Knowledge-Graph-Driven Mind Mapping for Immersive Collaborative Learning: A Pilot Study in Edu-Metaverse

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***Abstract*—One of the promises of edu-metaverse is its ability to provide a virtual environment that enables us to engage in learning activities that are similar to or on par with reality. The digital enhancements introduced in a virtual environment contribute to our increased expectations of novel learning experiences. However, despite its promising outcomes, there appears to be limited adoption of the edu-metaverse for practical learning at this time. We believe this can be attributed to the fact that there is a lack of investigation into learners' behavior given a social learning environment. This lack of investigation is critical, as without behavioral insight, it hinders the development of education material and the direction of an edu-metaverse. Upon completing our work with the pilot user studies, we provide the following insights: 1) compared to Zoom, a typical video conferencing and remote collaboration platform, learners in the edu-metaverse demonstrate heightened involvement in learning activities, particularly when drawing mind mapping aided by the embedded knowledge graph, and this copresence significantly boosts learner engagement and collaborative contribution to the learning tasks; and 2) the interaction and learning activity design within the edu-metaverse, especially concerning the use of MM.**

***Index Terms*—Collaborative learning (CL), constructivism, immersive learning (IL), knowledge graph (KG), mind map, virtual reality (VR), education metaverse.**

I. Introduction

METAVERSE has been an important focus in the e-learning community in the past few years. So much so that a new term, *edu-metaverse*, has been proposed to specify a class of metaverse that is reserved for the purpose of education [1]. Its main appeal is that edu-metaverse can enable learners to engage in various learning activities remotely and collaboratively in a digital realm. Aside from being able to transfer learners into another place of being [2], a virtual environment is also easier to manipulate for a learning environment [3]. It may also have the potential to uplift remote learning to be, perhaps, an effective substitute for face-to-face learning [4]. Thus, it is worth pursuing edu-metaverse as it can improve the overall learning experience over a multitude of dimensions.

However, a lingering issue for edu-metaverse is a lack of understanding of how learners will behave in a virtual learning environment of edu-metaverse. Although a previous study has explored the differences between conventional video conferencing platforms and edu-metaverse environments in a multi-learner setting [5], the study is focused on investigating learner-to-learner conversations in edu-metaverse, which is a small subset of learner behaviors. An essential question arises: Can the edu-metaverse support not only simple conversations but also more complicated interactions involved in various learning activities? Addressing this question is crucial, as without such insights, there will be a lack of direction on how to design future learning materials. In this work, we have conducted a pilot study aimed at providing general insights, particularly focusing on collaborative learning (CL) and mind mapping (MM).

Our decision to conduct our pilot study on general learner behaviors in edu-metaverse with collaborative MM is based on our previous theoretical work on a constructivist edu-metaverse framework [6]; we called for edu-metaverse learning environments that enable social learning and the feature to visualize knowledge in deconstructed knowledge graph (KG) form. Thus, our work on investigating CL and MM may assist in providing the foundation for an edu-metaverse.

Briefly, constructivism is a teaching methodology that aims to facilitate the learners to internalize and organize knowledge themselves. Our focus areas, CL and MM, are effective tools for assisting learners in internalizing and organizing knowledge. CL involves multiple learners working together to achieve a learning goal. It has a constructivist founding because social constructivism believes that knowledge can be constructed through interaction, correction, and agreement among learners. In addition, both socialization, which facilitates interpersonal interactions among learners, and social learning, which involves acquiring knowledge through these interactions, are expected

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to be key components of the edu-metaverse supporting many concurrent learners. Therefore, exploring CL, which inherently incorporates both aspects, is a vital area of investigation.

Similarly, as a much-used tool for learning, MM also has a constructivist root; this is related to the fact that an MM can effectively help us deconstruct and organize knowledge. Since MM is a tool that can be applied to various educational domains, constructing it is believed to be an ideal learning task for our general investigation of CL in edu-metaverse. We extend our discussion on the details in pedagogical terms in Section III to better lay the theoretical motivation.

In previous work [6], [7], we developed a graph visualization system called K-Cube, designed for a compact representation of knowledge concepts. We have since extended this system to a virtual reality (VR) platform, now referred to as K-Cube VR [6]. In this work, we further enhance K-Cube VR by integrating multilearner and MM functionalities to experiment with CL and MM in the edu-metaverse setting. The core of K-Cube VR is essentially academic yellow pages of connected educational concepts visualized as an explorable graph. Previously, we have shown its success as an immersive environment for course understanding [6]. Here, we transform it into an immersive environment for a collaborative workspace for drawing 3-D MMs. Learners are embodied in avatars in the virtual environment, and they can communicate with one another through speech. The MM in this variant of K-Cube VR can be drawn through various features, such as adding, moving, deleting, and stylizing (i.e., shape, color, label, etc.). The system also supported a speech-to-text and keyboard for typing the keyword for each node on the MM. K-Cube VR is embedded with a KG of relevant concepts. We also explored using the KG to provide recommendations when adding new nodes on the MM. We believe that this can help provide guidance to the learner, particularly in the case when the learner is not familiar with the subject in question.

In order to extract user behavior given the collaborative MM learning task, we have conducted a user study with our edu-metaverse prototype. The learners were asked to use the MM to learn together in designing a game. In order to compare the behaviorial difference from standard streaming platforms, we have conducted a similar CL MM task with Zoom as well. After the experiments, we conducted a focus group study and extracted both the conversation and the MMs. Furthermore, we conducted another user study focused on the useability of our proposed prototype. The result indicates that our prototype can better create a sense of copresence and spatial presence among the learners, allowing them to collaborate more effectively and be more engaged in the learning activity. This is in contrast to the conventional video conferencing and collaboration platform (i.e., Zoom), where learners may find it easier to disengage from the learning activity.

To summarize, this article proposed a system for collaborative MM in edu-metaverse, which can provide insights into learner behavior during remote CL. The contributions of our work are highlighted as follows.

1) A prototype that enables collaborative MM with good usability is proposed.
2) A pilot study that shows the generalized potential of using edu-metaverse for various learning activities through CL and MM is conducted.

The rest of this article is organized as follows. Section II presents related works. The pedagogical literature to discuss the benefit of CL and MM in the context of edu-metaverse is revisited in Section III. The technical overview and interactive details of our system are presented in Section IV. Sections V and VI present user study design. We present the result in Section VII and discuss its implication in Section VIII. Section IX presents limitations and future work. Finally, Section X concludes this article.

II. Related Work

This section discusses some previous related work or systems on VR, CL, MM, and edu-metaverse.

First, there is a growing amount of work investigating how to apply VR for e-learning. Learning with VR is also referred to as immersive learning (IL) [8] due to the immersiveness brought forth by VR. These works primarily focus on the use of extended reality (XR) for educational purposes, with evidence of its effectiveness in various educational settings. XR has been found to enhance traditional classroom education [9], aid in science education [10], [11], [12], raise awareness of social issues in an engaging manner [13], and simulate natural disaster protocols for public safety [14]. There is also ongoing research on improving the effectiveness of IL through the use of pedagogical agents [15]. However, the literature suggests that there has been limited research on learning outcomes, intervention characteristics, and assessment measures associated with XR in education [16], [17], [18]. How VR can enhance engagement in learning is also a well-discussed topic [6], [19], [20]. Last, there is also an attempt to frame VR systems for educational needs via a cognitive approach [21].

CL is a methodology in education. As such, many platforms and systems have been developed throughout recent times. Foremost, there is a survey paper that discusses platforms for CL [22]. Similarly, Li et al. [5] compare different VR platforms for CL. There is a work that has explored the benefits of using a CAVE system for IL [23]; based on this CAVE system, an extended work has also proposed design and implementation for a CAVE-based e-learning system [24]. A CL e-learning system oriented on user perceptions has also been investigated in [25]; they pinpointed pivotal elements to emphasize the importance of integrating user perspectives in improving collaborations on e-learning platforms. Gamification approaches can also be utilized when designing CL, as shown in previous works that aim to teach computational thinking [26] and improve student engagement [27]. Several studies have explored innovative approaches in the realm of CL enhancements through technology. For instance, Xie et al. [28] utilized a smart conversational agent to facilitate CL within a VR environment. Similarly, Harley et al. [29] introduced a system that provides prompts and feedback to guide participants and enhance learning outcomes in CL settings. More recently, VoRtex [30] has been proposed as a gamified metaverse platform for e-learning. KG has been investigated in the context of cooperative learning [31]. It has been shown that MMs can be used to drive KG construction [32]. Designing an e-learning CL system that can cater to the emotional aspect of learners has also been discussed in [33].

CL in virtual environments has been studied before [34], [35]; however, by comparison, CL work exclusively on immersive VR seems somewhat limited. What is the effect on symmetric/asymmetric pair learning has also been investigated for VR [36]. However, it is limited to the learning behavior when the two actors are one teacher and one student only. There are investigations of CL on XR, in general, [37], while, specifically, there is a CL work that investigated a 3-D tablet device [38]. In addition, there is a discussion on how CL can be applied to VR [39]. Overall, the investigation of CL in VR environments seems limited. However, there is a recent work that focuses on comparing the feeling of presence and engagement among conventional video conferencing platforms and VR platforms for CL [5], which is similar to ours. However, it should be pointed out that our work focuses on an interactive task (i.e., MM).

Like CL, MM is also a hot topic in education as it can visually assist learners in organizing their understanding and thoughts. Some VR systems have been developed for MM. First, VERITAS [40] is a MM VR application, of which the interaction design has been demonstrated to be effective. The most similar work in the context of VR to ours is MMVR [41], but their focus is limited to the development of a multiuser system and the evaluation of its usability. Both VERITAS and MMVR have yet to dip into collaborative MM and, therefore, do not discuss learner behavior in said context. There was, however, an investigation to use MMs as an assessment tool [42]. Combining MM with CL has also been attempted to drive the implementation of flipped classroom [43]. Related to MM, concept mapping has been used in a VR setting to drive CL [44], [45]. There is a recent work that investigated a CL MM reported in [46], but it is focused on using sentiment analysis to measure the outcome. To the best of our knowledge, there is generally a lack of investigation on learner behavior during the completion of a CL MM learning task in edu-metaverse.

III. Pedagogical Discussions

It is crucial to apply a set of pedagogy to drive the design of edu-metaverse. Thus, in our previous work, we have proposed a pedagogical framework that advocates for a constructivist methodology when designing learning in edu-metaverse [6]. In this section, we will discuss constructivism, CL, and MM in detail to further highlight the motivation and rationale of our study from the pedagogical perspective.

A. Constructivism in Edu-Metaverse

It can be said that the core of many educational discussions comes from constructivism. Its key tenet comes from the idea that learning is not a process of absorbing knowledge passively but a process of internally constructing knowledge actively. Crucially, this pillar of pedagogy can be encapsulated by the saying, "the fundamental feature is the course of this construction: Nothing is given at the start except some limiting points on which all the rest is based" [47].

The key issue, of course, is how this process of knowledge construction comes to be within the mental realm of the learner. In our previous work [48], we have proposed eight metaverse learning principles and how they can act as a guideline to drive constructivist learning in edu-metaverse. These principles are rooted in constructivism and are believed to assist in learners' internal knowledge construction. In this article, we only focus on four of the eight principles. Specifically, they are (`M1`) *Present Knowledge as Visualized Construct*, (`M2`) *Associate the Knowledge*, (`M5`) *Engage the Student in XR*, and (`M8`) *Embody Social Learning Avatars*. These four principles are particularly related to CL and MM. `M1` and `M2` are related to MM, and `M8` is related to CL, while an edu-metaverse learning environment naturally drives `M5`.

In order for a virtual learning environment to facilitate `M5`, it needs to be engaging, and a key appeal of VR and, by extension, edu-metaverse, is that it can bring us a feeling of "being there." Defined by Gibson [49], this feeling is called presence, "the sense of being in an environment" and it is induced by immersion, which is generated by technological means [50] (e.g., head-mounted display (HMD) and tracked controllers). Presence can be further deconstructed into more detailed components, which we will discuss soon.

B. Collaborative Learning

CL is an educational approach that involves groups of learners working together to solve a problem or complete a learning task. This pedagogical strategy is highly related to the social constructivist theory, which posits that knowledge is constructed through social interaction and negotiation [51]. During CL, learning becomes a shared experience among a group of learners, fostering a sense of community and collective responsibility for learning [52]. It can encourage active participation, interaction, and the exchange of ideas, thereby promoting critical thinking, the development of problem-solving skills, and the co-construction of knowledge. It has been shown that CL can enhance academic achievement [53], improve motivation [54], and increase engagement [55].

The effectiveness of CL is influenced by various factors, including group dynamics, task, and engagement. As such, for CL to work, one key is ensuring that the learners are engaged and attentive. Student engagement is widely recognized as crucial for achieving learning outcomes; therefore, interaction among members of a learner group is equally, if not more, vital for CL [56]. If some students are not engaged in the learning process, it is easy to see that the learning will collapse to individual learning. It has been recognized that presence plays a crucial role in ensuring effective collaboration [57]. In addition, a study proved that social presence is associated with the cognitive engagement model [58]. Particularly, in the context of CL in virtual environments (which is under the umbrella of computer-supported CL [59]), it is essential to facilitate and induce the sense of copresence (i.e., learner feels the presence of other learners) and cognitive presence (i.e., learner feels the presence of the content) in a virtual world [60].

C. Mind Mapping

MM is a process of using a visual tool called MMs to structure, organize, and represent information, ideas, or concepts. It is characterized by a central node from which branches radiate into more nodes, representing subtopics or related ideas. It has been used as a tool for personal note-taking [61]. According to visual literacy [62], the use of colors, symbols, images, and spatial arrangement in MMs can help learners think visually and thus structurally [63], and this may benefit their knowledge construction. Furthermore, with visual hierarchy and proximity [64], MM may particularly help with organizing knowledge as it can visualize different levels of abstraction as well.

In the context of education, MM has been considered an effective tool to help learners. It has been shown to be able to deliver benefits in many forms. Foremost, as mentioned, it is useful for abstraction [65] and can help learners encapsulate the intricacy of relationships and focus on the overall picture. MMs have also been known to assist in memorizing learning materials [66]. It has also been shown that MM can foster critical thinking [67], problem solving [68], and creativity [69] as well. Due to all these reasons, MM has been considered a powerful and general tool in education [66] that can be applied to a broad range of domains [70].

Particularly for our work, MM also serves a unique purpose in mixing with CL, as it has been suggested that MMs can facilitate CL [71]. MM can serve as a shared visual language for learners to exchange ideas, negotiate meanings, and co-construct knowledge when used in group activities [69], [72], [73].

D. Knowledge Graph

A KG is a collection of nodes that are connected by edges. Its main purpose is to represent the associative relationships between concepts for knowledge reasoning [74]. Many application domains have investigated its use, and education is no exception [75]. Foremost, how to construct an educational KG has been demonstrated [76], [77], and there is previous work that visualizes educational events with KG and news [78]. With a KG, relationship analysis has also been done; KnowEdu is a system that can not only generate KGs automatically but also provide analysis of the relationships of students' assessment data [79].

In general, it seems that most previous studies of KG in education focus on the construction for the purpose of data analysis. It is noted that KG and MMs can both organize information visually; however, KG is tailored for computational reasoning [74], whereas MMs facilitate personal knowledge organization for learners [66].

E. Collaborative MM in Edu-Metaverse

CL and MM are both foundational constructivist pedagogical methodologies that are general and can be applied in a wide array of domains. Furthermore, MM can benefit CL by providing a medium for learners to communicate or understand with one another. From the related work and discussion above, however, it seems that, currently, there is a lack of investigation on MM and CL in the VR realm of edu-metaverse, particularly in the realms of VR and edu-metaverse. Thus, this article aims to dip into this research gap and study learner behaviors during CL in edu-metaverse.

A particular point of investigation lies in the necessity of immersive edu-metaverse learning. As revealed by previous studies, conventional video conferencing and collaboration platforms, such as Zoom, suffer from issues such as poor engagement [80] and low attentiveness [81], making them not ideal for CL. Meanwhile, edu-metaverse is well positioned to fill this role. It has already been known that in a conversational setting, edu-metaverse can induce a better sense of presence and stronger engagement [5]. Also, VR technology enhances learning by promoting active engagement and practical application, providing clear advantages [82]. Thus, the focus of this study is to introduce an interactive learning task in the form of MM and further investigate the specific learner behaviors that are associated with the outcomes of this improved immersiveness.

IV. K-CUBE VR: Virtual Space for CL

To facilitate KG-driven MM for immersive CL in edu-metaverse, we developed a 3-D MM editor operational on HMD devices. It features a subsystem we call the KG-based recommendation system, which assists users in creating new MM nodes using straightforward nontraditional strategies for generating recommendations. As an application of edu-metaverse, our system also supports real-time communications, virtual avatars, and collaborative MM. The detailed description of our system is divided into the following subsections.

A. Overall Design

The players enter the game room wearing VR helmets with a specified task, i.e., brainstorm to conceptualize a video game with others and utilize the properties of the nodes to construct a brief overview of the consolidated proposal for their video game. Starting from the *root node* named "Game Design," players extend and expand the related topics stepwise upon it, with the suggestive guidance of our unique recommendation system. The production of this MM represents the results of the players' discussions and collaborations, and every player has the right to access and adjust any nodes in this game room. This leads to two main requirements in our system: 1) a VR-based 3-D MM editor supporting multiplayer collaborations; and 2) a recommendation subsystem that suggests the "next-node" based on the node being extended to with the pre-defined KG. Fig. 1 demonstrates our system's overall interfaces and how the MM appears from a player's perspective.

B. Collaborative MM

As the most basic feature of our system, the 3-D MM editor is capable of displaying to the player and supporting the adjustments by different user inputs. The MM in our system is developed based on the concept, that is, starting from a central

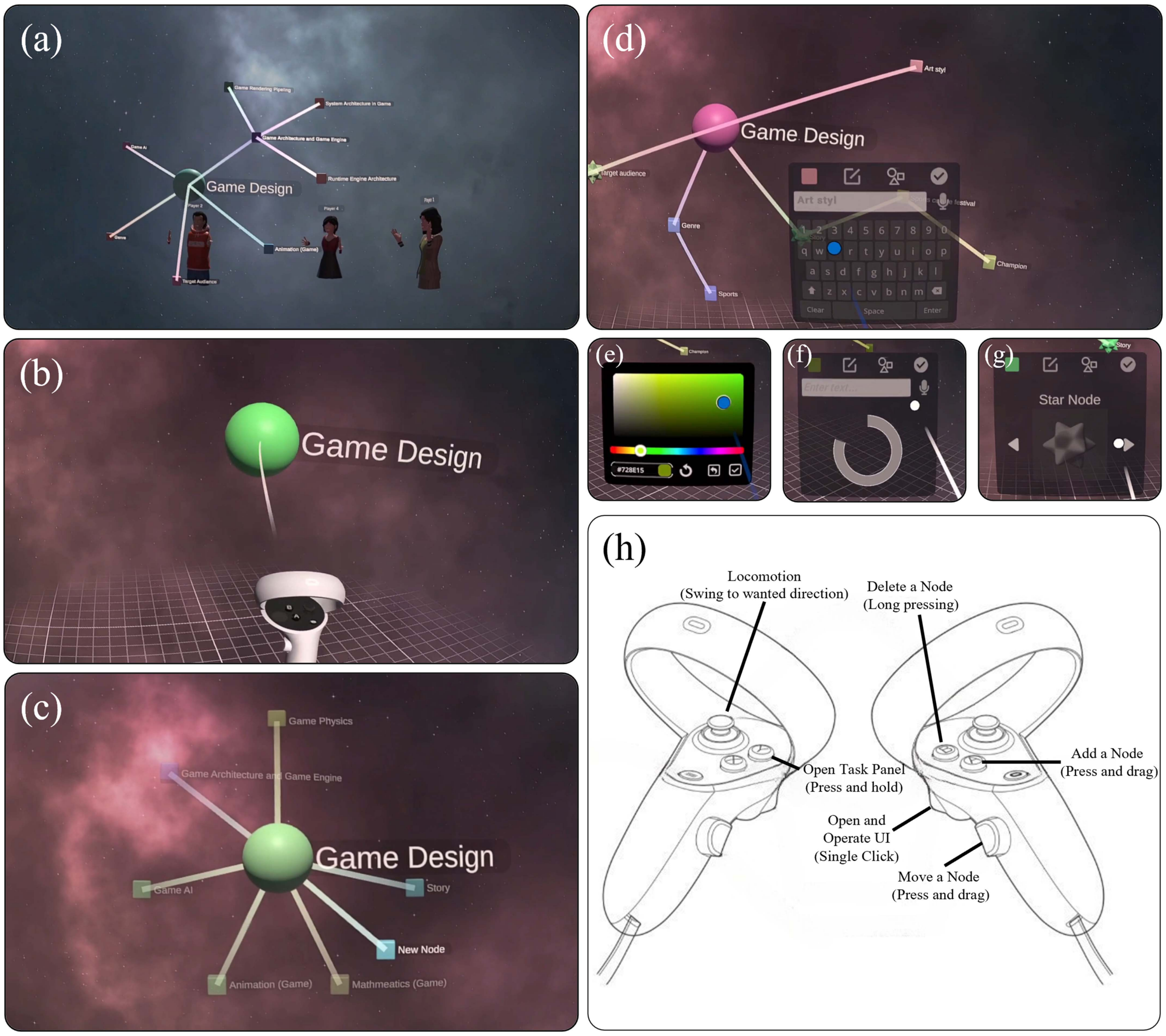


Fig. 1. Overview of our KG-driven MM editor in an edu-metaverse setting. (a) Players collaborating on an MM. (b) *Root node* and interaction ray between the controller and a target node. (c) Semitransparent dummy nodes for recommendations. (d)–(g) UI features: the text editor, color picker, voice-to-text, and shape selector. (h) Buttons and triggers bindings on controllers to operate in the system.

node, extending the graph by nodes with color, text, and spatial arrangements [62] in MMs to enhance memory recall [66], problem solving [68], and stimulate creative thinking [69]. The MM uses a graph-like setup with nodes and edges. The nodes appear as shapes of cube, sphere, star, or cone with user-specified colors and label names. The edges are the lines connecting pairs of nodes in a gradient form. The players can freely add, remove, move, or change the properties of the nodes.

To select a node, we provide an interaction ray hovering over the node when using the right-hand controller to navigate in close proximity to the node. The ray connects the player's virtual right hand and the most "potential" node, if any, which depends on the virtual hand's point direction [see Fig. 1(b)]. Through hovering and selecting, the player can add new nodes, connect existing nodes, and accept a node recommendation by dragging the controller in specific directions. To modify other properties of a node, the user opens up a user interface (UI) and operates on the interface. The UI provides functionalities including a color picker [see Fig. 1(e)], keyboard [see Fig. 1(d)], voice-based text input [see Fig. 1(f)], and shape picker [see Fig. 1(g)]. To delete a node, the player must press and hold for 2 s when hovering over the node. The node to be deleted will keep flashing as a reminder. The MM is initialized with a *root node* named "game design" [see Fig. 1(b)], and it is unchangeable on the shape and cannot be deleted. The *root node* is much bigger than other regular nodes for easy identity, and the construction of the MM should start with it. Locomotion helps players to view the 3-D MM from different perspectives using the left-hand controller. Players are free to navigate around the scene without moving their real bodies for convenience and safety. We adopt grid-based movements that suddenly move the player's virtual camera by a fixed distance to avoid dizziness. The controllers with usages are demonstrated in Fig. 1(h).

Real-time network communication among different end devices is vital to facilitate the immersive experience of multiple players aside from the VR system. The communication elements in our system consist of MM synchronization, avatar appearance and movements, and voice communication. A shared client mode is adopted as the network settings, that is, the server is only responsible for forwarding messages and assigning the

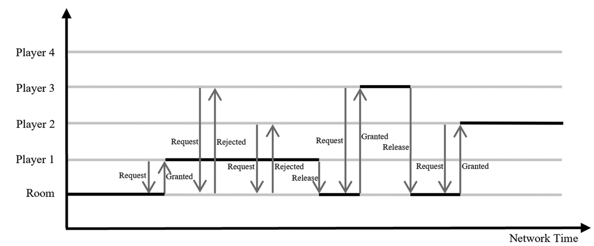


Fig. 2. Node control authority management of our system in a timeline chart: The virtual room allocates the authority in the FIFS manner. The clients send requests to the room applying for authority and will be rejected if other players take over the node.

control privilege upon shared objects in the game. In other words, the server does not maintain the data and objects in the scene, but the clients do. A virtual room, which stands as the context manager and communication media in the server, will be created when the first player goes online and is destroyed after the last player quits. As long as the virtual room exists, the MM will be synchronized when other players join, and rejoin is also possible. In our system, only the control rights of the nodes are varied over time, in the manner of first-in first-served (FIFS). Once the player is done with modifying a node, the authority is released and waiting for the next authority request. As for synchronization, the properties of the nodes are immediately spread to other players if the player has made modifications, and only the one who has the control authority can perform the modification. We force the player to keep the control rights during adding, moving, removing, and editing before releasing it to prevent multiple access to a single node. We present the control rights management in Fig. 2. The voices of the players are recorded by the microphone on the VR helmets and transmitted to anyone else so that the players can hear others' sounds and talk with each other. The rotation and movements of the player's virtual avatar body and hands are synchronized as well, which helps the players to feel the appearance of other team members [see Fig. 1(a)]. The rotation of the MM nodes is always designed to face the individual player for better readability and is not synchronized across users. However, all other changes to the nodes, such as updates or deletions, are synchronized to ensure that everyone in the multiuser environment sees the same content.

C. KG-Based Recommendation System

To take advantage of KG and stand as a reference helping the players add new MM nodes, our unique recommendation subsystem is designed to provide guidance based on our predefined knowledge base and drive MM. The knowledge base is single-track word mappings stored in a dictionary as key values ready for querying. The values are semantically the subtopics of the key, for example, an entry of the dictionary can be {Game Design: Genre, Target Audience, Game AI,... }. The values are possibly to be the key in other entries (e.g., {Genre: FPS, Adventure, Simulation,... }), which implicitly presents the KG with recursive operations.

This recommendation subsystem differs from traditional recommendation systems but in a more straightforward way. When the player adds a new node to the selected node, the subsystem starts work by taking the selected node's label name, comparing it with the keys, and finding the matches by calculating the Levenshtein distance between them. The values corresponding to the closet distance key will be picked and returned as the recommended results. If there are no sufficient values, the values of the second closest key will be fetched. Such progress continues until the recommendation list for the node label is filled with six words. The recommendation list is regarded as the potential word list for the label names of the new node.

The recommendations are displayed as semitransparent dummy nodes [see Fig. 1(c)], which are evenly scattered around the selected node and have already connected with it. If one of the dummy nodes fits the player's expectations, she/he can drag the interact ray to the expected one, and this dummy node will become a real node. When more than one recommendation fits the player's expectation, the steps can be repeated to add all the expected. The accepted recommendation will not appear twice. Moreover, to minimize the network traffic, the dummy node would not be synchronized to other users, only the final new node will be scattered over the Internet. In this manner, the recommendation is set locally on each end device but efficient enough to run.

V. Methods

A. Experimental Design

This study was meticulously designed to evaluate the efficacy of our KG-driven recommendation system in the context of CL utilizing MM. To facilitate a comprehensive comparison, we incorporated three distinct modalities. The first modality comprised the Zoom group, which functioned as the control group. The second modality, referred to as the MM group, consisted of participants who utilized the VR MM tool without access to the KG-based recommendations. The third modality, the MM+KG group, also operated within a VR environment but, unlike the second, was augmented with the KG-driven recommendation system.

The research involved two user studies. The first was a between-subject study design that evaluated the three aforementioned modalities to gauge the impact of each on the learning process. The second user study was supplementary, which adopted the same setting from MM+KG, focusing specifically on the usability of our KG-driven MM recommendation system within a CL framework.

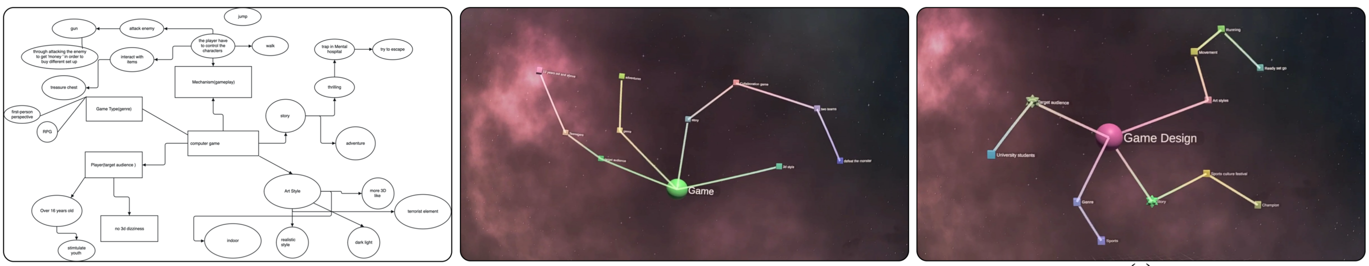
The objective of the two studies was to explore how KG recommendations influence both the process of CL and the effectiveness of MM.

B. Participants

For the first user study, all participants were invited from the campus and possess a background in science, technology, engineering and mathematics (STEM) . Initially, 37 participants responded to the recruitment, of which seven participants were

TABLE I
DEMOGRAPHICS OF THE PARTICIPANTS

	Group Name	No. of participants	Gender, male(%)	Age, mean (SD)	Game Experience (hours/week), mean (SD)
First User Study	Zoom	8	2 (25%)	21.13 (2.47)	10.19 (9.80)
	MM	8	2 (25%)	22.38 (2.33)	10 (8.83)
	MM+KG	8	2 (25%)	22.38 (2.56)	4 (3.74)
Second User Study	Usability Group	24	22 (92%)	24.58 (4.09)	6.81 (8.78)



(a) (b) (c)

Fig. 3. MMs from the three modalities. (a) Zoom group. (b) MM group. (c) MM+KG group.

excluded due to not studying in STEM-related disciplines and six participants due to time constraints or other private reasons that prevented them from participating in the experiment. Finally, a total number of 24 participants attended the experiment. Among them, some are currently pursuing their postgraduate degrees, while the rest are undergraduate students. They were randomly allocated to one of three experimental conditions.

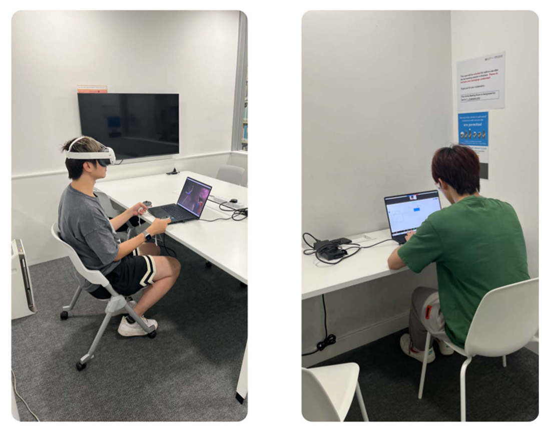
For the second user study, referred to as the *usability group*, we recruited 24 participants from a Metaverse technology master course. These individuals possess expertise in VR and Metaverse technologies, making them well-suited for assessing the usability of our KG-driven MM recommendation system.

Each experimental group consisted of four participants who engaged in the collaborative tasks. In the comparative user study, across each modality, there were a total of two groups. As for the *usability group*, there are six groups. To enhance the experiment's reliability, participants were asked to record their game experiences. Comprehensive demographic information about the participants is detailed in Table I.

Informed consent was obtained from all participants. For the first user study, participants were compensated with an HK$100 supermarket voucher, while those in the second user study received an HK$50 voucher as a token of appreciation for their time and contribution. The study was approved by the Institutional Review Board of the Hong Kong Polytechnic University (Application Number: HSEARS20240207002).

C. Task Materials and Environment

The participants were instructed to perform MM for a collaborative task adapted from the source cited in [69], which pertains to team-based brainstorming in the field of game development. To ensure the task's relevance and suitability for the students, it was reviewed and validated by two experts in game development. Details of the collaboration task can be found in Appendix A. We provided both Chinese and English versions of the task materials to accommodate participants who may not be familiar with certain terms in English. Throughout the experiment, participants were permitted to review the task instructions within VR or Zoom meetings as needed.



(a) (b)

Fig. 4. Overview of the experiment environment. (a) VR groups environment. (b) Zoom groups environment.

The study was conducted within the confines of the PolyU library. We booked two types of group rooms for the experiment. The room for the Zoom modality was approximately 2×2 m, suitable for single online meetings. In contrast, for the VR modalities, which necessitate bodily movement, a larger space was provided, measuring 4×4 m. The layout of these rooms is depicted in Fig. 4.

As detailed in Section IV, for the VR setting, participants were equipped with a VR-based MM tool capable of constructing 3-D MMs. This tool offered comprehensive and collaborative MM functions comparable to those in the Zoom setting, such as managing authority, communication, editing, node deletion, and modifying properties, among others.

Three instances of participants employing the MM for collaborative tasks are showcased in Fig. 3. While the MMs generated for the CL tasks varied slightly, they all retained the essential elements of the CL tasks.

TABLE II
RESULT OF THE CONVERSATION FOR CL OF FIRST USER STUDY

Categories	Description	Illustrative Example	Frequency		
			Zoom N = 143 K (%)	MM N = 281 K (%)	MM+KG N = 302 K (%)
(a) Cognition – divergent thinking					
Association	Associate concepts, objects, or situations (COSs)	MM: Graphics, blocks, Tetris?	2 (1.4%)	5 (1.8%)	4 (1.3%)
Decomposition	Decompose a COS into rich details	MM+KG: The popular games I know of include 'Flower Fairy, Seer, and The Legend of Sword and Fairy	3 (2.1%)	8 (2.8%)	6 (2 %)
Combination with Adjustment	Combine and/or adjust COSs	MM: I just put my idea first, and you can revise it after	3 (2.1%)	5 (1.8%)	2 (0.7%)
(b) Cognition – idea generation					
New Idea	Generate an idea from a new perspective that has not been mentioned before	Zoom: As for the story, you can simply write one that is unconventional, for example....	6 (4.2%)	7 (2.5%)	10 (3.3%)
Building on Ideas	Modify, refine, or extend previous ideas to develop a new idea	MM: two teams, and overcome challenges	10 (7 %)	27 (9.6%)	22 (7.3%)
(c) Metacognition					
Regulation	Manage and reflect on the process	MM: Quickly! Let's start with first point	18 (12.6%)	9 (3.2%)	2 (0.7%)
(d) Social communication					
Elaboration	Use examples, analogies, reasoning, or providing details to explain an idea or thought	Zoom: We can take a particular game as a reference, and then approximately talk about one	20 (14 %)	12 (4.3%)	7 (2.3%)
Question	Ask questions to seek information or further elaboration	Zoom: Do you know that one from Nintendo, Spelunker?	25 (17.5%)	48 (17.1%)	75 (24.8%)
Direct Response	Directly respond to a question without elaboration	MM+KG: Sure, we can do that	22 (15.4%)	37 (13.2%)	74 (24.5%)
Agreement	Positive evaluation on an idea or thought (e.g., agreement, acceptance, support)	MM: OK, OK	15 (10.5%)	26 (9.3%)	22 (7.3%)
Disagreement	Negative evaluation on an idea or thought (e.g., disagreement, doubt, rejection)	MM: My thought is, let's not do the Tetris, it's too commonplace, let me think.	10 (7 %)	6 (2.1%)	2 (0.7%)
Argument	Argue for the appropriateness or value of a perspective with explicit reasons	MM+KG: But it seems that we don't require animation, just an art style.	4 (2.8%)	4 (1.4%)	2 (0.7%)
(e) Technology use					
Mapping	Interact with the mind map	Zoom: Hold on, let me delete it first	4 (2.8%)	54 (19.2%)	27 (8.9%)
(f) Other					
Off-task	Dialogue not relevant to the given task.	MM+KG: So which key should I choose when I want to edit? Confirm Trigger?	1 (0.7%)	33 (11.7%)	47 (15.6%)

N = total number of utterances within a modality. *K* = number of utterances to each category within a modality. % = percentage of utterances.

VI. MEASURES AND INSTRUMENTS

A. Measures

1) Group Conversation: The group conversation refers to the talking of a group of participants during the CL task that was audio recorded and transcribed for analysis of the engagement. To gain a comprehensive understanding of the conversational dynamics in CL across three modalities, we build upon the findings of Sun et al. [69]. We adopted a similar approach to group interactions in our study, as summarized in Table II. This table delineates five principal levels of group conversation: Deliberative Thinking, Idea Generation, Social Communication, Technology Use, and Others.

The term "Deliberative Thinking" denotes the cognitive processes underlying how ideas are conceived and developed. "Social Communication" encapsulates the exchange of information within the context of social interactions. "Technology Use" pertains to the participants' manipulation of the MM tool during their discussions. Finally, the category "Other" accounts for instances when participants were distracted or engaged in activities unrelated to the task at hand.

2) Usability: The System Usability Scale (SUS) was employed to evaluate our proposed KG-driven MM in CL [83].

B. Procedure

The overview of the experiment is illustrated in Fig. 5 . The experiment began with participants being guided by a team of four assistants into separate rooms. Initially, they completed a demographic survey to collect background information. Subsequently, they watched an instructional video on MM to ensure that they grasped the fundamental concepts of organizing knowledge using this technique.

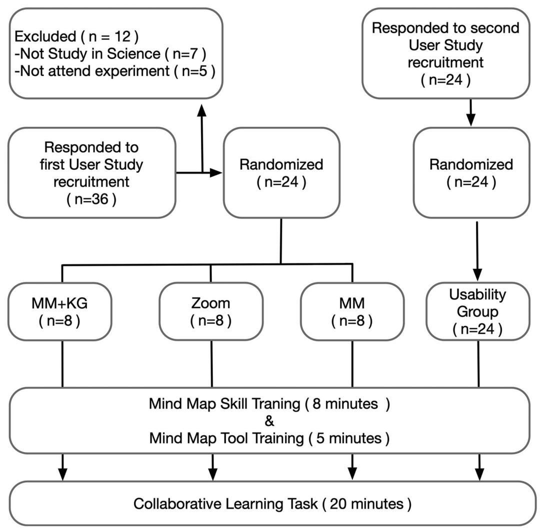


Fig. 5. Procedure of two user studies.

Each group was then introduced to the MM tools by the assistants. This introduction included a demonstration of a detailed MM, adapted from the result of previous research [69], to provide a clear example of the expected outcome. Once the participants felt comfortable with the tools, as indicated by their acknowledgment of familiarity, they were presented with the specific tasks of the experiment. They were informed that they could refer back to the instructions at any point during the session.

The participants then moved into the collaborative spaces tailored to their respective experimental conditions and started the experiment. For the Zoom group, this space was a shared whiteboard, while for the VR groups, it was a virtual environment modified from our previous edu-metaverse [6].

If participants in any group did not initiate conversation, the assistants would prompt them once to begin. Apart from this, the assistants refrained from offering further guidance, except when requested for technical assistance. The participants were not allowed to have any unnecessary interaction with the assistants to prevent the experiment from deviating from its original plan and objectives.

Observations were conducted discreetly and unobtrusively. For the Zoom group, remote monitoring was enabled through the meeting platform, with assistants exiting the experiment room post-initiation to preserve the integrity of the experimental conditions. In the VR groups, the HMDs inherently isolated the participants from the physical presence of the assistants, who remained inside the experimental space to monitor the proceedings, ensuring that the experiment's immersive experience was left undisturbed.

After 20 min, the assistants concluded the experiment. For the two VR modalities, a focus group was conducted to elicit user feedback on the MM CL. Upon the completion of the focus group, all participants from all conditions signed a receipt to acknowledge their participation and exited the experiment rooms.

C. Apparatus

For the Zoom modalities, all four laptops were outfitted with high-definition cameras and microphones to facilitate clear communication. The HMDs used in this study were four Meta Quest 3,[1] each verified to support a maximum refresh rate of 120 Hz.

D. Focus Group

We are interested in the user feedback for the CL using MM in VR. For the two VR modalities' groups in the first user study and the *usability group*, a semistructured interview was conducted for each group. The interview questions were asked sequentially in Appendix B.

E. Data Analysis

Coding of group conversation: Group conversations were recorded and transcribed in mixed with Chinese and English. To ensure the reliability of the analysis, after the transcript, we translated all Chinese into English. All conversations were segmented into separate turns of students' talk for the analysis.

VII. Results

A. Group Conversation

Chi-square tests were conducted to evaluate the presence of significant differences across three modalities in various categories of interaction. The significance level was set at 0.05. The results revealed a significant association between the modalities and the categories of conversation, $\chi^2(26, N = 456) = 146.85$, $p < 0.001$. This indicates a strong statistical significance, suggesting distinct patterns of communication across the modalities. Further detailed analysis was carried out on Cognition and Social Communication, our study focus. For Cognition, no statistically significant relationship was detected, as evidenced by $\chi^2(8, N = 120) = 3.46$, $p > 0.05$. Conversely, for Social Communication, the analysis demonstrated a statistically significant relationship, with a Chi-square statistic of $\chi^2(10, N = 411) = 48.50, p < 0.001$.

Furthermore, in the experimental group using Zoom, the total number of utterances was notably lower compared to both the MM and MM+KG groups. There was an almost complete absence of discussion pertaining to "Technology Use." Furthermore, the proportion of participants focusing on "Regulation" differed significantly from that of the VR group. It was also observed that in terms of "Social Communication," the Zoom group had a propensity for more elaborative communication. In contrast, the two VR groups exhibited similar patterns, except for differences in "Questions" and "Technology Use." The number of utterances from the MM+KG group was marginally higher than that from the MM group.

[1] [Online]. Available: https://www.meta.com/us/quest/quest-3/

B. Usability

The mean score for the SUS is 56.25, with a standard deviation of 11.59. This suggests that our KG-driven MM generally achieves an "OK" level of usability in CL, as defined by Bangor et al. [84].

VIII. Discussion

A. Higher Group Involvement

Based on the observations and results from our group conversations, it seems that people in the Zoom group are less inclined to engage in conversations compared to the VR group. In our experiment, we noticed that in each Zoom group, there were one or two participants who remained silent and focused on manipulating their MM nodes, appearing quite disturbed. Another observation worth mentioning is that when we started the experiment and opened the camera on Zoom, all participants subconsciously either covered the camera with their hands or hid their faces from the camera. This behavior might indicate that when they are faced with unfamiliar individuals and forced into a collaborative environment, they feel anxiety. As argued by Guo et al. [85], when people interact with others without a mask, they experience social anxiety. In this context, it could be the reason why the VR group with avatars, which function as masks to cover people's faces, had more conversation utterances. This observation is further supported by the feedback from the Focus Group, where one participant from the MM group stated that "*VR is the 'gospel' for social anxiety, as it provides anonymity.*" From this perspective, using the MM modality in VR with avatars can be an effective way to increase involvement. Although the MM and MM+KG groups are quite similar, the MM+KG groups had more conversations regarding questions and off-task discussions. The frequencies of questions and off-task discussions are [see Table II(f)], respectively, 75 and 47 for MM+KG, and 47 and 33 for MM. This might be attributed to the fact that our recommendation system successfully provided the users with the necessary information, allowing them to overcome technological hurdles and saving more time for asking and answering questions. This positive outcome indicates that our KG-based recommendation system can further enhance user involvement and provide more discussion opportunities, building upon the normal VR MM modality.

B. Feeling of Copresence

It has been known that a VR environment can provide a greater sense of presence compared to typical streaming platforms [5]. But what does that entail, given an interactive learning task such as MM? Based on user behavior, it appears that a stronger sense of presence can facilitate greater engagement among learners. This is evident in the Cognition-Idea Generation categories [see Table II(b)], where participants in the VR group were observed to generate double the number of building ideas compared to those in the Zoom group; the frequency for Building on Ideas is 22 and 27 for MM and MM+KG, while it is 10 for Zoom. This finding is further supported by the feedback from the focus group, where one participant expressed that "*Using VR makes me feel more collaborative*" and another participant mentioned feeling "*connected to each other when using VR.*" As one participant said: "*(In Zoom), I feel less connected to each other.*" An additional insight gleaned from participant feedback suggests that the heightened sense of copresence experienced during CL tasks could be a contributing factor. This observation resonates with our theoretical framework, which posits that a strong sense of copresence is pivotal when engaging in joint educational activities. The perceived increase in copresence among participants likely facilitated a more cohesive and IL environment, in line with the principles underpinning our approach (refer to Section III-A).

Together with the conversation result, we can see that the VR group shows a consistent degree of collaboration between learners. This user behavior and feedback show that the copresence of an edu-metaverse learning environment has the potential to be more involved in a CL task as it may help with copresence.

C. Realistic Avatar is Not a Must

Another interesting finding is that it seems that a realistic avatar is not a must. Despite previous studies suggesting the significance of a realistic pedagogical agent for teaching [15], it appears that for collaborative learners, the realism of an avatar holds less weight. Following the discussion of our previous point, learners provided feedback that they feel stay together even though the avatar is very less realistic, but still, now participants said: "*The avatar does not move a lot, but we still feel like to be in the same room.*"

Thus, it seems that simply placing the learners in the VR environment is already sufficient to generate a feeling of copresence within them. Regardless, it is believed that a realistic avatar can help learners to better engage, but, if that is not possible, the edu-metaverse system may consider focusing resources other than optimizing the avatar.

D. Concurrent Work in Edu-Metaverse

The advent of VR technology brings a transformative potential to collaborative educational environments, often referred to as the edu-metaverse. A notable advantage of VR over traditional desktop displays is its expansive field of view, offering users a more extensive virtual space. This can facilitate a sense of freedom and spatial abundance conducive to collaborative efforts. In an edu-metaverse setting, the ability to accommodate numerous participants within a single shared virtual environment is a key feature, enabling synchronous collaborative activities and interactions that closely mimic physical presence.

However, this enlarged virtual arena also presents certain challenges. The copious space can lead to increased distractions as users may find themselves more susceptible to environmental stimuli. In addition, the complexity of functions within such an immersive space can lead to a dilution of attention. For instance, in the case of the MM+KG groups, there was a noticeable uptick in off-task conversation. This trend suggests that participants' focus could be diverted by the intricate and perhaps alluring features of the virtual environment, such as sophisticated recommendation systems.

Despite these potential distractions, users appear to retain a preference for the extensive collaborative space offered by VR. This sentiment was encapsulated during a focus group discussion, where one participant emphasized the benefits of VR by stating, "*VR provides more space to work on compared to a screen.*" Such feedback underscores the enduring appeal of VR's immersive qualities, suggesting that the benefits of increased spatiality may outweigh the drawbacks associated with environmental distractions. Future designs of Edu-metaverse platforms might need to balance the allure of expansive virtual spaces with mechanisms that help maintain user focus and task-oriented collaboration.

E. Focused Environment

Another benefit of performing CL tasks in VR is that it provides a focused environment that is less distracting. As the desktop, they can see the environment around them; thus, it can be very easy to distribute. One participant said "*In reality, there may be things that distract us. In (edu-metaverse), we can just focus on the area. We can hear the sounds of our teammates. We can do it more (focused).*"

Although it can be considered as a disadvantage for a VR/metaverse system, the HMD may act as some sort of constraint to isolate the learner from reality and focus on the learning material. This user feedback may also provide insight on why a VR environment can provide a better sense of presence compared to streaming platforms as a platform such as Zoom can be easily disengaged.

F. KG Guidance

The principal objective in the development of a KG-based recommendation system is to assist users in discovering potential discussion topics. It is acknowledged that participants engaged in collaborative activities may lack the necessary background knowledge, potentially hindering their ability to effectively initiate discussions. Often, this leads to the creation of MMs that reflect only the immediate task or personal experiences.

Our KG-driven recommendation system is intentionally crafted to steer participants toward meaningful reflection on the subject matter, which, in turn, promotes more profound engagement in dialogue. This benefit is supported by a testimonial from a participant within the MM+KG group, who said "*We first use the element given by (the system) in the recommendation.*" Furthermore, the recorded conversations demonstrate an increase in social interactions within MM+KG groups [see Table II(d)], suggesting that such an environment fosters a greater propensity for communication.

In addition, it is noteworthy that despite the recommendation system's directive nature, the generation of new ideas flourished within the MM+KG groups [see Table II(b)]. This indicates that our recommendation system does not stifle the cognitive process of ideation. These observations affirm the system's capability not just to anchor participants' comprehension but also to enhance the caliber of collaborative discourse by ensuring that discussions are rooted in pertinent and substantial material.

G. Difference of MMs Among Three Modalities

Our study uncovered a notable divergence in the MM formalization across the three distinct modalities we examined, as illustrated in Fig. 3. From our observation, in the Zoom groups, a dominant pattern emerged where a single individual tended to guide the discussion, with the MM predominantly shaped by this leader. This dynamic led to seemingly intricate MM outcomes when compared to those of the VR groups.

Within the VR environment, different patterns were observed. In the standard VR group with MM, all members contributed to the MM, closely aligning the content with the designated tasks. Conversely, in the MM+KG group, we noted a dynamic evolution of the MM. Initially, the MM conformed to the structure suggested by our KG-driven system; subsequently, participants adapted and pruned nodes in response to task requirements.

Although the Zoom group's MMs appeared more complex, they may not fully represent collective consensus, as not all members were equally engaged in the MM development process. In contrast, the VR groups' MMs, while simpler, reflected a broader participation in their creation, suggesting a more unified group understanding and problem-solving approach.

H. Usability Needs to Be Improved

Usability is a critical component that significantly affects user experience. Although our KG-driven MM has achieved an "OK" level of usability, there remains substantial scope for enhancement. We gathered feedback from the usability group's focus group, which highlighted several areas for improvement. A predominant concern relates to the authenticity of the experimental environment. One user pointed out, "*The setting of the environment needs to be close to reality, whether it is from the light effect or, slightly more serious environment.*" This factor could potentially impact learning efficiency. Another notable issue arises as the MM becomes increasingly complex, making it challenging for users to manage effectively. A participant remarked, "*For example, if multiple people cooperate, in a 3D scene you see such a complex node will be a little messy, not as good as the automatic layout function of some PC software.*" We will keep working on improving these issues in our future work.

IX. Limitations and Future Work

A. Avatar

In prior work, we advocated for avatars optimized for communication over photorealism. We proposed gaze tracking to visualize user focus and enhance avatar communication. However, in this study, examining a KG-driven recommendation system for multimodal conversational tasks, we have not yet implemented gaze tracking. Instead, we only track limited hand gestures and head turns. This approach has limitations, as it does not capture full nonverbal cues essential for engagement. We aim to later incorporate gaze tracking and advanced motion tracking to enable avatars to convey natural engaging nonverbal cues.

B. Gender Balance

Most of the participants who responded to our recruitment were predominantly female, despite attempts to recruit a gender-balanced sample. This imbalance is noteworthy as communication styles differ between genders, as highlighted by Burleson [86]. The overrepresentation of females could thus influence the study's outcomes and its applicability to a broader population.

X. Conclusion

Investigating user behavior in CL tasks is crucial for realizing an edu-metaverse. One of the issues to look into is what benefits can edu-metaverse bring when conducting learning activities compared to streaming platforms such as Zoom. Based on our previous study, we have selected MM as a CL task because it is both generally applicable to many learning scenarios and also an important component of constructivist teaching methodology. Furthermore, we utilize the KG from K-Cube VR, our edu-metaverse prototype, to provide guidance during the MM designing session. Our work indicates that in contrast to platforms such as Zoom, conducting collaborative tasks in edu-metaverse, particularly MM, can have several advantages. The conversation analysis shows that students in edu-metaverse may be more engaged as a group, in contrast to that of Zoom, which may be prone to detachment. Furthermore, the edu-metaverse enhances the feeling of copresence among students, which contributes to a more effective virtual environment for CL.

Appendix A
CL Task

The collaborative learning task is shown in Fig. 6.

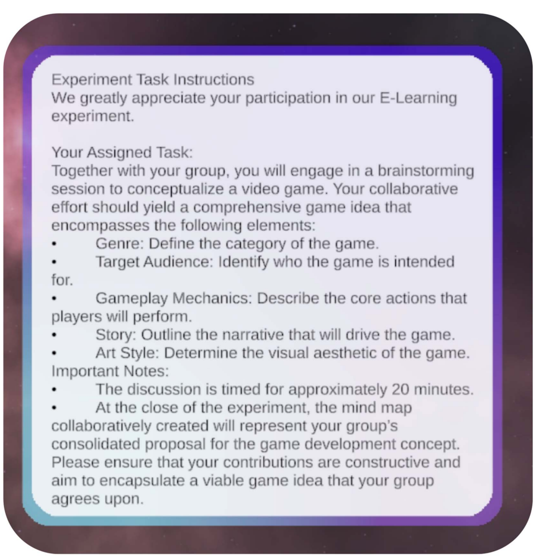


Fig. 6. Collaborative learning task panel.

Appendix B
Focus Group Questions

(FQ1) What is your first thought when immersed in this environment?

(FQ2) How do you collaboratively decide to add a new word or not?

(FQ3) What can further assist you in adding a new word or not?

(FQ4) Compare to drawing a mind map via Zoom, what is your expectation of the difference between VR and Zoom?

(FQ5) What concerns/issues do you have in a VR e-learning session?

(FQ6) Do you think VR can make learning more engaging or enjoyable? Why or why not?

(FQ7) How would you feel about group work or collaborative projects in a VR environment?

(FQ8) What is the difference between a 2-D and 3-D mind map?

(FQ9) How well have you been interacting with the mind map? Is it natural, if not, how can it be improved?

(FQ10) What is your thinking process during the session?

(FQ11) Will you find yourself to be less distracted?

(FQ12) Let's start by sharing our thoughts about VR as a tool for learning together. What do you see as the most significant benefits of using VR for CL, based on your own experiences or expectations? Potential drawbacks of CL in VR.

(FQ13) How do you feel the experience of CL in VR compares to more traditional learning environments, such as classrooms or online forums without immersive elements? Suggestions for improvement.

(FQ14) While we've considered the positives, it's also important to look at the other side. What drawbacks or challenges might arise when using VR for CL sessions? Comparative experiences with traditional learning methods.

(FQ15) Considering both the pros and cons we've discussed, what improvements or features would you suggest could enhance the experience of CL in VR? As for the MM+KG group, we also asked the following question to receive participants' feedback.

(FQ16) What do you feel about the suggestion nodes? When you see the recommendation, did you change your understanding?

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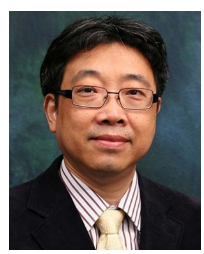

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