

Explore the Effect of Metacognitive Awareness on University Students' Learning Outcomes in the Metaverse: Evidence from Eye-tracking Data

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Abstract: In the current study, we explored the learning outcomes of five learners with different levels of metacognitive awareness in inquiry-based learning activities within the metaverse, and used eye-tracking technology to reveal the changes in eye movements of different learners during the learning process. The results showed that learners with high metacognitive awareness levels dealt with problems more comprehensively in general during problem-solving than learners with low metacognitive awareness levels. In addition, eye movement data showed that students with high metacognitive awareness levels tended to identify the inquiry question first and then carry out specific activities during their interactions; at the same time, they also had a more reasonable sequence of interactions with the learning materials compared to students with low metacognitive awareness levels. The study has practical implications for the future design of inquiry-based learning activities in the metaverse.

Keywords: Metacognitive awareness, Inquiry-based learning, Metaverse learning environment, Eye-tracking technology, Mind map

1. Introduction

The development of online learning has encouraged students to learn strategically. The metaverse, a virtual environment created through the integration of various technological advancements, is widely recognized as a parallel landscape within education (Ning et al., 2023). However, according to Chen et al. (2022), although the majority of students are enthusiastic about the metaverse learning, they may not be able to fully regulate their learning process. Learners with high levels of metacognitive awareness can significantly improve their regulated abilities (Ramadhanti & Yanda, 2021). Therefore, we aimed to figure out the learning outcomes of students with different levels of metacognitive awareness and their eye movements patterns by using eye-tracking technology in the metaverse based on inquiry-based learning.

2. Literature Review

2.1 Inquiry-based Learning

Inquiry-based learning is becoming increasingly popular in learning science subject (Pedaste et al., 2015). One of the underlying reasons is that the success rate of the inquiry process can be greatly improved due to recent technological developments that enable it to be supported by electronic learning environments. However, some researchers have suggested that the potential of inquiry-based learning is also constrained in online education environments. For example, some scientific inquiry that is costly or even impossible to experience in person in

reality will hinder learners' conceptual understandings. Song et al. (2023) explored the metaverse as an alternative learning environment to provide learners' opportunities to conduct inquiry activities that are impossible to be experienced physically (such as assembling the solar system). Thus, it is a promising trend to conduct an empirical study about inquiry-based learning in the metaverse.

2.2 Eye-tracking Technology

Eye-tracking technology has been successfully and widely employed in various fields of research. According to the eye-mind hypothesis, there is a close relationship between the students' eyes on and the content they process (Schindler & Lilienthal, 2019). For example, the temporal scale of eye movement involves areas of interest (AOIs) which provides insights into "when" and "how long" they process the specific content. Furthermore, the differences in the count and sequences of interactions with specific knowledge points can reveal the differences in the processing of students with different metacognitive awareness, and thus discover the optimal visual processing. In the light of this, this study aims to explore the eye movements patterns of learners with different metacognitive awareness levels.

3. Methods

In the current study, the research questions are: (1) Do students with different levels of metacognitive awareness have the same inquiry-based learning outcomes in the metaverse? (2) What are the differences in their eye movement patterns between students with different levels of metacognitive awareness?

3.1 Learning Topic and Instructional Design

Our learning topic focused on atomic theory and models, which not only demonstrates the sustainable development goals that the education community currently concerns about, but also has a certain degree of difficulty that could highlight the advantages of metaverse learning. As noted, learning atomic theory usually involves understanding three-dimensional atomic models. In the metaverse, after learning text and video materials, learners were allowed to directly switch to the three-dimensional model for observation, which was conducive to improving their cognition in the same learning environment. Furthermore, our metaverse also provided them with scaffolding the digital human teacher, which assisted inexperienced learners to brainstorm solutions to the climate change crisis based on their understanding of atomic theory and the immense power contained with atoms. Therefore, this metaverse could be a three-dimensional personalised learning space rarely explored in existing online learning. Regarding the instructional design, we adopted the five-stage inquiry-based learning pedagogy adapted from Song et al. (2022).

To be specific, stage 1 is "Engage", which required students to familiarize the metaverse platform and identify the inquiry question, and write down "what they know (K)" and "what they want to know (W)" regarding the inquiry question. Stage 2 refers to "Explore", in which students were allowed to interact with text, PPTs, and related videos. Stage 3 is "Analyze" which required students to present their thoughts using a mind map to address the inquiry question. Next stage is "Explain", students needed to match atomic models with theories and explain their mind maps. In the last stage – "Reflect", students were required to make reflections about "what they had learned (L)". It was worth noting that the platform provided a digital teacher with specific prompts to support learners' behaviors at each stage.

3.2 Participants

The participants recruited in this study were students from a university in Hong Kong. The selection of participants was based on the following two criteria: (1) the participants had normal

eye movements so that the eye tracking software could be correctly calibrated; (2) the participants were willing to conduct inquiry-based learning in the metaverse. Finally, 5 students (4 females and 1 male) were recruited with age ranging from 20 to 30. Consent was sought before the experiment.

3.3 Research Procedure

The experiment was conducted in a soundproof laboratory, and consisted of a 5-minute pre-survey, 40 minutes of eye-tracking, and a 5-minute post-test. Firstly, a pre-survey was conducted to understand the participants' demographics, levels of their metacognitive awareness, and their familiarity with the learning topic. A 5-point Likert scale with 30-item was adopted from Jaleel (2016) to measure metacognitive awareness. One example is 'When learning something new, I would compare it to what I've learned before'. Secondly, Pupil eye-tracking device was used. This device features high-resolution scene and eye cameras for monocular and binocular gaze estimation. Participants were familiarized with the equipment, learning procedures, and the purpose of the eye tracking experiment under guidance, and then allowed their behavior to be recorded. Lastly, all participants completed a post-test after the eye-tracking experiment.

3.4 Coding Scheme

3.4.1 Eye Movement Behaviour Coding

In our study, we primarily focused on participants' interactions with digital humans (IDH), texts (IT), videos (IV), 3D objects (IO), and the time spent on watching self-regulated sheets (ISR) and writing on the whiteboard (WW). Firstly, the temporal scale involves measuring the interactive time of each event. Secondly, the spatial scale examined the sequences of different interactions. Lastly, the count scale tracked the interactive count of each event.

3.4.2 Mind Map Coding

This study referred to previous studies (Abd Karim et al., 2016), and developed a coding scheme by two experienced educational technology experts. The final scheme included five categories: participants involved, subject domains, applications, promotions, and emotions and attitudes (see Table 1). Two experienced coders were asked to code according to the coding scheme and resolve disagreements through full discussion and achieve consensus.

Table 1. Coding Scheme of Participants' Mind Map

Categories	Sub-categories	Categories	Sub-categories
1.Participants involved	1.1 Government staff	2.Subject domain	2.1 Science
	1.2 Educators and students		2.2 Social science
	1.3 Scientists		2.3 Others
	1.4 Others	4.Promotion	4.1 International cooperation
3.Application	3.1 Industry		4.2 National policy
	3.2 Agriculture		4.3 Social initiatives
	3.3 Service industry		4.4 Individual efforts
	3.4 Others		
5.Emotion and attitude	5.1 Positive		
	5.2 Neutral		
	5.3 Negative		

4. Results

4.1 Mind Map Analysis

Based on the self-reported data, researchers obtained the metacognitive awareness scores of different participants, dividing those with higher than average scores into the high-scoring group and those with lower than average scores into the low-scoring group. Referring to the mind map coding scheme in Table 1, the mind maps of the five students were analyzed. A total of 36 codes were obtained, including 15 codes for the low-scoring group and 21 codes for the high-scoring group. Table 2 showed the item frequency and percentage results of the drawings of students with different levels of metacognitive awareness. Overall, the most to least categories were participants involved (27.78%), promotions (25.00%), applications (19.44%), subject domains (13.89%), and emotions and attitudes (13.89%).

Table 2. *Distribution of the elements of mind maps of students with high and low metacognitive awareness levels by the categories and subcategories.*

Categories and sub-categories	High-scoring group N (%=N/3)	Low-scoring group N (%=N/2)	Total N (%= N/5)
Participants involved			
Government staff	2 (66.67%)	2 (100.00%)	4 (80.00%)
Educators and students	1 (33.33%)	1 (50.00%)	2 (40.00%)
Scientists	3 (100.00%)	1 (50.00%)	4 (80.00%)
Others	0 (0.00%)	0 (0.00%)	0 (0.00%)
Subject domains			
Science	3 (100.00%)	2 (100.00%)	5 (100.00%)
Social science	0 (0.00%)	0 (0.00%)	0 (0.00%)
Others	0 (0.00%)	0 (0.00%)	0 (0.00%)
Applications			
Industry	3 (100.00%)	1 (50.00%)	4 (80.00%)
Agriculture	0 (0.00%)	1 (50.00%)	1 (20.00%)
Service industry	1 (33.33%)	1 (50.00%)	2 (40.00%)
Others	0 (0.00%)	0 (0.00%)	0 (0.00%)
Promotions			
International cooperation	2 (66.67%)	1 (50.00%)	3 (60.00%)
National policy	1 (33.33%)	1 (50.00%)	2 (40.00%)
Social initiatives	1 (33.33%)	1 (50.00%)	2 (40.00%)
Individual efforts	1 (33.33%)	1 (50.00%)	2 (40.00%)
Emotions and attitudes			
Positive	3 (100.00%)	2 (100.00%)	5 (100.00%)
Neutral	0 (0.00%)	0 (0.00%)	0 (0.00%)
Negative	0 (0.00%)	0 (0.00%)	0 (0.00%)

4.2 Eye Movement Analysis

In order to further explore the reasons why learning outcomes were different among students with different levels of metacognitive awareness, this study conducted an in-depth analysis of eye movement behavior. Figure 1 shows the participants' eye interactions over time.

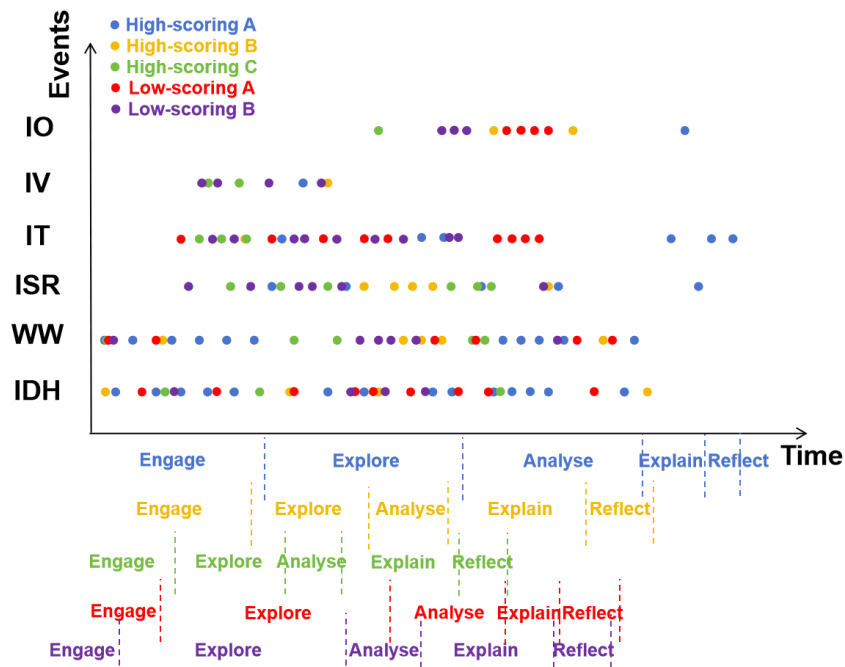


Figure 1. The interactive events of participants with different levels of metacognitive awareness (High-scoring and low-scoring) in the metaverse over time.

5. Discussion

This study investigated the mind maps of students with different levels of metacognitive awareness based on inquiry-based learning in the metaverse. In addition, we explored their eye movement patterns during learning. The results showed that students with high levels of metacognitive awareness considered problems more comprehensively when making mind maps. It can also be seen from Table 2 that high-scoring students believed that multi-party cooperation (participants involved) was more likely to produce results in the issue of nuclear energy mitigation of climate change. Furthermore, students who performed well may plan, monitor and adjust their learning strategies strategically based on their own cognition in the brand-new metaverse environment, especially when faced with unfamiliar topics.

In order to further explore the learning trajectory of high-scoring students in the metaverse, the study also found that they generally stayed longer in the “Engage” stage according to eye movement data, showing their planning for inquiry questions. First, in terms of time, high-scoring participants generally did not engage in a particular interaction for too long, but instead use frequent interactions to constantly adjust and reinforce their learning strategies. They may not good at memorizing, but understand knowledge points through the connections between learning materials. In the metaverse, recitation is no longer the core ability of students, but rather the metacognitive ability to regulate. Thus, participants who had high levels of metacognitive awareness were likely to perform better in the metaverse. In addition, compared with the low-scoring group, the high-scoring group generally spent more time interacting with digital humans than with other learning materials. Interacting with digital human were more flexible in the metaverse, which helped learners promptly discover their own cognitive deficiencies and cognitive errors. Second, in terms of spatial scale, high-scoring participants preferred not to organize answers before interacting with the digital human, but instead started inquiries after in-depth communication with the digital human. According to information processing theory, learners who have a holistic understanding of the problem inside the metaverse can better understand the background and logical structure of it, so as to carry out inquiries in a targeted manner (Swanson, 1987). High-scoring participants regarded the digital human as a support to understanding the learning topic in advance, which was conducive to achieving better performances. Lastly, the high-scoring group generally

interacted more often than the low-scoring group, because they needed to frequently go back and forth between different knowledge points to find connections.

6. Research Implications, Limitations and Recommendations

This study explored different effectiveness of students with different levels of metacognitive awareness in the metaverse through inquiry-based learning. Moreover, we focused on using eye-tracking technology to analyze their eye movement trajectories during inquiry learning in the metaverse, which would be a major innovation compared to the majority of previous studies focusing only on 2-D learning environments or virtual environments with a headset. Furthermore, our research included the digital human teacher that could provide different students with corresponding scaffolding based on different stages of inquiry-based learning. In addition, using eye-tracking technology could help figure out their interaction times, counts and sequences with digital teachers. This could be a practical example of how to apply generative AI in the metaverse. Thus, this current study has practical implications for the future design of metaverse teaching platforms and how to better intervene and enhance learners' metacognitive awareness as well.

However, this study also had some limitations. First, the sample of this experiment only came from the same university in Hong Kong, and the number of people was relatively limited, so the results may only represent some students. Second, the mind map and scale used in this study to collect data may have subjective bias. Based on these limitations, this study made the following suggestions for future research. Firstly, it was recommended to recruit students from different universities or educational levels to participate. Secondly, in addition to mind maps and surveys, additional methods such as quiz analysis and interview analysis should be added.

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