the affective support subscale was removed due to cross-loadings, indicating that it did not distinctly measure emotional support. The final two-factor solution, comprising emotional support and instrumental support, demonstrated strong internal reliability and conceptual coherence (7 items, $\alpha = 0.93$). Therefore, teacher support in this study was redefined into two dimensions: *Emotional support* refers to encompasses teacher encouragement, care, and interpersonal warmth, fostering a sense of belonging and motivation in AR-based science learning (2 items, Cronbach's $\alpha = 0.84$). *Instrumental support* refers to integrate technical guidance, behavioral structuring, and problem-solving facilitation, ensuring students effectively engage with AR tools and complete science learning tasks (5 items, Cronbach's $\alpha = 0.93$). The sample survey items are "My science teacher encouraged us to explore the AR activities by ourselves" (Emotional Support); "My science teacher demonstrated how to use the different functions of the AR app" (Instrumental Support).

3.5 | Data Analysis

Descriptive analyses and paired t-tests were conducted to examine students' science self-efficacy before and after the AR-based learning, as well as teacher support across four dimensions: CU, PW, EA, and SC. The mean, standard deviation, and significance levels were reported to determine whether significant changes occurred after the intervention.

Multiple linear regression analyses were used to assess the effects of teachers' emotional support and instrumental support on the four dimensions of science self-efficacy. Four separate regression models were constructed, each predicting one dimension of science self-efficacy. Presurvey self-efficacy scores were included as covariates in all regression models to control for initial individual differences in students' self-efficacy before the AR activity. Standardized regression coefficients (β), p-values, and adjusted R^2 values were reported to determine the relative contribution of each predictor.

To further explore the relationship between teacher support and science self-efficacy, a mediation analysis was performed using PROCESS Model 4 (Hayes 2012), with students' attitudes toward AR features as the mediator. The bias-corrected bootstrap method, utilizing 5000 samples, was employed to evaluate the indirect effects at a 95% confidence interval. Following the recommendation by Shrout and Bolger (2002), a confidence interval that does not include zero indicates a statistically significant mediation effect.

Additionally, thematic analysis of the interview data was conducted to supplement and explain the quantitative findings. Following the six steps of thematic analysis (Braun and Clarke 2006), the first and second authors reviewed and familiarized themselves with the transcribed recordings. Adopting an inductive, data-driven approach, they identified excerpts that were relevant to interpreting or supplementing the quantitative findings, particularly related to teacher support and student experiences with AR learning.

Relevant data segments were initially coded independently by the two researchers. Codes were grounded in the data and related to "enhanced engagement through AR visualization," "four dimensions of self-efficacy or the emotional/instrumental teacher support," and "AR novelty and limitations." The first author clustered similar utterances and generated preliminary categories, which were discussed with the second author to reach agreement. The final thematic categories were confirmed collaboratively by all three authors to ensure interpretive reliability.

Teacher and student interviews were coded and analyzed separately as individual cases. Subsequently, the findings were synthesized to generate shared thematic categories across perspectives. This inductive approach allowed for themes to emerge from the data, grounded in participants' articulated experiences (Rossman and Rallis 2012).

4 | Results

4.1 | The Designed AR Inquiry Learning Promoted Students' Science Self-Efficacy

Descriptive statistics and paired t-tests were conducted across four dimensions of self-efficacy (Table 1). The results indicated a statistically significant increase in concept understanding self-efficacy ($t = 5.17$, $p < 0.01$) and SC self-efficacy ($t = 3.27$, $p = 0.001$), suggesting that the AR learning environment effectively enhanced students' confidence in understanding and explaining scientific concepts. Students' qualitative responses further support the observed increase. For example, Student 1A shared "I think this plant transport system, the AR thing is quite fun, because once you get past knowing how to use it, it's very fun and it's like the plant transport system isn't that hard to understand." During the AR activities, students also actively "study with friends" and "ask friends to help." As Teacher C noted, "It's a very interactive tool, students can see something, really touch and feel in a way."

In contrast, changes in PW self-efficacy ($t = 1.49$, $p = 0.14$) and EA self-efficacy ($t = 1.31$, $p = 0.19$) were not statistically significant. This suggests that the AR experience did not substantially improve students' confidence in conducting experiments or applying scientific knowledge in real-world scenarios. As students' reflections on usability challenges like "hard to cut" and "it's quite laggy" may have disengaged them in PW with AR.

Both teachers and students consistently reported that AR significantly enhanced students' confidence in engaging with science learning, particularly by increasing their sense of control and competence in handling abstract scientific concepts. For instance, Teacher C emphasized:

TABLE 1 | Descriptive statistics of paired t-test results for self-efficacy.

		Pretest		Posttest				
Self-efficacy variables	***N***	**Mean**	**SD**	**Mean**	**SD**	**SE mean**	***t***	**Sig. (two-tailed)**
CU	114	3.74	0.59	3.97	0.61	0.04	5.17**	0.001
PW	114	4.31	0.71	4.40	0.63	0.07	1.49	0.14
EA	114	4.09	0.59	4.15	0.65	0.05	1.31	0.19
SC	114	3.90	0.73	4.11	0.67	0.06	3.27**	0.001

Note: CU: conceptual understanding, EA: everyday application, PW: practical work, SC: science communication.
*$p < 0.05$.
**$p < 0.01$.

> I think it is the ability to go through the experience that adds the most value because the students can, let's say, as visual learners, they might be able to retain the information you demonstrate, or you present on the screen. I think this gives them a chance to really touch and feel in a way, in a safe way like what the systems are. It gives them a chance to also move about during the lessons.

Similarly, student 1B described the AR as " get to do interesting stuff like go to the science lab and be able to explore things" and student 1A noted that it " it taught me to be more confident," confirming the quantitative finding of increased science self-efficacy. However, both students and teachers consistently indicated that AR alone is insufficient for meaningful science learning. For example, Student 1B shared that the AR activity was "a bit hard If I were to do it on my own." Teacher A also noted that: "I think the first part there were two cuts that they needed to do, but they couldn't understand why. But in general, once we set the stage like give them the explanation, telling them what to do, they were able to catch it on very quickly."

4.2 | Teacher Support on Students' Science Self-Efficacy

Descriptive results indicated that students reported high levels of perceived teacher support in the postsurvey, with a mean score of 4.15 (SD = 0.89) for emotional support and 4.37 (SD = 0.72) for instrumental support (see Table 2). Many students attributed their confidence in science to the clarity and effectiveness of teacher guidance. For example, Student 2B noted, "I think I am quite confident about my science as the teacher has gone through everything clearly," and teachers' conveyed confidence in students' activities made students "taking science seriously," emphasizing the role of explicit instruction in building self-efficacy.

TABLE 2 | Descriptive statistics on students' perceived emotional and instrumental support.

Variables	*N*	Mean	SD
Emotional support	114	4.15	0.89
Instrumental support	114	4.37	0.72

Table 3 shows the multiple regression results examining the effects of emotional and instrumental teacher support on different dimensions of students' science self-efficacy in AR-based learning. Students' perceived emotional support significantly contributed to their science concept understanding self-efficacy after controlling for pretest scores ($\beta = 0.24$, $R^2 = 0.63$). Teacher A described how she encouraged student autonomy in exploring AR content: "But then this time around it was sort of like letting them explore first and then they sort of like come up to the conclusion about certain concepts in general."

Emotional support was also a significant predictor of students' self-efficacy in conducting PW ($\beta = 0.23$, $R^2 = 0.34$). Teacher A expressed her trust in students' abilities of AR experiments, "they have done a lot of like experiments an inquiry-based together, so doing the AR, I could just simply give it to them, and I know that among their groups, more or less everybody would cooperate." And she also noted that with minimal explanation and guidance, students were generally able to understand the tasks and perform them quickly.

Meanwhile, students perceived instrumental support significantly influenced their confidence to apply scientific concepts in daily life after controlling for pre-test scores ($\beta = 0.35$, $R^2 = 0.49$), whereas emotional support did not show a significant effect. The interview data reinforce this finding, revealing that teachers employ instructional strategies such as clear explanations and structured materials to support students in the EA of science. Teacher B and Teacher A both emphasized that "clear instructions" help students make connections between abstract concepts and real-world experiences. As Teacher A noted, "they really see it happening ... they were telling me after that that like ohh my grandma put this in and everything. So they could relate to it, it was something exciting for them." Additionally, Teacher C highlighted the value of integrating AR with physical specimens to strengthen connection to real-life contexts:

TABLE 3 | Multiple regression results of teacher support on students' science self-efficacy.

Explanatory variable	Concept understanding	Practical work	Everyday application	Science communication
Pretest score	0.58*** (0.56)	0.28*** (0.31)	0.45*** (0.40)	0.33*** (0.36)
Emotional support	0.16 *** (0.24)	0.16* (0.23)	0.04 (0.05)	0.16* (0.22)
Instrumental support	0.08 (0.10)	0.12 (0.14)	0.32*** (0.35)	0.30*** (0.32)
R^2	0.63	0.34	0.49	0.43

Note: Values outside parentheses are unstandardized coefficients (b); values in parentheses are standardized coefficients (β).
*$p < 0.05$.
***$p < 0.001$.

> I want them to understand there are some things that we can actually bring in live specimens. This is my intention of the whole entire lesson to let them see the real thing. AR is good because I can't see the internal tubes, from the live specimen, they can actually see the water carrying tubes through the different colors used and how this cascade down to the basic concept that we are trying to teach here.

Both emotional support ($\beta = 0.22$, $R^2 = 0.43$) and instrumental support ($\beta = 0.32$, $R^2 = 0.43$) significantly contributed to students' SC self-efficacy after controlling for pre-test scores. In the interviews, Teacher C emphasized that her use of group-based strategies fostered that students could exchange ideas and benefit each other's learning:

> So when they are sitting through the session with those with some knowledge, those with concepts learned, they actually can learn better. And those with prior knowledge can actually teach these students. When someone doesn't know what's going on in the topic, but when they went through the first time, they will have a lot of thought provoking questions, to ask those who have already learned before. So they are actually benefiting each other.

Teacher D highlighted her encouragement of intergroup communication: "I see the groups will come to me and say they're done, Then I can direct them—oh this group is ready. You can go to them for help if you don't understand. Yeah." Teacher C also emphasized mutual encouragement between teachers and students, noting "they have an even better idea how to get it done in a faster way. So we actually learn from the children as well. So we find it out in our own way, but the children taught us another way. So we actually share. It is a two-way sharing."

4.3 | Students' Perception of AR Features as a Mediator of Teacher Support and Science Self-Efficacy

The mediation analysis revealed that mediation occurred only in the relationship between emotional support and concept understanding self-efficacy (as shown in Figure 3). Specifically, students who received greater emotional support from teachers were more likely to develop positive attitudes toward AR features, which, in turn, were associated with higher levels of CU self-efficacy. No significant mediation effect was found for instrumental support in predicting any dimension of self-efficacy.

As shown in Table 4, students perceived emotional support from teachers had a significant positive effect on their attitude toward AR features ($b = 0.36$, SE = 0.07, $t = 5.33$, $p < 0.001$, 95% CI [0.23, 0.49]), indicating that students who received higher levels of emotional support were more likely to develop positive perceptions of AR features. In turn, attitudes toward AR features had a significant positive effect on CU self-efficacy

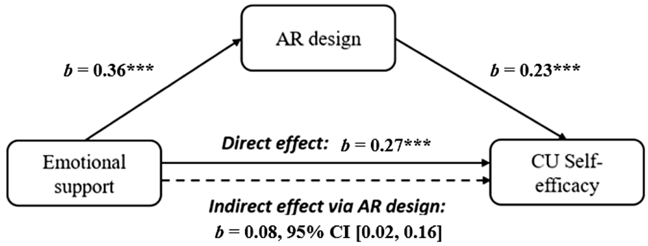


FIGURE 3 | Mediation model of emotional support on students' conceptual understanding (CU) self-efficacy, with AR features as a mediator.

($b = 0.23$, SE = 0.07, $t = 3.26$, $p < 0.001$, 95% CI [0.09, 0.37]). Emotional support also directly influenced concept understanding self-efficacy ($b = 0.27$, SE = 0.06, $t = 4.67$, $p < 0.001$, 95% CI [0.15, 0.38]).

As presented in Table 5, the direct effect of emotional support on CU self-efficacy was $b = 0.27$ (SE = 0.06, 95% CI [0.15, 0.38]), and the indirect effect through students' attitudes toward AR features was $b = 0.08$ (SE = 0.04, 95% CI [0.02, 0.16]). The bias-corrected bootstrap confidence interval for the indirect effect did not include zero, indicating a significant mediation effect. The direct effect accounted for 76.38% of the total effect, while the indirect effect contributed 23.62%, suggesting that students' attitudes toward AR features partially mediate the relationship between emotional support and CU self-efficacy.

5 | Discussion

5.1 | AR as a Supplement, Not a Substitute in Science Class

The results demonstrated that the AR learning environment significantly enhanced students' self-efficacy in CU and SC. This finding aligns with prior research emphasizing the affordances of AR for visualizing abstract scientific concepts and supporting interactive discourse (Cai et al. 2021). As Teacher C highlighted, AR is "a very interactive tool" that allows students to "really touch and feel in a way," reinforcing existing literature suggesting that AR's immersive and dynamic learning process supports deeper conceptual comprehension. Students also reported that AR provided more opportunities for them to "study with friends" and "ask friends to help," which is associated with greater confidence in explaining and communicating scientific knowledge (Lin et al. 2023).

However, the study found no significant improvements in students' self-efficacy in PW and EA. This finding further underscores that while AR provides opportunities for virtual experimentation, it may not fully replicate the hands-on experience of traditional laboratory work, which is crucial for developing procedural confidence (Makamu and Ramnarain 2023). Additionally, research has shown that students often struggle with bridging theoretical knowledge and real-world application, particularly, in technology-mediated environments where contextualization is limited (Liu et al. 2021). These results suggest that simply providing access to technology alone may be

TABLE 4 | Mediating effect of AR features on the relationship between emotional teacher support and conceptual understanding self-efficacy.

	On AR features				On concept understanding self-efficacy			
Predictors	***b***	**SE**	***t***	**95% CI**	***b***	**SE**	***t***	**95% CI**
Emotional support	0.36	0.07	5.33***	[0.23, 0.49]	0.27	0.06	4.67***	[0.15, 0.38]
Students' attitudes toward AR features					0.23	0.07	3.26***	[0.09, 0.37]

Note: Analyses conducted using PROCESS Model 4.
***$p < 0.001$.

TABLE 5 | Direct and indirect effects.

Effect type	Path	Unstandardized coefficient (*b*)	Boot SE	Boot CI lower	Boot CI upper	Relative effect size (%)
Direct effect	Emotional support → CU self-efficacy	0.27	0.06	0.15	0.38	76.38
Indirect effect	Emotional support → students' attitudes toward AR features → CU self-efficacy	0.08	0.04	0.02	0.16	23.62

Abbreviations: *b* = unstandardized coefficient; Boot SE = bootstrap standard error; CI = confidence interval.

insufficient to promote students' effective and confident science learning. Teachers also need to play an active role in guiding students' use of technology and helping them make meaningful connections to the content (Lai 2015; Hoi and Mu 2021). Findings from this AR-based study further indicate that teacher support, both emotional and instrumental perspectives, may contribute to improving students' science efficacy in PW and real-life scientific applications, respectively.

5.2 | Teacher's Emotional Support: A Key to Conceptual Understanding and Practical Work

As shown in the multiple regression result, teachers' emotional support was significantly associated with students' self-efficacy in concept understanding and PW within AR settings. Student interviews further reinforced that when teachers consistently conveyed confidence in students' abilities and made the AR-based science learning accessible, students were more likely to construct a self-image of themselves as competent science learners and to "take science seriously." Existing studies have highlighted the importance of teacher encouragement in fostering students' intrinsic motivation, academic resilience, and engagement (Chong et al. 2018; Wang et al. 2022; Guo et al. 2025). In AR-based science learning environments, understanding abstract scientific concepts and conducting PW can be cognitively demanding and potentially stressful (Lin et al. 2013), especially when students engage with interactive simulation tools that they are not familiar with (Coştu 2025). These challenges may lead to increased intrinsic and extraneous cognitive load, particularly, in the absence of clear guidance or emotional reassurance (Arztmann et al. 2025). Students, therefore, need encouragement to build confidence in their understanding and experimentation. Studies also confirmed that teachers' trust and autonomy support increase students' feeling of receiving emotional support (Federici and Skaalvik 2013). Therefore, emotional support such as teachers' sharing about how AR could enhance learning, offering students autonomy to explore, and encouraging their exploration of AR-based activities is crucial to help students manage cognitive demands, sustain focus, and engage more deeply with both the conceptual and practical aspects of AR-based science inquiry.

Furthermore, the mediation analysis revealed that students' attitude toward AR has a significant indirect association with the effect of emotional support on concept understanding self-efficacy. AR's potential to promote immersive and interactive learning also depends on students' ability to navigate and make sense of the digital environment. Qualitative data reinforced this finding: both teachers and students repeatedly highlighted AR's engaging features but also pointed out the technical disruptions, such as confusing interfaces or difficulties in navigation. For example, students 1C and 2B commonly described "it's very hard to cut," and "it's quite laggy and sometimes the things just disappear," which disrupted the flow of concept learning and created frustration. These moments suggest that teachers' emotional support may play a guiding role in helping students persevere through technological setbacks and maintain a positive learning attitude.

5.3 | Teachers' Instrumental Support: Bridging Science to Everyday Life

Although teachers' instrumental support did not significantly enhance students' self-efficacy in concept understanding and

PW, it was strongly associated with their confidence in relating science to everyday life. This distinction between the effects of teachers' instrumental support and AR's built-in features suggests a complementary relationship. While AR provides sufficient scaffolding for CU and practical tasks, it is teachers' support that plays a crucial role in helping students apply their learning to authentic, real-world contexts.

This transfer gap is, particularly, obvious among younger learners. Research consistently shows that children often struggle to differentiate between virtual and real environments, especially when engaging with narrative-rich, immersive, and interactive media (Kaimara et al. 2022). To learn effectively with virtual tools, learners must understand the representational nature of on-screen simulations and relate to real-world contexts (Oranç and Küntay 2019). However, developmental constraints in symbolic understanding, working memory, and representational flexibility often limit their ability to make this connection.

Evidence further confirms that transferring knowledge from 2D media to 3D, and to real-world contexts is cognitively demanding for younger learners (Troseth 2010). The greater the gap between the learning context and the real-life application, the higher the cognitive work and memory demands, making successful transfer more difficult (Oranç and Küntay 2019). Moreover, different media forms can shape children's perception of reality, blurring the boundary between fantasy and real-life experiences. This highlights the critical role of adult facilitation, especially teachers, in guiding primary school learners to interpret virtual content meaningfully and relate it to tangible, everyday contexts (Rapti et al. 2025). Therefore, instrumental teacher support such as clear explanations and targeted questioning becomes essential (Luo et al. 2014), not as a complement to AR, but as a cognitive bridge between virtual representations and real-life understanding. This aligns with the finding that instrumental support was significantly associated with students' self-efficacy in EA and SC, both of which require meaningful transfer from AR to real-life contexts.

5.4 | Emotional and Instructional Support From Teachers Promote SC

The findings showed that students' self-efficacy in SC improved significantly after the AR activity, and both emotional and instructional support from teachers played a crucial role in supporting this improvement. This result further highlights that such support is particularly salient within AR-based learning environments, given the unique cognitive and communicative demands posed by AR.

SC self-efficacy involves students' confidence in expressing ideas with others and competence in structuring and delivering scientific information effectively (Lin et al. 2013). In AR-enhanced environments, students need to interpret and articulate complex visual–spatial information, such as 3D models, simulations, or virtual interactions. Communicating scientific ideas in such environments can be intimidating for students due to the fear of public speaking and concerns about correctness. Emotional support from teachers mitigates these concerns by creating a psychologically safe environment where students feel encouraged to share their thoughts and learn from others (Othman and Kiliç 2018). In the postlesson interviews, we found that teachers actively encouraged students to seek help and share knowledge within their groups while completing the AR activities. When students perceive teachers to be emotionally supportive, they are also more likely to seek help (Federici and Skaalvik 2013) and engage in collaboration (Shen et al. 2024) while experiencing reduced anxiety.

In addition to emotional support, we also observed teachers provide communication strategies and structured opportunities for discussion, including helping students connect their AR-based observations with prior knowledge and supporting collaborative learning. These help students develop concrete skills in communicating scientific information (Carless and Winstone 2023). Therefore, the findings of this study suggest that teachers should consider not only providing emotional encouragement but also offering instructional guidance to support students' SC in an AR-based environment effectively.

6 | Conclusion, Implications, and Limitations

The findings highlight that as a supplement in the science classroom, AR can significantly improve students' self-efficacy in concept understanding and SC. The study revealed differentiated effects of emotional and instrumental support. Emotional support played a more significant role in CU and PW self-efficacy, while instrumental support was particularly influential in EAs. Both forms of support significantly influence SC self-efficacy. Additionally, mediation analysis revealed that students' attitudes toward AR features significantly mediated the relationship between emotional support and concept understanding self-efficacy.

These differential impacts carry important implications for designing AR-based science learning experiences. First, teachers and instructional designers should recognize that emotional support is a key driver of academic confidence in cognitively challenging tasks. In practice, teachers implementing AR in their science classes should intentionally cultivate an emotionally supportive climate by recognizing emotional cues in students, encouraging questions, and normalizing struggles with the technology or content.

Second, the findings underscore the importance of strategically integrating instrumental support to bridge classroom learning and real-world application. Teachers should provide concrete guidance on how abstract concepts learned via AR simulations relate to everyday phenomena. From a design perspective, built-in support features such as on-demand hints or adaptive feedback can help to enhance learning efficacy (Çeken and Taşkın 2025). Nevertheless, teachers play an irreplaceable role in helping students make connections between visualized concepts and learning activities with EA.

Third, promoting students' SC requires both emotional and instrumental support. Beyond creating a psychologically safe environment for communication, it is essential to enact instructional guidance to facilitate structured discussions and collaboration. Such support enables active and meaningful knowledge exchange and co-construction among students, ultimately strengthening their ability to communicate scientific ideas with confidence and clarity.

Finally, the results suggest that the value of teacher support may generalize beyond the AR environment, offering insights into how educators can scaffold student self-efficacy in various digital, simulated, or multimodal settings. Furthermore, the mediating role of students' attitudes toward technology points out that positive student-technology interactions are often socially conditioned and co-shaped by the affective and pedagogical presence of teachers.

Several limitations should be acknowledged. First, the study sample was drawn from a single school, which may limit the generalizability of the findings. Future research could employ structural equation modeling (SEM) with a larger dataset to validate the proposed relationships. Second, this study did not control for potential variables, such as students' prior experience with AR technology, students' readiness for collaborative learning, or individual differences in cognitive and affective traits. As a result, it remains uncertain whether the observed effects are solely attributable to teacher support and AR features or if external influences may have contributed to the variations in self-efficacy. Furthermore, while the mediation model offers valuable insight into potential relationships among teacher support, perceptions of AR features, and self-efficacy, the nonexperimental design limits the ability to draw causal inferences. Future research should incorporate control variables to better isolate causal relationships and track changes in self-efficacy over time. It is also important to note that participants in the focus group were selected based on their verbal expressiveness, which may have resulted in an overrepresentation of more confident students and an underrepresentation of quieter students' perspectives. Additionally, the measures of teacher support and student attitudes relied on self-reported data, which are inherently subjective and may have been influenced by prior experiences, personality traits, or classroom norms. The following studies could benefit from incorporating behavioral data related to teacher support to provide a more comprehensive understanding. Although the mediation analysis indicated that students' attitudes toward AR features partially mediated the effect of teacher support, it remains unclear whether pre-existing attitudes influenced their evaluation of teacher support.

Funding

This study is funded by the Ministry of Education (MOE) Social Science and Humanities Research (SSHR) Fellowship for the project MOE SSHRF 8/22 WY [MOE2021-SSHR-009]. The views expressed in this paper are the author's and do not necessarily represent the views of the host institution.

Ethics Statement

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.

Consent

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

Data Availability Statement

The data that support the findings of this study are not publicly available due to privacy or ethical restrictions. NTU Research Data Policy requires retaining 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.

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