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Investigating primary school students' epistemic beliefs in augmented reality-based inquiry learning

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ABSTRACT

The impact of Augmented Reality (AR)-based science learning on cognitive development has been established, but the effect of AR on the improvement of students' academic performance remains inconclusive. Additionally, while epistemic beliefs as a significant determinant on student learning outcomes is well-documented, there is little research in AR-supported science learning exploring the effectiveness of AR activities on students' epistemic beliefs. This mixed-methods study investigates the relationship between students' engagement in an AR-based inquiry learning environment and their epistemic beliefs. It aims to examine if students' engagement in AR activities has an impact on their epistemic beliefs and academic performance, as well as which aspects of students' epistemic beliefs may be affected by the designed activities. 159 fifth-grade students participated in the AR activities for two months. The findings revealed that students' academic performance improved significantly, evidenced in the pre- and post-tests. While students' perceived engagement did not significantly affect their academic performance, students' perceived engagement in the activities did influence their epistemic beliefs, particularly in the dimension of justification of knowledge in science. The study identified features of learners' interactions in the AR learning environment and these findings provide insights into potential areas for improvement in AR-based science learning.

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1. Introduction

Augmented Reality (AR) is an emerging technology that superimposes digital information onto real-world environments. Several studies have demonstrated that due to its media characteristics such as sensory immersion, navigation, and manipulation, AR can have a positive impact on learning, especially in stimulating positive emotions in learning (e.g. Huang et al., 2016; Ibáñez & Delgado-Kloos, 2018; Pedaste et al., 2020). Research has also shown that AR-supported science learning can have a positive impact on students' cognitive development (e.g. Cheng & Tsai, 2013; López-Belmonte et al., 2020; Sahin & Yilmaz, 2020; Sırakaya & Alsancak Sırakaya, 2020; Wu et al., 2013) especially in helping students better understand and visualise complex and abstract scientific concepts (e.g. Dunleavy, 2014; Dunleavy et al., 2009) and promoting scientific inquiry through 3D manipulation and learning (e.g. Rosenbaum et al., 2007; Squire & Jan, 2007; Squire & Klopfer, 2007). Moreover, research has shown that AR, when used with inquiry-based learning, helps to

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enhance cognitive, motivational, and emotional learning outcomes (Pedaste et al., 2020) and has shown to elicit deeper thinking and more diverse responses from students (Cai et al., 2021).

Inquiry-based learning is an active learning pedagogical method emphasising active participation (De Jong & Van Joolingen, 1998) and problem-solving skills (Pedaste & Sarapuu, 2006), and can be enhanced with the use of technology (Cai et al., 2021; Pedaste et al., 2015). A systematic review by Pedaste et al. (2020) found that the affordances of AR render it a useful tool for supporting inquiry-based learning. The combination of inquiry-based learning and AR allows students to conduct their own research and explore highly realistic virtual modules in real-world settings, thereby enhancing the overall inquiry experience (Garzón et al., 2020). By incorporating inquiry-based learning into AR applications, students can be empowered to be more active creators. This can be achieved by providing them with more opportunities to share and communicate their discoveries (Nielsen et al., 2016), which can lead to an improvement and transformation in the way they inquire and learn science (Chiang et al., 2014; Nielsen et al., 2016). Despite the growing literature indicating the benefits of AR for cognitive, metacognitive, emotional, and collaborative dimensions of inquiry-based learning (Pedaste et al., 2020), there has been relatively little research done on the potential and impact of AR-based inquiry learning activities on learners' epistemic beliefs.

Epistemic beliefs are the beliefs that individuals form about knowledge and the processes of knowing (Conley et al., 2004; Kampa et al., 2016). Studies have shown that these beliefs can positively impact a learner's conceptual learning, science inquiry, or laboratory practices (e.g. Ding, 2014; Hofer & Pintrich, 2002; Lising & Elby, 2005; Peffer & Ramezani, 2019). Individuals who hold adaptive epistemic beliefs tend to exhibit epistemic cognitive abilities and skills that are essential for argumentation, critical thinking, deeper understanding, and higher academic performance (Tsai, 2004). Epistemic beliefs play a crucial role in inquiry-based learning, as they are instrumental in shaping students' learning outcomes (Khaleghinezhad et al., 2012) and has the potential of influencing the inquiry experience (Wang et al., 2022). However, studies providing evidence for the influence of inquiry-based experiences on shaping epistemic beliefs have produced conflicting results. In the study of Zhao et al. (2021), students who underwent an inquiry-based science intervention on the topic of light exhibited more sophistication in their epistemic beliefs compared to the students from the control group. On the contrary, Wu and Wu (2011) found in their study that majority of fifth-grade students' epistemic beliefs remained at the naïve level though they had participated in 5 weeks of inquiry activities.

Students' epistemic beliefs can be considered as a type of learner characteristic. The need for more research on how characteristics of learners affect the AR learning experience has been noted (Cheng and Tsai (2013; Ibáñez & Delgado-Kloos, 2018). Given the scarcity of studies on the influence of AR activities on students' scientific epistemic beliefs and its corresponding impact on students' academic performance (Chang et al., 2014; Erbas & Demirer, 2019; Khaleghinezhad et al., 2012; Wang et al., 2022), this study aims to investigate the effect of an AR-based inquiry learning approach on students' epistemic beliefs and learning performance. The two research questions of the study are as follows:

(1) What is the relationship between students' perceived efficacy and engagement in the AR-based inquiry learning environment and their scientific epistemic beliefs and academic performance?
(2) How can AR-based inquiry learning design be enhanced to promote students' scientific epistemic beliefs?

To investigate these research questions, this study utilised a mixed-methods approach. The quantitative approach data collected was in the form of pre-and post-tests and post-survey questionnaires for students, meant to examine the learning effectiveness of the designed AR-based inquiry learning by focusing on students' epistemic beliefs. Next, content analysis was used to examine the discourse of students as they completed the AR-related activities. This data was collected to understand the level of engagement of students in the AR-based inquiry learning sessions. Additionally, interviews with teachers were conducted and analysed to shed light on the findings from the quantitative data. The findings of qualitative data help to elaborate features of learners' interactions in the AR learning environment and to provide insight into potential areas for improvement in AR learning environment design that can promote deeper scientific thinking and learning.

2. Hypothesis development

Engaging students in learning science has been a longstanding challenge for educators (Hadzigeorgiou & Schulz, 2019; Waldrip & Prain, 2017). It is widely recognised that engagement plays a crucial role in the learning process, as it is linked to internal emotions and cognitive perceptions of the learning environment (Li & Song, 2018; Xie et al., 2019), and it can positively impact learning performance (Afflerbach & Harrison, 2017; De Freitas et al., 2015; Hamari et al., 2016).

Meanwhile, researchers in AR-supported learning have been studying how the approach aids students' engagement for decades (Squire & Klopfer, 2007). Measures of engagement in AR studies mainly depend on student responses to questionnaires probing perceptions and attitudes (Bacca et al. 2014; Wen, 2021). Studies have found that AR-based inquiry can help to promote student engagement (e.g. Hsu et al., 2017; Wang et al., 2014). The use of technology (Linn, Davis, & Bell, 2013) and other creative means of representation have proved to be helpful in engaging students in science (Waldrip & Prain, 2017). With AR, users have access to an environment that offers embodied representations of educational content in addition to being able to interact with real-world scenarios through physical manipulation (Bujak et al., 2013). The systemic review by Ibáñez and Delgado-Kloos (2018) studied the evaluations made in quantitative studies and reported that engagement was one of the positive affective states fostered by AR. Hsu et al. (2017) examined how high school students' STEM interest is affected by authentic AR-embedded inquiry lessons focused on medical surgery exploration. The study found that students' engagement in the AR lessons was high. Additionally, Wang et al. (2014) compared the use of an AR simulation system to a traditional 2D simulation system and found that the AR system was more effective in engaging students in the inquiry process, so as to improve their learning outcomes. Hence, we hypothesise in this study:

H1: Students' perceived efficacy of AR-based inquiry learning activities (PAR) positively predicts their perceived learning engagement (PLE).

H2: Students' perceived learning engagement (PLE) positively predicts their learning outcomes.

Kuhn (1993) contends that having strong scientific epistemic beliefs is crucial for developing scientific thinking and reasoning in students. A lack of these epistemic beliefs may be the reason why many students exhibit limited reasoning skills. By introducing students to scientific epistemic beliefs early on in their education, it can help them build a strong foundation for understanding science in the future (Kuhn & Weinstock, 2002; Schiefer et al., 2020). This means that students' acquisition of knowledge will transition from a simple transfer of knowledge from an authority to being able to think independently (Schommer, 1994). Individuals' epistemic beliefs are continuously changing (Lee et al., 2021) and have been suggested to be related to the engagement of learning environment (Ozkal et al., 2009) and academic achievement (Cano, 2005). To promote the development of epistemic beliefs, educators can foster critical thinking by providing learning environment that encourages active questioning, and critical examining of evidence (Walker et al., 2020).

As proposed by Hofer and Pintrich (1997), epistemic beliefs are characterised by four dimensions: certainty of knowledge, simplicity of knowledge, source of knowing and justification of knowing. The certainty dimension reflects beliefs that knowledge can be fixed or tentative, while the simplicity dimension reflects knowledge as absolute or relative. Source of knowing dimension reflects an understanding that knowledge can reside in an authority figure or can be challenged. Justification of knowing dimension reflects beliefs that knowledge is accepted in accordance with experts, versus one's own opinion or experience.

Research also has shown that the design of the learning environment can nurture the development of epistemic beliefs of diverse dimensions (Brownlee et al., 2001; Tsai, 2000). The four dimensions of epistemic beliefs proposed by Hofer and Pintrich have been widely used in science education studies to investigate the relationship between learners' epistemic beliefs and science learning (Lee et al., 2021). Some studies have examined the impact of specific dimensions of learners' epistemic beliefs on their learning (Liang et al., 2010; Schroeder et al., 2019). This study focuses on the impact of AR-based inquiry learning environments on students' epistemic beliefs in science. Therefore, we considered the sub-dimensions of epistemic beliefs and hypothesised that:

H3: Students' PLE is positively related to scientific epistemic beliefs (SEBs) about the "Source" of knowledge.

H4: Students' PLE is positively related to SEBs about the "Certainty" of knowledge.

H5: Students' PLE is positively related to SEBs about the "Development" of knowledge.

H6: Students' PLE is positively related to SEBs about the "Justification" of knowledge.

H7: Students' SEBs about the "Source" of knowledge are positively related to students' academic performance.

H8: Students' SEBs about the "Certainty" of knowledge are positively related to academic performance.

H9: Students' SEBs about the "Development" of knowledge are positively related to academic performance.

H10: Students' SEBs about the "Justification" of knowledge are positively related to academic performance.

3. Method

3.1. Participants

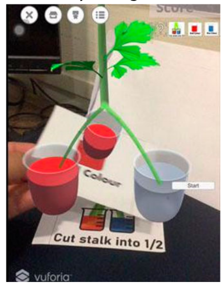
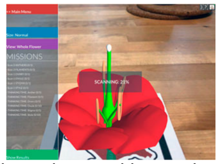
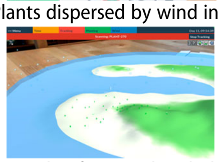
The study involved a total of 159 5th grade students from four classes of a Singapore government primary school. The students participated in AR-based inquiry learning activities during their science lessons on the topic of plants. The study took place for two months and each lesson was between 30 minutes to an hour, based on the lesson objectives. All classes participated under similar conditions, using AR and the same pedagogical framework. The teachers involved were from a Professional Learning Community team, and their aim was to explore how to increase the effectiveness of learning through the novel use of technology. All four teachers went through teacher professional training on how to use the apps together with a pedagogical framework comprising Questioning, Investigating, Making, and synthesising (QIMS) (Wen et al., 2023). In terms of teaching experience, all four teachers have more than 10 years of teaching experience.

3.2. AR based inquiry learning activities

The students participated in AR-based inquiry learning activities on the topic of Plants, including curriculum units on the Plant Transport System and Plant Reproductive System (see Table 1). During the first lesson, the teacher introduced the overarching problem scenario, in which the students were tasked with helping alien friends whose planet was dying due to a lack of plant growth. Accompanying these topics were five AR activities with two apps focused on the Plant Transport System (Oil beaker puzzle and Celery lab) and two on the Plant Reproductive System (Flower Anatomy and Seed dispersal), with the last app being a consolidation of all previous learning on the topic of Plants (Plant engineer).

The objective of the Oil Beaker Puzzle activity was for students to retrieve treasure that was stuck in a beaker filled with oil, designed to help students understand the principle of capillary action. Students were meant to apply the principle of capillary action found in plants to solve the puzzle. The Celery Lab app was designed to help students understand the function of food- and water-carrying

Table 1. AR-enabled inquiry activities of the study.

AR apps	Learning objectives	AR-based Activities	Examples of the AR environment
Topic 1: plant transport system			
Oil beaker	Apply understanding of capillary action in plants.	• Retrieve treasure stuck in a beaker filled with oil.	Pouring a specific colour into the beaker by using a marker 
Celery lab	Identify food- and water-carrying tubes and their functions	• Conduct AR experiments with virtual celery • Observe movement of water and food particles in the celery; • Complete quiz	
Topic 2: plant reproduction system			
Flower anatomy	Locate basic parts of a flower and their functions.	• AR investigation of parts of a virtual flower; • Complete quiz.	Scanning a part of a flower. 
Seed dispersal	Explain patterns of water dispersal, wind dispersal and explosive action in plants.	• Grow virtual seeds on an island and monitor their dispersal patterns.	Plants dispersed by wind in a pattern. 
Plant engineer	Consolidate students' learning of all concepts in the two topics	• Make a virtual plant that will survive harsh weather conditions. • Presentation of plant with scientific explanations.	Example of a completed plant model. 

tubes in celery plants. Through the app, students could conduct virtual experiments and observe changes happening in the plants in real-time animations. For the Flower Anatomy app, Students were given a "Mission list" and tasked with identifying and scanning the main parts of a virtual plant to understand the basic structure and function of a flower. Once a part was located, students were presented with a textual description of the part and a question to check their understanding. In the Seed Dispersal app activity, students planted fictional plants on a virtual island and observed the growth and dispersal patterns of the plants. Students were asked to hypothesise which seeds could be dispersed by wind, water, or explosive action and provide evidence for their hypothesis. The last app, Plant engineer was designed as a final consolidation of all the previous learning for all the topics. It aimed to summarise the students' botanical knowledge by providing a fictional scenario where students had to help aliens "re-green" their planet, which had harsh weather conditions such as drought and strong winds. Students were asked to apply what they had learned in the previous units and design a plant that could survive and reproduce in those conditions. After completing the activity, students presented their designs and explained the scientific reasoning behind their choices.

The activities were designed to engage students in hands-on, interactive learning, with the aim of helping them understand key concepts and principles related to plant transportation and reproduction. The students were also given opportunities to apply their learning and demonstrate their understanding through a final presentation.

3.3. Data sources and instruments

Each student took pre-and post-tests which assessed learning gains; post-surveys which evaluated their perceptions towards the AR activities, their level of engagement in the learning process, as well as epistemological beliefs after experiencing the learning activities.

3.3.1. Pre-and post-tests

To investigate students' learning gains on the topics covered in the study, pre-and post-tests comprising a total of 13 questions (6 MCQ and 8 open ended) were administered to all the students from the 4 classes. The students completed the post-test after the intervention and the test questions were the same for both pre- and post-tests. Both pre-and post-testes had a maximum score of 20 marks. It comprised questions about plant reproduction, in the areas of pollination, plants' life cycle processes and seed dispersal methods. An example an open-ended question is as follows:

> Ming saw some brightly-coloured and fleshy fruits growing in her garden even though she did not plant them there. The edible fruits contained many small, inedible and indigestible seeds. How do you think these fruits are dispersed? Please provide explanations.

Open ended questions require critical thinking and application. The students completed the post-test after the intervention and the test questions were the same as the pre-test.

3.3.2. Questionnaires

The post-survey was developed based on existing questionnaires for measuring learning engagement and epistemic beliefs and consisted of 6 scales and 21 items. The Items were rated on a 5-point Likert Scale (1 = strongly disagree; 5 = strongly agree). The measurement items on AR activities were self-developed to investigate students' perceptions of the effectiveness of the designed AR activities in helping them understand the topics covered in the study. Examples include "the animations and pictures in the AR app made me want to explore more about the science topics on my own" and "the tasks in the AR app helped me to understand the given topics".

The measurement items for learning engagement were adapted from a study by Fu et al. (2020), designed to assess both emotional and cognitive engagement. Example questions from the survey include, "I stayed with the app until I completed all the tasks" and "Using the AR app to learn science was very absorbing".

The measurement items on epistemic beliefs were adapted from the scientific epistemic beliefs' questionnaire developed by Conley et al. (2004). The questionnaire is one of the most widely used questionnaire for epistemic beliefs that measures the four different facets of epistemic beliefs (Lee et al., 2021). The four facets are "source of knowing" (e.g. knowledge is given down by authority or can be tested); "certainty of knowledge" (e.g. knowledge is static or continuously developing); "simplicity or development of knowledge" (e.g. knowledge is absolute or relative); and "justification of knowing" (e.g. knowledge can be learned from critical thinking processes or by accepting existing facts).

3.3.3. Post study interviews with teachers and screen recordings of group work

Four teachers from the four participating classes were interviewed after the intervention. The interview with each teacher lasted an hour and the teachers were asked about their reflections on using AR and how it affected their teaching beliefs. Additionally, during the lessons, screen recordings of students' interactions and discussions during pair work were collected. These data were analysed using a coding scheme proposed by Lee et al. (2006) to assess the level of inquiry and depth of explanation in the AR-based learning activities.

3.4. Data analysis

The quantitative data were analysed using structural equation modelling (SEM), using the learning gains as the endogenous variable and learners' perception of the AR experience, their learning engagement, and epistemological beliefs as the exogenous variables, to reveal the working mechanism behind AR experience and the learning gains. CFA and SEM analysis were conducted in AMOS 28, using maximum Likelihood Estimation as the estimation method. The model fit was assessed using the following criteria: RMSEA <0.05, CFI and TLI value close to 0.95, and $\chi^2/df < 2$ (Hu & Bentler, 1999).

To further explain the findings drawn from the statistical analysis, content analysis was used to analyse the qualitive data that was transcribed from students' discourse during their AR-based inquiry learning activities. The discourses of four groups from two classes were selected for transcription as the discourse of these four groups were fully recorded in each AR-based activity. Two coders, who were skilled in content analysis, encoded all the discourse data based on the coding schemes of inquiry and explanation. The unit of coding was the turn of students' dialogue that reflected students' questioning and explanation. Students' questions were coded on a 4-point scale for the levels of inquiry, and students' responses were coded on a 7-point scale to ascertain the levels of depth of explanation, that were proposed by Lee et al. (2006). Tables 2 and 3 show the description of each level and its corresponding examples. After discussion, the inter-rater reliabilities of coding were .90 and .94 in terms of Pearson Correlation.

4. Findings

4.1. Students' participation and learning gains from the AR-based inquiry learning activities

As shown in Table 4, the descriptive analysis of the six constructs showed that the students had positive perceived efficacy of AR-based inquiry learning activities ($M = 3.773$, SD = .961). Students felt they were engaged in the learning activities ($M = 4.062$, SD = .832). The findings are consistent with the feedback from teachers. One teacher mentioned that students were more excited and that it "generate[d] a lot of discussion, which is usually absent … it actually generate[d] a lot of sharing of ideas and affirmation by friends". She believed that AR improved communication generated between students, because of the AR, and was "the most valuable part". Teachers agreed that most students found using AR "fun and interesting". It was also observed that students found it "cool" when they could see the AR simulations of abstract science concepts. For instance, when students were able to see the movement of food and water particles in the celery stem, students expressed awe, remarking that "it was so cool", and that it was something they could not see with the naked eye when examining the actual celery specimens.

Statistical results of the pre-test ($N = 139$, $M = 8.953$) and the post-test ($N = 139$, $M = 15.155$) showed that students' academic performances improved after intervention. A paired two-sample t-test for means indicated a statistically significant difference between performances on the pre- and post-tests ($t = 19.905$, $p < 0.001$). Furthermore, students showed more sophisticated beliefs about development of knowledge ($M = 4.106$; SD = 0.807) and justification of knowledge in

Table 2. The rating scheme for depth of inquiry.

Rating	Description
1	Questions on definitions and simple clarification
2	Questions asking for factual, topical and general information
3	Questions identifying specific gaps and asking for open-ended responses and different viewpoints
4	Explanation-based questions – Focus on problems not topics; identifies sources of inconsistencies; generates conjectures and possible explanations.

Table 3. The rating scheme for depth of explanation.

Rating	Description
1	Repeat or simply restate a fact or a statement that has been made.
2	Give factual information and general description; responses are usually centred on facts and topics;
3	Give responses and make inferences supported with some relevant information.
4	Make assertions supported with explanation, evidence and relevant examples.
5	Refocus discussion or highlight key conceptual issues for further inquiry; bring out other aspects of issues for discussion.
6	Recognise high points in discourse; metacognitive, show personal reflection.
7	Synthesise different points of views and make a "rise-above" summary.

science ($M = 4.365$; SD = 0.730), and comparatively less sophisticated beliefs about the source ($M = 3.076$; SD = 0.857) and certification of knowledge in science ($M = 3.496$; SD = 0.898) (Table 5).

4.2. The working mechanisms behind the AR experience and the learning gains

4.2.1. Measurement model

Confirmatory factor analysis (CFA) was conducted to validate the constructs and assess the quality of structural reliabilities. Results of CFA showed that the overall fit of the model is within the threshold (χ^2/df = 1.226, $p < .022$; CFI = 0.975; RMSEA = 0.038; TLI = 0.966). Three to four items remained for each dimension. All the factor loadings of the measured items were statistically significant and higher than 0.60 (see Table 2). The reliability coefficients (Cronbach's alpha) for all the dimensions ranged from 0.707, to 0.879. The composite reliability (CR) coefficient exceeded 0.7 (ranged from 0.768 to 0.916), and the AVE exceeded 0.50. Discriminant validity was tested using the correlation matrix of the constructs and the results are shown in Table 4. The square root of AVE exceeded the bivariate correlations between structs, demonstrating adequate discriminant validity (Tables 6 and 7).

4.2.2. Structural model

Structural equation modelling (SEM) was used to evaluate the conceptual model. The conceptual model was tested against the dataset. Then, the link between SEB_Justification and SEB_Development and the link between SEB_Source and SEB_Certainty were added based on modification indices. It has been widely acknowledged that justification and development were correlated to reflect students' sophisticated beliefs, and source and certainty were correlated to reflect students' beliefs about absolutist knowledge and knowledge (Tsai et al., 2011; Cheng, 2018). The model yielded the following model fit indices: χ^2/df = 1.347, CFI = 0.956, and RMSEA = 0.047, TLI = 0.944. The indices all met the recommended guidelines (Tabachnick & Fidell, 2013), which suggests that the conceptual model fit the survey data (Figure 1).

The structural model revealed that students' perceived AR-supported inquiry-based learning activities had a significant positive influence on students' perceived learning engagement ($\beta = 0.825$, $p < .001$). Perceived learning engagement positively influenced students' epistemic beliefs in the facet of justification of knowledge ($\beta = 0.440$, $p < .001$). Moreover, students' epistemic beliefs in the facet of certainty of knowledge had a positive influence on students' learning gains ($\beta = 0.702$, $p < .05$). Contrary to the hypotheses, perceived learning engagement did not influence

Table 4. Descriptive statistics.

	N	Mean	SD
PAR	141	3.773	0.961
PLA	141	4.062	0.832
SEB_ Source	141	3.076	0.857
SEB_ Certainty	141	3.496	0.898
SEB_ Development	141	4.106	0.807
SEB_ Justification	141	4.365	0.730

Table 5. Paired *t*-test for the conceptual understanding improvement.

Test	No. of students	Estimated marginal means	SD	*t*	*P*
Pre-test	139	8.953	3.845	19.905	<.001
Post-test	139	15.155	3.027		

students' epistemic beliefs in the facet of source of knowing ($\beta = 0.025$, $p > .05$), certainty of knowledge ($\beta = 0.062$, $p > .05$) and development of knowledge ($\beta = -0.025$, $p > .05$). Additionally, perceived learning engagement did not influence students' learning gains ($\beta = -0.075$, $p > .05$). Table 8 summarises the hypothesis testing results of the separate paths in the conceptual model.

4.3. Students' depth of inquiry and explanation in AR-based inquiry learning activities

As shown in Table 9, students' inquiry and explanation did not take place frequently when they were completing the AR-based activities, and the depth of inquiry or the depth of explanation were at a comparatively low level. We also observed that students were generally more comfortable with a classroom discourse pattern where teachers would direct questions to them, and they would answer. Teachers were required to actively steer the discussion to encourage students to participate more actively in inquiry-based discursive practices.

Table 10 shows the example how the higher level of explanation that occurred in one of groups we observed from Class 1. The teacher cut a celery stem unto half, placed half into blue coloured water and the other half in red-coloured water. He then got the students to make a prediction, before they used the AR app to determine the outcome of the experiment. After students used the app, he again reiterated the outcome of the experiment with the actual live specimens of the celery plant. In the interview with the teacher, he said the use of AR and live specimens must be planned carefully so they can "work hand in hand" to better support learning that will "allow [students] to connect the dots" and "to make sense of what they are learning or what they are observing". We observed how prediction questions can trigger a sense of excitement in students. As they use the app, they will be motivated in their quest to determine if their predictions are accurate. Once that motivation and engagement is present, teachers can use that as opportunity to get students to explore answers to the question, providing evidence and reasoning. As the teacher reflected in the post-intervention interview,

Table 6. Factor loading and Cronbach's alpha.

	Items	Standardised factor loading	Cronbach's alpha	Composite reliability
Perceived AR-based Inquiry learning (PAR)	PAR1	.849	.875	.916
	PAR2	.886		
	PAR3	.919		
Perceived Learning Engagement (PLE)	PLE1	.789	.817	.83
	PLE2	.724		
	PLE3	.857		
	PLE4	.578		
SEB_ Source (SEBS)	SEBS1	.705	.843	.846
	SEBS2	.799		
	SEBS3	.718		
	SEBS4	.816		
SEs_ Certainty (SEBC)	SEBC1	.677	.707	.706
	SEBC2	.716		
	SEBC3	.606		
SEB_ Development (SEBD)	SEBD1	.749	.827	.828
	SEBD2	.765		
	SEBD3	.839		
SEB_ Justification (SEBJ)	SEBJ1	.755	.879	.884
	SEBJ2	.894		
	SEBJ3	.807		
	SEBJ4	.776		

Table 7. Discriminant validity.

	PAR	PLE	SEBJ	SEBD	SEBC	SEBS
PAR	**0.885**					
PLE	0.828	**0.744**				
SEBJ	0.329	0.442	**0.810**			
SEBD	0.266	0.353	0.750	**0.785**		
SEBC	0.081	0.056	0.415	0.436	**0.668**	
SEBS	0.012	0.015	0.296	0.383	0.805	**0.761**

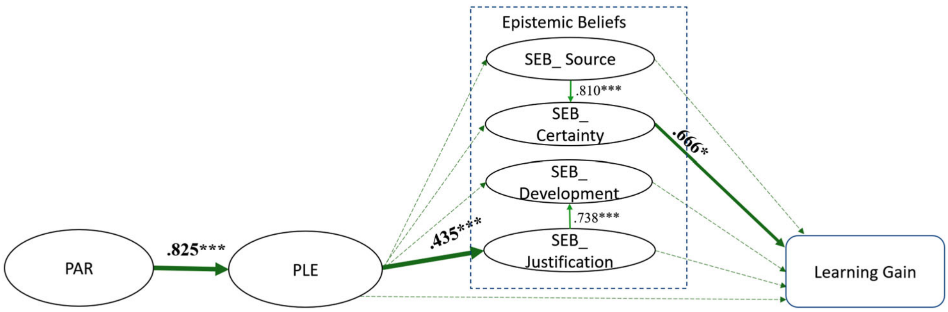


Figure 1. The structural model.

> I realise it's up to the teacher to […] sort of make [students] or allow them to connect the dots themselves. As in, they are doing all these apps and all, they are using this AR to discover and all but how do they make sense of what they are seeing? How do they interpret the observation?

Table 11 illustrates an example where the teacher of class 2 was attempting to consolidate the learning from the oil beaker activity through a review discussion. The discourse took place at the class level. While the main concept to be addressed was water transportation in plants, a student brought up two concepts – one was heat, which was taught in the previous year – and the other, evaporation, which was not taught yet. Students also brought up differing perspectives during the reviewing discussion and the teacher tried to get each student to explain their perspectives. After the lesson, the teacher shared that she capitalised on this and tried to engage them in the scientific discussion practice. As she reflected in the post-intervention interview, some students

> may not be correct, but again, we do listen to their explanations. So, some of them will explain why they want to do it that way. So, indirectly, I will not say to tell them that is wrong. But I will also tell them that [to suggest] if you have a better solution, so that will motivate them to think of other ways

Taken together, the results of content analysis suggest that the teacher's instruction had an impact on the depth of students' questioning and explanation. As teachers mentioned in the post interview, they needed to provide supports to direct scientific discussions that could lead the students to

Table 8. Hypothesis testing results

Hypotheses	*B*	*t*-value	*p*-value	Decision
H1: Perceived AR Activities → Engagement	.821	9.393	<.001	Supported
H2: Engagement→LearningGain	-.097	-0.835	.404	Not supported
H3: Engagement→EB_Sources	.056	0.576	.564	Not supported
H4: Engagement→EB_Certainty	.143	1.357	.175	Not supported
H5: Engagement→EB_Development	.403	3.982	<.001	Supported
H6: Engagement→ EB_Justification	.473	4.827	<.001	Supported
H7: EB_Sources→ LearningGain	.074	0.816	.414	Not supported
H8: EB_Certainty→ LearningGain	.364	3.372	<.001	Supported
H9: EB_Development→ LearningGain	.099	0.959	.338	Not supported
H10: EB_Justification→ LearningGain	.066	0.634	.526	Not supported

Table 9. Distribution of students' discourse

Types of Discourse	Class	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Inquiry	1	13	17	4	0			
	2	9	20	12	6			
Explanation	1	8	20	4	6	0	0	0
	2	4	15	21	6	3	1	0

Table 10. Transcribed example of higher-level explanation triggered by teacher.

Turns	Teacher/students	Transcripts	Level of inquiry	Level of explanation
1	Teacher 1	Can you see the cross section of the plants? How come the red and the blue did not combine to become purple? Why?		
2	Student 1.1 (S1.1)	Different tubes.		2
3	Teacher 1	Ask yourself, why the colour is not purple, why the red and blue are not mixed together.		
4	S1.1	They are in different tubes. They will never be in contact.		4
5	S1.2 to S1.1	Why?	2	
6	S1.1 to partner (S1.2) by pointing to the coloured water particles moving up the cross section of a cut celery stalk with AR app	See, the red one is in there and it will go up and the blue one is in there and it will go up. Look at that- look there red and there's blue, and it's going up. Look at the particles. The particles are there, can you see?		4

participate more actively in the use of scientific and inquiry communication. Additionally, the teachers also mentioned the challenge of time constraints. Teacher 2 said

> It's just that sometimes that I may cut this short because of time constraints. Sometimes I would like to discuss even further, but because of time constraints that we need to finish this […] And also, I have limited periods.

Table 11. Opportunities for students to reflect on different perspectives.

Turns	Teacher/ students	Transcripts	Level of inquiry	Level of explanation
1	Teacher 2	Does it matter if I use the lamp first or the filter paper first?		
2	S2.1	Yes, I guess it matters because you must first absorb the oil first before the water evaporates		3
3	Teacher 2	Are you saying if I don't remove the oil, the water will not be able to evaporate? Any idea why?		
4	S2.1	I think because the oil will block the oxygen from entering so water cannot evaporate		4
5	Teacher 2	You have anything to share? [towards S2.2 who raised his hand]		
6	S2.2	Oxygen will not make the water evaporate … because oxygen will not cause things to evaporate.		4
7	S2.1	Then, what do you think?		
8	S2.2	Heat is the one that will cause evaporation, not oxygen		5
9	S2.1	Oxygen will help in the process of evaporation		3
10	Students of class 2	[chorus] No, still wrong.		
11	Teacher 2	How many agree that oxygen helps in the evaporation process?		
12	Teacher 2	How many think that heat is the one that helps in the evaporation process?		
13	Students of class 2	[chorus] Both		
14	Teacher 2	Why do you think there was a layer of oil in the beaker? I want you to do some research first at home and google – what happens when you have a layer of oil on top of some water – we will discuss at the next lesson		

> Sometimes I also have to just cut short the discussion. Not that I want to, but it's sometimes [*sic*] time limitation. So sometimes I address a little, then I will divert them back to the activity. Because to get them back to the activity sometimes also will take a while.

6. Discussion

The findings of this study indicated that students had positive perceptions of the AR-based inquiry learning activities and were engaged during the designed activities. Additionally, students' academic performance improved significantly as evidenced by their scores on the pre- and post-tests. The findings of the study suggest that the AR activities were generally well-designed. Moreover, the findings demonstrated that students' perceived engagement in the AR-based inquiry activities predicted their epistemic beliefs, with a significant positive association with the dimensions of development and justification of knowledge in science. Conley et al. (2004) revealed that young children's epistemic beliefs about science changed over a few weeks when they were engaged in hands-on science classes. It is worth noting that in Conley et al.'s study (2004) students did not show significant improvement in the development or justification dimensions of the epistemic beliefs. They argued that it could be due to the lack of emphasis on argumentation and reflection in the instructions and suggested that an inquiry-based approach might lead to epistemological development in these two dimensions. Our study's findings support the assumptions made in Conley et al.'s study. When students participated in AR-based inquiry learning activities, their epistemic beliefs about the dimension of justification improved, and their epistemic beliefs about the dimension of development would be improved accordingly.

Meanwhile, we found evidence that students tended to have more advanced beliefs about the nature of scientific knowledge after the AR-based inquiry learning activities. These beliefs include that scientific knowledge is contextual and constantly evolving (development) and verified through multiple sources (justification) rather than absolute and unchanging (source) and certain (certainty). These findings align with Cheng's research (2018) on the relationship between students' epistemic beliefs and conceptions of learning science through AR books. It is possible that this result is due to the way the source and certainty dimensions were measured through reverse questions in the survey, but it also suggests that the AR learning environment may provide learners with more contextual information and multiple sources.

Additionally, epistemic beliefs on the dimensions of certainty positively predicted academic performance. That means students who viewed scientific knowledge as uncertain tend to have better academic performance. This finding is consistent with most existing studies that students with sophisticated epistemic beliefs are likely to have better academic performance. Schommer-Aikins (2004) explained that a learner who views authority as the only valid source of knowledge would think that learning is passive. If students feel that knowledge must be given to them by an authority, they may see themselves as a non-authority figure and thus incapable of knowledge construction. This learner may not tend to challenge authority in class and would easily abandon learning if it is perceived as too difficult or is required too much effort. However, if critical thinking was encouraged and students are taught to evaluate authority assertions, the student might re-examine his/her view of knowledge and be willing to question authority, leading to a more active learning process and better academic performance.

However, the study found that students' perceived engagement in the AR-based inquiry learning activities had no significant effect on their academic performance. As Radu and Schneider (2019) indicated in their study, AR visualisation, regardless of any educational content, influences learner engagement, but the high engagement may be simply due to the exposure to new technology, irrespective of the presence of learning content. Moreover, the findings of this study demonstrated that the epistemic beliefs of the dimension of justification did not significantly predict students' academic performance. In other words, the designed AR-based inquiry learning activities helped to raise students' awareness that scientific knowledge can be learned from critical thinking processes, but they may not help develop students' inquiry or critical thinking skills directly. From our observations, questioning, explanations, and argumentation-related interactions did not take place frequently when students were completing AR-based tasks. The depth of inquiry and explanation remained at a comparatively lower level.

Researchers in the field of epistemic cognition have suggested that students need to optimise the right skills for critical thinking (Chinn et al., 2011; Greene & Yu, 2015; Sandoval, 2012). Moreover, researchers pointed out that one's epistemic beliefs – how one would internalise knowledge, the process of knowing, with the awareness of understanding how knowledge is constructed – is related to the learning process of adopting cognitive strategies (Ozkal et al., 2009) which subsequently could translate to higher levels of achievement (Muis & Duffy, 2013). This is particularly so when students are involved in open-ended learning activities with complex and controversial viewpoints (Mason et al., 2010). As the findings of the content analysis in this study have shown, despite the teachers creating an encouraging and active learning environment, the depth of questions asked by students remained at a superficial level. Most of the asked questions were at the level of clarification. This may indicate that more effort is needed to develop students' ability to ask good questions.

The findings of the study indicated that there is room for improvement in the design of AR-based inquiry learning. Firstly, as observed, teachers' prediction-related questions helped to trigger higher-level explanations from students. From the design perspective, these types of prediction questions could be incorporated into the AR-based activity design. Secondly, more attention should be paid in providing more opportunities for students to engage in argumentation or reflection, either individually or in groups, beyond just exploration and direct observations. Learners should be provided with opportunities to examine the validity of information gathered when confronted with complex or challenging topics (Greene & Yu, 2015; Sinatra & Hofer, 2016). As suggested by Schommer-Aikins et al. (2010), to support young learners in their development of epistemic beliefs, opportunities should be created for students in discussions to reflect on different perspectives and consider conflicting views. Teachers should get students to think critically by encouraging them to evaluate contradictory perspectives (Walker et al., 2020). With reference to the episode shown in Table 11, these strategies are also applicable to teaching in the AR environment. Thirdly, as observed, teacher-guided discussions played an essential role in promoting students higher-level thinking. A learning dashboard could be designed to help teachers monitor students' work progress in AR activities and trigger students' reflections in the classroom environment.

7. Conclusion

This study contributes to the understanding of the interplay between AR-based inquiry learning and students' epistemic beliefs. The findings suggest that the designed AR activities can help to engage learners, and the engagement is positively related to students' epistemic beliefs, particularly in the dimensions of justification of scientific knowledge. Beyond providing learners with an immersive environment for observation, AR learning design should take into account ways to scaffold learners in argumentation and reflective thinking, to move learners from hands-on activities to minds-on activities. Instead of the shaping students' critical skills in the AR-based inquiry learning, students' questioning skills should be deliberately cultivated.

There are some limitations to this study. Firstly, there is no control class of the study because the teachers of the partner school expected that every student would have an equal opportunity to experience the new learning environment. Secondly, the content analysis only focused on the discourse of two groups in each class. We did not manage to record the screen recordings from every group for all the lessons. The data included the students' interactions and discussions which were recorded using the iPad's screen recording function. However, some students accidentally turned it off, some recordings malfunctioned, or the sound was not recorded. Hamilton and Duschl (2017) argued that researchers have turned research interest in students' epistemology to practical epistemology. If more comprehensive process data could be collected, we will further investigate the interplay between students' epistemic beliefs and their epistemic behaviours. Thirdly, the structural model could be improved with a larger sample size. Epistemic beliefs have been evidenced to be a factor that influences the way students engage in argumentative discourse and reasoning (e.g. Noroozi et al., 2016). The interrelationships between engagement and epistemic beliefs could be further tested by considering contextual factors such as students' capabilities or teachers' instructional styles.

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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-2020-04-037. The author affirms that all participants provided informed consent for the publication of the images.

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