EXAMINING HIGHER EDUCATION STUDENTS' COGNITIVE LOAD AND FLOW IN 2D AND 3D METAVERSE LEARNING ENVIRONMENTS

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Examining Higher Education Students' Cognitive Load

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DECLARATION OF ORIGINALITY

I, Emre Yıldırım, certify that

- I am the sole author of this thesis and that I have fully acknowledged and documented in my thesis all sources of ideas and words, including digital resources, which have been produced or published by another person or institution;
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- this is a true copy of the thesis approved by my advisor and thesis committee at Boğaziçi University, including final revisions required by them.

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ABSTRACT

Examining Higher Education Students' Cognitive Load

and Flow in 2D and 3D Metaverse Learning Environments

By using an explanatory sequential mixed-methods design, this study examines the cognitive load and flow experiences of higher education students who attended the same lectures in either a 2D (n = 38) or 3D (n = 43) desktop virtual reality (DVR)-based metaverse learning environment. Quantitative data were collected through the cognitive load scale and flow scale; the qualitative data were collected via reflection forms and semi-structured interviews. Results indicated a statistically significant difference in intrinsic cognitive load, and the 3D environment caused higher intrinsic cognitive load. However, no significant differences were found in extraneous load, germane load, and flow of groups. Thematic analysis indicated that interactivity, simulations, immersive visuals, and collaborative tasks helped optimize cognitive load and enhanced flow. However, technical difficulties, verbal lecture style, digital distractions, and visual complexity caused cognitive overload and decreased flow. In the 3D group, technical issues were the primary reason for cognitive overload, while immersive visuals, realism, and presence supported cognitive load optimization and flow. In contrast, in the 2D group, cognitive overload increased due to verbal lecture style, lack of face-to-face interaction, and technical limitations, while the use of visual simulations, simplicity, and collaborative activities facilitated more efficient cognitive processing and supported flow. In metaverse-based education, the study emphasizes the significance of instructional strategies, collaboration, interaction, and technical reliability. Recommendations and future research are provided to optimize cognitive load and support flow in metaverse-based education.

ÖZET

Yükseköğretim Öğrencilerinin 2 Boyutlu ve 3 Boyutlu Metaverse Öğrenme Ortamlarındaki Bilişsel Yük ve Akışlarının İncelenmesi

Bu çalışma, açıklayıcı sıralı karma yöntem desenini kullanarak, aynı derslere 2 boyutlu (n = 38) veya 3 boyutlu (n = 43) masaüstü sanal gerçeklik tabanlı metaverse öğrenme ortamlarında katılan yükseköğretim öğrencilerinin bilişsel yük ve akış deneyimlerini incelemektedir. Nicel veriler bilişsel yük ve akış ölçekleriyle; nitel veriler ise açık uçlu sorular ve yarı yapılandırılmış görüşmeler yoluyla toplanmıştır. Sonuçlar, içsel bilişsel yük açısından istatistiksel olarak anlamlı bir fark olduğunu ve 3 boyutlu ortamın daha yüksek içsel bilişsel yüke neden olduğunu göstermiştir. Ancak gruplar arasında dışsal yük, etkili yük ve akış düzeylerinde anlamlı bir fark bulunmamıştır. Tematik analiz; etkileşim, simülasyonlar, etkileyici görseller ve iş birlikçi görevlerin bilişsel yükün optimize edilmesine yardımcı olduğunu ve akışı artırdığını ortaya koymuştur. Öte yandan teknik sorunlar, sözel ders anlatımı, dikkat dağıtıcı dijital unsurlar ve görsel karmaşıklık bilişsel aşırı yüklenmeye ve akışın azalmasına neden olmuştur. 3 boyutlu grupta bilişsel aşırı yüklenmenin temel nedeni teknik sorunlarken; etkileyici görseller, gerçekçilik ve ortamda bulunma hissi bilişsel yükün optimize edilmesini ve akışın desteklenmesini sağlamıştır. 2 boyutlu grupta ise, sözel anlatım tarzı, yüz yüze etkileşim eksikliği ve teknik problemler bilişsel aşırı yüklenmeyi artırırken; görsel simülasyonlar, sadelik ve iş birliğine dayalı etkinlikler daha verimli bilişsel işlemeyi kolaylaştırmış ve akışı desteklemiştir. Bu çalışma, metaverse tabanlı eğitimde öğretim stratejileri, etkileşim, iş birliği ve teknik güvenilirliğin önemini vurgulamaktadır. Bilişsel yükü optimize edici ve akışı destekleyici faktörler ve araştırma önerileri sunulmuştur.

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ABBREVIATIONS

2D: Two-dimensional

3D: Three-dimensional

AI: Artificial Intelligence

AR: Augmented Reality

CET: Computer Education and Educational Technology

DVR: Desktop-based Virtual Reality

EEG: Electroencephalography

HMD: Head-mounted Display

HiVR: High-immersion Virtual Reality

IVR: Immersive Virtual Reality

LiVR: Low-immersion Virtual Reality

NFT: Non-fungible Token

SBINAREK: Institutional Review Board in Social Sciences and Humanities

UNESCO: The United Nations Educational, Scientific and Cultural Organization

VR: Virtual Reality

CHAPTER 1

INTRODUCTION

The rapid advancement of digital technologies has fundamentally transformed education and introduced novel technologies that enhance learning and teaching. Recent global crises and events such as the COVID-19 pandemic and major earthquakes in Türkiye became an obstacle for face-to-face education and have strongly highlighted the critical importance of using online education platforms to ensure continuity of education. For example, according to The United Nations Educational, Scientific and Cultural Organization [UNESCO] (n.d.), during the COVID-19 pandemic, education was disrupted for more than 1.6 billion students worldwide. As a result, this global circumstance forced educational institutions to rapidly use remote teaching platforms. These events further accelerated the digital transformation of education and led researchers to explore innovative education platforms to be used in remote teaching. However, both educational institutions and instructors had some hesitations about whether these remote teaching platforms would be as effective as face-to-face education. In this manner, metaverse-based education has emerged as an important concept to provide an effective and uninterrupted education when face-to-face education is not accessible.

The metaverse can be defined as a network of immersive virtual worlds in which users interact with objects and other users via their digital avatars in a realistic virtual reality (VR) environment similar to the real world (Maghaydah et al., 2024). In recent years, as a potential tool for teaching and learning, educational institutions have shown great interest in metaverse-based education (Maghaydah et al., 2024). Metaverse-based learning environments include opportunities such as rich interactivity, collaboration, socialization, increased student motivation, and improved learning outcomes (George Reyes, 2020; González Crespo et al., 2013; Maghaydah et al., 2024; Siyaev & Jo, 2021). Unlike traditional video conferencing platforms (e.g., Zoom), which were mainly used in the COVID-19 pandemic, a metaverse-based classroom environment can closely imitate a real-world classroom experience. For example, students and instructors meet with their digital avatars in shared virtual spaces, have real-time discussions, and engage in collaborative activities much as they would face-to-face (George Reyes, 2020; González Crespo et al., 2013; Maghaydah et al., 2024; Siyaev & Jo, 2021). The features provided by the metaverse, and especially the sense of presence and realism in it, could make the metaverse learning environment more engaging and motivating compared to video conferencing platforms like Zoom (Cheng et al., 2024). By enabling social interaction and being able to act in the environment freely with their digital avatars, metaverse learning platforms have the potential to keep students motivated and involved even when they are in geographically different places. Therefore, the metaverse opens up new perspectives for educators and educational institutions to maintain educational activities in crisis situations by offering an online digital space that feels more like a real classroom than flat video conferencing platforms.

As mentioned, although metaverse-based education has important benefits, there is also a need to investigate how to best maintain the continuity and quality of education through the metaverse learning environment. Therefore, the effectiveness of the different metaverse learning environments across multiple dimensions of the students' learning experience should be critically evaluated (Al-Sharafi et al., 2024). In this manner, there are still concerns, specifically regarding the emotional and cognitive demands of learning in these kinds of virtual settings, and there is a need to understand whether these highly interactive environments actually help in education or they create new challenges for education. Since there are a variety of metaverse learning environments available, this problem has become particularly important to consider. Not all metaverse learning platforms are created and designed in the same manner. For example, fully immersive virtual reality (IVR) systems require the use of head-mounted displays (HMDs), which are wearable devices that cover the eyes and track the head movements to provide a more realistic and immersive experience. As a result, IVR can create very real-life experiences in the metaverse, but they also lead to some problems, such as high equipment costs and potential health drawbacks (e.g., eye strain or motion sickness) (Kamińska et al., 2019). In other words, receiving education in IVR platforms can be expensive and cause user discomfort. Therefore, the accessibility challenges due to the high cost of HMDs and potential health problems make them difficult to apply and use IVR for education in metaverse learning environments (Abraham et al., 2023; Chen, 2022; Kaddoura & Al Husseiny, 2023).

By contrast, desktop-based virtual reality (DVR) platforms allow users to enter the virtual world through a standard computer screen, a mouse, and a keyboard without requiring an HMD. Therefore, since it needs a standard personal computer, DVR-based metaverse environments can be considered more accessible and affordable for use in education as an alternative to IVR, which makes them practical for wider adoption (Chen, 2006; Sudár & Csapó, 2024). For that reason, as students generally have easier access to computers compared to HMDs to use metaverse learning environments, there is a need to study and investigate the effects of DVR-based metaverse learning environments in the context of education from pedagogical, technological, and student engagement perspectives. In this context, there is a critical aspect that needs further investigation within DVR-based metaverse platforms, which is the effect of the dimension of the metaverse learning environment. Therefore, the question of whether a DVR-based two-dimensional (2D) or three-dimensional (3D) metaverse learning environment offers more advantages or challenges for learning remains relatively underexplored. As a result, for a better learning experience, it is important to examine how 2D and 3D DVR-based metaverse learning environments impact students during educational activities within those environments.

From this perspective, in the scope of this study, a critical gap will be addressed by investigating the effects of two different types of DVR-based metaverse platforms that are 2D and 3D metaverse learning environments. While 2D platforms provide a simplistic environment, 3D platforms provide a more immersive learning environment. In the literature, it was stated that 3D virtual environments, even when used via desktop computers, could lead to equal or better learning performance and lower mental effort compared to traditional 2D platforms (Sudár & Csapó, 2024). In addition, according to Barrett et al. (2022), learning accuracy did not significantly differ between 2D, flat-screen desktop, and 3D VR conditions. Furthermore, Hwang et al. (2023) examined social and emotional presence in the metaverse learning environments and found that students' perceptions and the degree of reality experienced by them were more positive in 3D VR settings as opposed to 2D VR settings. Similarly, a study conducted by Lataifeh and Ahmed (2024) stated that immersive metaverse settings were more engaging for students than conventional 2D platforms. Nevertheless, in the literature, a majority of studies mainly focus on IVR with HMD or single-platform interventions (Han et al., 2021). Although DVR-based metaverse learning platforms are more accessible and affordable for educational purposes, there are not many studies comparing different DVR-based metaverse learning platforms, like 2D and 3D environments. Besides that, most studies have generally focused on variables such as usability and learning gains and less on the cognitive load or flow experiences, which are important concepts for a better learning experience in these kinds of platforms. In other words, while the educational potential of metaverse-based platforms is well recognized by researchers, studies that examine how DVR-based 2D and 3D metaverse learning environments might differ in their cognitive and affective impacts on students remain limited.

Therefore, the lack of direct comparisons between 2D and 3D metaverse learning environments on critical learner-centered outcomes such as cognitive load and flow experiences was determined to be an important gap in the literature. Cognitive load is based on the cognitive effort required during learning and problem-solving to process new information (Sweller, 1988). To prevent overloading learners cognitively in the metaverse-based learning process, cognitive load and its theory are significant in terms of how to design learning environments that are aligned with cognitive limits of humans (Thorp et al., 2024). In addition, flow experience can be described as the state of deep absorption and optimal experience that can happen when a person is fully engaged in an activity (Csikszentmihalyi, 1990). The flow experience is an important concept to study because when they reach the state of flow experience, it increases the students' engagement and learning (Shernoff & Twersky, 2022). The aspect of cognitive load and flow experience has rarely been explored in educational metaverse studies, and this situation makes it unclear whether students experience the cognitive load and attain a flow experience state more in 2D environments or in 3D environments.

This study aimed to fill these gaps by using a mixed-methods approach to gather both quantitative and qualitative data to provide a comprehensive understanding of the research topic (Creswell & Plano Clark, 2018). By the integration and synthesis of quantitative and qualitative data, this study aimed to create a general and complete understanding of the research problem by looking at it from various perspectives (Ivankova et al., 2006). Also, by directly comparing higher education students' cognitive load and flow experiences in 2D and 3D metaverse learning environments, this research will provide much-needed data on the relative strengths and drawbacks of 2D and 3D metaverse learning environments regarding students' cognitive load and flow experiences.

All in all, previous studies have stated the potential of metaverse-based education in increasing student motivation, engagement, and presence compared to traditional video conferencing tools (Cheng et al., 2024; Jeong et al., 2022; George Reyes, 2020). However, while these studies provide important insights into the general benefits of using metaverse technologies in education, they often focus on specific platforms or general usage without systematically comparing different types of DVR-based environments, such as 2D and 3D. In other words, although the educational use of the metaverse is a growing research field, there are not enough comprehensive and comparative investigations into how different DVR-based metaverse learning environments impact learner experiences, particularly from cognitive and emotional perspectives. This indicates a significant gap in the literature that this study aims to address. Through the findings of this study, understanding the cognitive and emotional experiences of students in metaverse-based classrooms will also be valuable to several groups to improve the learning experiences in these environments. Researchers can use the results of this study to further extend and advance the studies about metaverse learning environments. Educators and instructional designers will gain insights into optimizing cognitive load and supporting flow experience by selecting the appropriate metaverse learning environments. Lastly, through the findings of this study, developers of virtual learning platforms can design more learner-centered environments by understanding which features promote cognitive efficiency and flow experiences.

1.1 Purpose of the study

The purpose of this study was to examine the effects of 2D and 3D metaverse learning environments on higher education students' cognitive load and flow experiences.

1.2 Research questions

In light of the overarching research question—"How do 2D and 3D DVR-based metaverse learning environments affect higher education students' cognitive load and flow experiences?" — This study aimed to answer the following sub-questions:

Research question i: How do 2D and 3D DVR-based metaverse learning environments affect higher education students' cognitive load?

> i.i: Is there a statistically significant difference in the intrinsic cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?
>
> i.ii: Is there a statistically significant difference in the extraneous cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?

i.iii: Is there a statistically significant difference in the germane cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?

i.iv: How do students describe the factors influencing their cognitive load in 2D and 3D metaverse learning environments?

Research question ii: How do 2D and 3D DVR-based metaverse learning environments affect higher education students' flow experiences?

ii.i: Is there a statistically significant difference in the flow experience scores of higher education students using the 2D and 3D metaverse learning environments?

ii.ii: How do students describe the factors that enhance or hinder their flow experiences in 2D and 3D metaverse learning environments?

1.3 Organizations of the sections

In this thesis, Chapter 1 explains the background, research problem, significance, gaps in the literature, purpose, and research questions of the study and also the organization of the sections. Chapter 2 reviews the role of VR and metaverse technologies in education; theoretical and empirical literature related to cognitive load theory, flow theory, and the method vs. media debate; and comparative studies on 2D and 3D environments with a focus on their effects on students' cognitive load and flow experiences. Chapter 3 explains the research design, variables, participants and sampling, context and setting of the study, data collection instruments, data collection procedure, the methods used for data analysis, trustworthiness, and the researcher's positionality. Chapter 4 reports the quantitative and qualitative findings related to the students' cognitive load and flow experiences in 2D and 3D metaverse learning environments. Finally, Chapter 5 includes a discussion of the findings in light of the literature, practical implications, recommendations for future research, and limitations of the study.

CHAPTER 2

LITERATURE REVIEW

The objective of this literature review is to explain and synthesize the relevant theoretical foundations as well as current research findings in the literature in order to provide comprehensive insight into the concepts that frame this study. The concepts discussed in this section include VR technologies in education, the metaverse in education, cognitive load theory, flow theory, the Clark vs. Kozma debate, a comparison of 2D and 3D environments, and the impacts of these environments on students' cognitive load and flow experiences. The studies included in this section were selected based on their relevance and association with previous and present research conducted on these concepts.

Firstly, a discussion of the current literature on VR in education is presented by also comparing and distinguishing between the IVR and DVR technologies of VR. After that, the concept of the metaverse is defined, and its advantages, challenges, and current applications in education are presented. Then, cognitive load theory, flow theory, and the Clark vs. Kozma debate that are related to this study theoretically are introduced. These are then followed by comparative studies on 2D and 3D environments that focus on the students' cognitive load and flow experiences.

2.1 VR in education

In the educational context, VR has been gaining much attention as it has the potential to further improve the educational experiences of students (Makransky & Petersen, 2019). In this aspect, VR has brought significant changes in educational activities by offering immersive and interactive learning experiences to increase student engagement and attention (Ghafar, 2024). VR can be defined as computer-based technology or simulation that is created to simulate real or imagined environments to allow users to connect and interact with this virtual world (Casquero et al., 2023). VR provides a number of opportunities to improve learning outcomes, including improved engagement, improved motivation, the enrichment of learning experiences, greater understanding, and higher knowledge retention (Kalunga & Elshobokshy, 2023; Paramita et al., 2024). For instance, the visualizations and simulations used in the scope of virtual reality make the understanding of complex concepts or topics easier (Paramita et al., 2024). The component of immersion, interaction, and active participation in a VR environment makes the learning process more engaging and motivating (Freina & Ott, 2015). VR also helps the development of theoretical and practical skills of students in different fields such as science, engineering, education, and medical education through realistic simulations (D’Urso et al., 2023; Yang et al., 2024). In addition, VR-based educational platforms can also be used to enable learners to work collaboratively with other learners as they learn and can ease the process of collaborative learning (Sims et al., 2022). Furthermore, in many cases, learning through the VR-based simulation has positive effects on the students’ motivation when compared to the other pedagogical approaches, and VR provides fun and excitement for learners during the learning process (Jiang & Fryer, 2024; Sims et al., 2022; Yildirim et al., 2020).

Besides, VR training has the advantage of providing a safe, controlled virtual environment with relatively low cost, and this allows people to practice through immersive and simulated dangerous scenarios without actually experiencing any dangerous situations (Xie et al., 2021).

Mainly two types of VR are used and common in education: IVR and DVR. In the literature, different terms that have the same meanings are also used to express IVR and DVR. For instance, in the literature, while high-immersion VR (HiVR) is used for describing IVR, non-immersive virtual reality or low-immersion VR (LiVR) is used for describing DVR (Kaplan-Rakowski & Gruber, 2019).

IVR typically uses HMDs, which provide an immersive experience and immerse the user in a 360-degree virtual environment (Kaplan-Rakowski & Gruber, 2019). The high level of immersion provided by HMD can increase the sense of presence by allowing people to feel the environment, which has an impact on creating effective learning experiences and cognition (Ou et al., 2021). Furthermore, IVR has a positive effect on skill and knowledge development (Jiang & Fryer, 2024). However, the use of HMDs may also lead to other problems, including motion sickness, eye fatigue, headaches, nausea, sweating, dizziness, physical discomfort, and increased cognitive overload due to the complexity of the visual environment (Carnegie & Rhee, 2015; Caserman et al., 2021; Freina & Canessa, 2015; Roettl & Terlutter, 2018). On the other hand, the technical requirements of IVR highlight practical considerations, such as the need for adequate space for movement, the weight of the equipment needed to wear, and the risk that users may become fatigued, which may make long-term use in educational settings difficult (Feng et al., 2022; Sin et al., 2023). Additionally, the cost and technical requirements of HMDs and health effects can be considered disadvantages for use in education (Pantelidis, 2009). Besides, IVR can increase emotional arousal and extraneous cognitive load, and this situation may lead to decreased learning outcomes compared to desktop environments (Parong & Mayer, 2021). As a result, although IVR has some good benefits, it also has serious challenges to using it in education, such as technology issues (e.g., equipment, cost, VR sickness) that inhibit learning.

By contrast, DVR employs standard personal computers without needing any additional equipment to interact with virtual environments, which provides a less immersive but more accessible and cost-effective alternative to IVR (Chen, 2006; Hawes & Arya, 2022). Compared to IVR systems, DVR systems may also provide similar educational outcomes without giving rise to health problems associated with HMDs (Jensen & Konradsen, 2018; Srivastava et al., 2019). Similarly, Farr et al. (2023) stated in their empirical study that DVR and IVR are equally effective in retention of the learning. DVR platforms enhance students' ability to achieve learning outcomes through interactive and immersive experiences, and also by offering 3D representations of complex systems, DVRs enable learners to understand structural and functional principles more quickly and enjoyably (Onyesolu & Eze, 2011). Besides that, DVR-based platforms can reduce motion sickness and cognitive overload, which are frequently mentioned in HMD-based environments, while still enabling effective spatial learning (Srivastava et al., 2019; Zhang & Liu, 2023). Although DVR provides a lower immersion level compared to IVR, it still supports learning through visual simulations and promotes understanding and retention of knowledge (Hawes & Arya, 2022). In some contexts, the reduced sensory stimulation by DVR may even be beneficial in decreasing the extraneous cognitive load (Zhang & Liu, 2023). Also, a 3D DVR environment can allow conducting the experiments within a controlled natural environment (Karacan et al., 2010).

However, DVR may not provide the same amount of presence or emotional engagement as experienced in IVR, and this situation potentially limits students' motivation or attention in certain learning scenarios (Hawes & Arya, 2022). DVR is especially suited for widespread implementation in educational settings in which high system requirements are not feasible and where moderate immersion is sufficient for learning goals (Robertson et al., 1997; Srivastava et al., 2019). As a result, DVR can still be considered a valuable educational tool due to its ease of use, lower cost, and compatibility with students' own personal computers (Chen, 2006; Sousa Santos et al., 2009).

2.2 The emergence of the metaverse in education

The metaverse is a significant evolution of VR and augmented reality (AR) technologies, which provide an immersive, collaborative, interactive, and online virtual environment in which multiple users can engage with their avatars that can represent themselves (Onu et al., 2024). In other words, the metaverse can be defined as a network of immersive virtual worlds in which users interact with objects and other users via their digital avatars in a realistic environment similar to the real world (Maghaydah et al., 2024). Unlike the virtual world, which is mainly based on VR technology, the metaverse can employ and integrate various technologies, such as AR, VR, artificial intelligence (AI), blockchain, cryptocurrency, and non-fungible token (NFT) technologies (Johri et al., 2024; Zainab et al., 2022). The concept of the metaverse, which is a collective virtual shared space, originated in a science fiction novel called "Snow Crash" (Stephenson, 1992). However, early educational uses of metaverse-like environments date back to the reveal of virtual worlds such as Second Life, which was launched in 2003, and Second Life allowed people to create avatar-based learning communities and work collaboratively (Lee & Wong, 2014). The term "metaverse" itself gained popularity and attraction in 2021 when major technology companies highlighted the potential of immersive online worlds called metaverse for work and learning (Kaddoura & Al Husseiny, 2023). This renewed interest towards the metaverse was accelerated more by the COVID-19 pandemic, which forced a rapid transition to online education and exploration of more engaging virtual platforms like the metaverse (Kye et al., 2021; Latino et al., 2024).

In the context of educational technology, the metaverse has the power to create engaging, interactive, and immersive learning environments in which both students and teachers can interact with each other in real time like in real life (Rahman et al., 2023). Main features of the metaverse in education contain the ability to create personalized learning experiences, interactive 3D simulations, immersiveness, learning environments that closely mimic physical environments, collaboration, and providing students with opportunities for exploration and hands-on learning (Rahman et al., 2023). Therefore, since the metaverse-based learning platform is an interconnected web of immersive environments, it provides continuous support for social communication, content creation, and experiential learning activities (Mystakidis, 2022).

In this manner, there are numerous potential benefits of integrating metaverse platforms into education (Chen, 2022). Compared to traditional online platforms, metaverse-based learning environments can offer students more hands-on and engaging learning opportunities because of the metaverse's enhanced interactivity and immersion of learning experiences (Abraham et al., 2023; Latino et al., 2024). For instance, students can engage in virtual simulations, participate in role-playing activities, and collaborate on works with their peers who are in geographically different locations (Abraham et al., 2023). Latino et al. (2024) also stated seven main advantages of metaverse-based teaching, which can be defined as (i) higher student motivation and enjoyment, (ii) facilitation of teaching processes, (iii) improvement of students' technical and professional skills, (iv) increased student engagement, (v) enhanced learning outcomes, (vi) greater knowledge gain, and (vii) richer interaction between students and instructors.

In addition, the strong sense of presence that metaverse-based learning platforms increase is another advantage (Chen, 2024). According to Makransky and Petersen (2019), presence could be defined as the feeling of being physically "there" in a virtual environment with other people. In this manner, a study conducted by Cheng et al. (2024) compared a 3D virtual classroom to Zoom and found the metaverse setting provided a significantly better sense of place and social presence for students. Similarly, a study conducted by Jeong et al. (2022) included 22 students, and they attended a class in two conditions (a conventional Zoom meeting and a 3D virtual metaverse environment called FrameVR). The findings showed that when compared to the Zoom platform, the FrameVR environment increased student engagement, particularly for emotional engagement (Jeong et al., 2022). Compared to other conventional video conferencing platforms like Zoom, this study showed that the immersive metaverse environment more effectively attracted students' interest and attention (Jeong et al., 2022). Also, FrameVR, which is a type of metaverse, has been stated as a tool for increasing engagement through spatial and constructivist learning opportunities, particularly when educators use its interactive and social features (Jeong et al., 2022).

Another benefit is the platform’s support for real-time collaboration because metaverse learning platforms allow multiple users to interact simultaneously in a shared space, manipulate virtual objects, and solve problems together (George Reyes, 2020; González Crespo et al., 2013; Maghaydah et al., 2024; Siyaev & Jo, 2021). Hu et al. (2023) indicated this benefit via their study conducted with university students by using the Gather.Town platform, which is an avatar-based 2D metaverse learning environment. The findings of the study indicated significantly higher learning motivation, peer connection through real-time collaboration, and better outcomes on ethical decision-making tasks than a control group that used a standard learning platform (Hu et al., 2023). Song et al. (2023) also stated that Learningverse, which is a 3D platform based on the Community of Inquiry framework, led to increased teaching, social, and cognitive presence in higher education settings.

All in all, metaverse-based learning environments provide great opportunities such as rich interactivity, collaboration, socialization, increased student motivation, engagement, and improved learning outcomes (George Reyes, 2020; González Crespo et al., 2013; Kye et al., 2021; Maghaydah et al., 2024; Siyaev & Jo, 2021). However, the use of the metaverse in education also brings about some challenges. The accessibility and usability of the metaverse in the context of education might be limited by the high costs of developing and maintaining metaverse platforms, as well as technical prerequisites related to hardware and software requirements (Abraham et al., 2023; Chen, 2022; Kaddoura & Al Husseiny, 2023). Besides that, privacy and security concerns pose some challenges because using avatars and virtual environments raises some questions about data protection and the ethical use of digital identities (Chen, 2022; Wang et al., 2025). In addition, there are some concerns about the possibility of technology addiction and the effects of prolonged use of immersive environments on students' mental and social health (Chen, 2022). In order to overcome the challenges, the long-term effects of metaverse-based education on educational outcomes must be investigated further, and the design and implementation of these virtual environments must be improved to optimize their educational potential while minimizing risks (Pradana & Elisa, 2023).

2.3 Theoretical perspectives relevant to the study

2.3.1 Cognitive load theory

Cognitive load theory was proposed by Sweller (1988) and focuses on the cognitive effort required during learning and problem-solving to process new information (Sweller, 1988). Human working memory has a limited capacity and can only process a limited amount of information at once, according to Sweller (1994). Therefore, this theory proposes to optimize instructional design by understanding and managing the cognitive load imposed on learners (Sweller, 1994). Cognitive load theory states the three types of cognitive load, which are intrinsic, extraneous, and germane loads. First of all, intrinsic cognitive load refers to the inherent complexity of the task or material that is learned (Sweller, 1994). The level of intrinsic cognitive load is determined by the elements that can be defined as the procedures or concepts that are learned (Sweller, 2010). If the elements do not include complex relationships, this is defined as low element interactivity, which has a low impact on working memory (Sweller, 2010). On the other hand, if the elements include a complex relationship with the other elements, this is defined as high element interactivity, which has a heavy impact on working memory and increases the intrinsic cognitive load (Sweller, 2010). In addition, according to Sweller et al. (2011), since the intrinsic cognitive load is based on the specific task or the materials, it cannot be changed without changing either the nature of the learning task itself or the learners' knowledge level. Secondly, extraneous cognitive load stems from the way, method, or instructional material through which information is presented (Sweller, 1994). Engaging in other activities unrelated to the relevant interacting elements constitutes an extraneous cognitive load that interferes with learning (Sweller, 2010). As a result, poor instructional design can increase extraneous cognitive load by leading to unnecessary complexity that distracts from the learning process (Sweller, 1994). Thirdly, germane cognitive load can be defined as the cognitive effort that a learner devotes to processing and understanding the information and constructing schemas (meaningful knowledge structures) associated with the learning (Sweller, 2010). These three types of loads should be managed by effective instructional design by reducing extraneous load and optimizing intrinsic load to increase germane processing (Sweller et al., 1998). For example, dividing complex tasks into smaller steps can lower intrinsic load, and removing unnecessary elements from the lecture material can reduce extraneous load, and these situations bring about increased germane load by opening spaces for cognitive resources (schema construction and learning) (De Jong, 2010). All in all, to prevent overloading learners' limited capacity and distractions from the learning process, cognitive load theory provides a foundation for understanding how to design learning environments that are aligned with cognitive limits of humans (Thorp et al., 2024).

2.3.2 Flow theory

Flow theory, which was introduced by Csikszentmihalyi (1975), describes the state of deep absorption and optimal experience that can happen when a person is fully engaged in an activity (Csikszentmihalyi, 1990). In other words, Csikszentmihalyi (1975) stated that people often experience a deep sense of enjoyment and involvement when they are completely absorbed in an activity where people lose time awareness and self-consciousness. This circumstance was stated by Csikszentmihalyi (1975) with the term "flow." The flow theory proposes that flow experience emerges when there is a perfect balance between the challenge of a task and the skills of the participant, alongside clear goals and immediate feedback (Csikszentmihalyi, 1975, 1990). In this manner, there are some key conditions explained below to reach the flow experience state, which are clear goals, immediate feedback, a challenging task that is hard enough but does not overwhelm a person's skills, deep concentration, a loss of self-consciousness, a sense of control, and an altered sense of time (feeling of time seems to pass quickly) (Csikszentmihalyi, 1990).

i) Clear Goals: The activity must have clear and structured goals. This allows people to focus and maintain their attention solely on the task.

ii) Immediate Feedback: People must receive direct and timely feedback about their performance. This allows people to maintain their engagement towards the task.

iii) Balance Between Challenge and Skill: Flow experience emerges when the task presents a challenge that matches one's current level of skill. If the task is too easy, it leads to boredom, or if the task is too difficult, it leads to anxiety. Therefore, the challenge and the skill should be moderate to attain the flow experience state.

iv) Deep Concentration: The activity should absorb one’s full attention and allow them to become fully engaged in the task and disengage from distractions.

v) Loss of Self-Consciousness: One should be in deep involvement in which they are not aware of their everyday frustrations and worries.

vi) Sense of Control: During the flow experience, individuals feel a strong sense of control over their actions and environment, even if this control is more psychological than physical.

vii) Altered Sense of Time: Time may seem to pass faster or slower than usual. Minutes can feel like hours, or hours may pass in what feels like a few minutes.

When these conditions are together, individuals experience intrinsic motivation in which they find the activity rewarding for its own sake (autotelic experience), and this situation leads to reaching the flow experience state (Csikszentmihalyi, 1990).

2.3.3 Method vs. media debate (Clark vs. Kozma)

In the field of educational technology, there is a well-known discussion on the “media vs. method” debate, which is primarily between Richard E. Clark and Robert Kozma.

Clark (1983) strongly stated that media itself used for teaching does not have any effect on students’ learning outcomes, and only the teaching or instructional methods have an impact on learning outcomes. Clark supported his idea with an analogy, which is “media are mere vehicles that deliver instruction but do not influence student achievement any more than the truck that delivers our groceries causes changes in our nutrition” (Clark, 1983, p. 445).

Clark also argued that researchers should stop conducting media-comparison studies (e.g., textbooks vs. computers) because media differences alone were viewed as irrelevant to learning (Clark, 1983).

About a decade later, Kozma (1994) stated a counter idea as a response to Clark's (1983) idea. Kozma (1994) asked the question of whether media could be designed in ways that do influence learning. Kozma (1994) argued that features of the media may affect the learning process, and researchers should continue exploring how the unique capabilities of new media might foster learning. In Kozma's (1994) view, media and method are intertwined and have integral relationships (Akyol & Cagiltay, 2007; Kozma, 1994).

Clark (1994) also responded to Kozma's (1994) idea by maintaining his idea and stating that any benefits of a medium in the learning process were due to methodological improvements confounded with the medium. Clark (1994) stated that "media and their attributes have important influences on the cost or speed of learning, but only the use of adequate instructional methods will influence learning" (p. 27). In his statement, Clark (1994) acknowledged media might make instruction more efficient or affordable but strongly stated that they do not mainly change learning effectiveness.

Although this debate has been continuing over the years, rather than debating the influence of media on learning, the main discussion should be on how media should be designed in order to improve teaching and learning (Akyol & Cagiltay, 2007). In this manner, this study aligns with the essence of this debate by comparing two different media environments (2D and 3D DVR-based metaverse platforms) while keeping instructional content constant. The aim is to determine whether the medium itself contributes to differences in cognitive load and flow experiences and also determine whether media can influence learning-related experiences beyond the instructional method alone. In other words, by examining how different metaverse learning environments impact learner experiences while keeping content and pedagogy constant, this study shows empirical evidence for the method vs. media debate on whether media themselves have significant value on learners' cognitive load and flow experiences or solely function as education delivery tools.

2.4 Comparative studies on 2D and 3D environments

The comparative effectiveness of 2D and 3D environments in education has been frequently investigated, and different findings were found depending on the context, domain, and learner profile. For example, Dalgarno and Lee (2010) mentioned the positive learning affordances of 3D environments, such as enhanced spatial knowledge representation, experiential learning, contextualization, and collaborative engagement, which are typically limited in 2D environments. Likewise, De Lucia et al. (2009) stated that 3D platforms like Second Life enhanced interaction and community awareness in e-learning, which contributed to a more effective and socially rich educational experience. De Boer et al. (2016) found that dental students using 3D vision performed significantly better than those using 2D displays, with over 90% of participants expressing a preference for 3D, suggesting both cognitive and affective advantages. Prior research also emphasizes the potential of 3D technologies to increase learners' engagement and intrinsic motivation by providing immersive and interactive learning experiences.

For instance, Quest Atlantis, which was a 3D-based virtual learning environment, not only enhanced real-time collaboration and content organization but also engaged teachers and children—including girls and underrepresented groups—in intrinsically motivating challenges through advanced technological contexts (Barab et al., 2005).

However, in the literature, not all findings related to 3D environments were positive compared to 2D environments. According to Richards and Taylor (2015), 2D NetLogo models performed better than 3D Unity simulations in terms of learning outcomes in biology instruction because this may potentially stem from the distractions and cognitive overload experienced in 3D immersive environments. Besides that, Chen (2024) further demonstrated that 2D virtual platforms like Gather.Town can significantly improve lesson planning, engagement, and social, physical, and self-presence among pre-service teachers, particularly for high achievers who experienced deeper immersion. Johnson-Glenberg et al. (2021) also stated that the usefulness of 3D VR depends on the level of user interaction and control. If the user cannot interact much in the VR environment (if they have a low-participation experience), then even worse results can be obtained than in 2D environments (Johnson- Glenberg et al., 2021). In other words, it is not enough to use 3D VR alone; the important thing is to offer a design that allows the user to actively participate (Johnson- Glenberg et al., 2021). Similar to this, Van Der Land et al. (2013) found that although 3D visualization improved individual understanding, realism, immersion, and interactivity, it also increased cognitive overload, making it difficult to reach group decisions in group projects.

2.5 Effects of 2D and 3D environments on cognitive load

As mentioned, cognitive load theory provides a critical perspective for evaluating the efficiency of the learning process in virtual learning environments. Breves and Stein (2023) found that 3D immersive VR environments caused significantly higher cognitive load than 2D, largely due to cybersickness rather than spatial presence, and this finding showed the role of physical discomfort in students' cognitive performance. However, studies based on electroencephalography (EEG) results confirm that 2D environments can be more cognitively demanding for certain tasks, particularly for learners with low spatial ability, while 3D environments distribute cognitive resources more effectively for complex situations (Dan & Reiner, 2017; Liu et al., 2023). Based on participant performance data and EEG-derived cognitive load indices, Dan and Reiner (2018) demonstrated that 3D stereoscopic displays optimized cognitive load and enhanced learning in origami tasks when compared to 2D videos.

However, the results generally do not positively support 3D environments in terms of cognitive load. According to Liu et al. (2023) and Yin et al. (2023), 3D environments tend to increase cognitive load when performing simple observation tasks, but their effect on cognitive load diminishes when performing computational or problem-solving tasks. Roettl and Terlutter (2018) also stated that cognitive load was highest in VR gameplay and lowest in 3D, with 2D in between, and this suggested a non-linear relationship between immersion and cognitive load. In addition, Sudár and Csapó (2024) found that well-designed 3D dashboards can lessen cognitive load compared to traditional 2D layouts, but this depends on minimizing unnecessary elements within virtual space. Shin and Park (2019) stated that hybrid 3D animations supported with static visual cues reduced cognitive load without hindering learning, and this emphasizes the importance of visual design strategies. Wenk et al. (2023) also observed that although cognitive load remained unchanged across 2D, AR, and VR conditions, immersive VR improved motivation and embodiment.

2.6 Effects of 2D and 3D environments on flow experiences

One of the most important aspects of effective learning engagement is flow experience, which is mainly affected by deep focus, immersion, and enjoyment (Csikszentmihalyi, 1990). Studies in the literature showed that 3D environments are generally better at facilitating the flow experience than 2D environments. For instance, Huang et al. (2010) stated that 3D virtual worlds significantly increase flow experiences by increasing presence and interactivity, which also positively affects students' attitudes toward virtual learning. Cooper (2010) applied Csikszentmihalyi’s (1990) flow theory to Second Life-based military training and stated that immersive environments could result in deeper flow experiences and that perceptions of control and loss of time were powerful predictors of learning engagement. According to Hassell et al. (2009, 2012), learner satisfaction is positively correlated with the flow experience and presence in 3D learning environments, yet they did not find a direct correlation with increased effectiveness with flow experiences. This suggests that flow experiences may improve engagement more than performance (Hassell et al., 2009, 2012). In addition, Lo and Tsai (2022) supported the previous results in their environmental education study by highlighting that 3D metaverse-based training improved the flow experience, motivation, and self-efficacy. Song et al. (2023) also stated that by combining immersion with easily accessible interactivity, Learningverse, which was a 3D metaverse learning environment, enhanced teaching, cognitive, and social presence, which are important constructs closely related to flow experiences. Although Nah et al. (2011) stated that 3D environments trigger enjoyment and flow experiences, they also stated that too much interactivity may cause attentional conflicts, and this would ultimately hinder learning. Also, despite high presence, low-agency VR conditions resulted in less learning, and this finding highlighted the importance of interactivity and embodiment for flow experiences (Johnson- Glenberg et al., 2021).

2.7 General summary of the literature

The literature review examined the importance of VR in education, which provides immersive and interactive experiences that can enhance learning engagement and motivation (Ghafar, 2024; Makransky & Petersen, 2019; Paramita et al., 2024). Two main types of VR were mentioned, which are IVR with HMDs, which is more immersive and costly, and DVR, which is less immersive but more accessible and cost-effective (Jensen & Konradsen, 2018; Kaplan-Rakowski & Gruber, 2019). While IVR increases presence and spatial understanding (Ou et al., 2021), it may also increase cognitive overload and cause physical discomfort (Carnegie & Rhee, 2015; Parong & Mayer, 2021). DVR, though less immersive, can still foster effective learning without the downsides of IVR (Chen, 2006; Zhang & Liu, 2023).

Then, the literature review reviewed the metaverse in the context of education, which is a networked virtual environment and enables avatar-based collaboration and immersive learning (Maghaydah et al., 2024; Onu et al., 2024). Metaverse-based education provides higher student motivation, engagement, and learning outcomes through features such as real-time interaction and personalized experiences (Jeong et al., 2022; Latino et al., 2024; Rahman et al., 2023).

Nonetheless, challenges of the metaverse, such as technical costs, data privacy, and potential addiction, express significant concerns (Chen, 2022; Kaddoura & Al Husseiny, 2023; Wang et al., 2025).

Then, the literature review synthesized main theoretical concepts and empirical studies related to the virtual learning environments. According to Sweller (1988, 1994, 2010), human working memory has limited capacity, and this situation necessitates instructional designs that manage three types of cognitive load, which are intrinsic, extraneous, and germane. Effective learning experiences happen when extraneous cognitive load is minimized, intrinsic cognitive load is optimized, and germane cognitive load is maximized (De Jong, 2010; Sweller et al., 1998; Sweller et al., 2011; Thorp et al., 2024).

In parallel, flow theory describes a psychological state of deep engagement and optimal experience when learners are immersed in a task that balances challenge and skill (Csikszentmihalyi, 1975, 1990). Conditions that are necessary to reach the flow experience state include clear goals, immediate feedback, a sense of control, and an altered perception of time (Csikszentmihalyi, 1990).

The “media vs. method” debate is also an important debate in the scope of educational technology through the contrasting views of Clark (1983, 1994) and Kozma (1994). Clark (1983) stated that media are solely delivery vehicles and do not influence learning outcomes, emphasizing that instructional methods are responsible for the learning. In contrast, Kozma (1994) stated that media and method are intertwined and that the characteristics of media can influence how learning occurs (Akyol & Cagiltay, 2007; Kozma, 1994).

Comparative studies of 2D and 3D environments showed mixed results. While 3D platforms often improve spatial understanding, engagement, and presence (Dalgarno & Lee, 2010; De Boer et al., 2016; De Lucia et al., 2009), they can also increase cognitive overload or distract learners if not designed properly (Johnson-Glenberg et al., 2021; Richards & Taylor, 2015; Van Der Land et al., 2013). In some circumstances, 2D platforms like Gather.Town have shown stronger performance in lesson planning and engagement, especially for high-achieving learners (Chen, 2024).

Regarding cognitive load, research indicates that 3D environments can both increase and decrease load depending on task complexity, design quality, and learner characteristics (Breves & Stein, 2023; Dan & Reiner, 2017, 2018; Liu et al., 2023; Shin & Park, 2019; Sudár & Csapó, 2024; Wenk et al., 2023). Similarly, flow experiences experienced by students tend to be higher in 3D environments due to their increased immersion and interactivity (Cooper, 2010; Huang et al., 2010; Lo & Tsai, 2022), although excessive interactivity or low learner agency may hinder performance (Johnson-Glenberg et al., 2021; Nah et al., 2011).

2.8 Purpose of the study and research questions

The purpose of this study was to examine the effects of 2D and 3D metaverse learning environments on higher education students’ cognitive load and flow experiences.

In light of the overarching research question — "How do 2D and 3D DVR-based metaverse learning environments affect higher education students' cognitive load and flow experiences?" — this study aimed to answer the following sub-questions:

Research question i: How do 2D and 3D DVR-based metaverse learning environments affect higher education students' cognitive load?

i.i: Is there a statistically significant difference in the intrinsic cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?

i.ii: Is there a statistically significant difference in the extraneous cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?

i.iii: Is there a statistically significant difference in the germane cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?

i.iv: How do students describe the factors influencing their cognitive load in 2D and 3D metaverse learning environments?

Research question ii: How do 2D and 3D DVR-based metaverse learning environments affect higher education students' flow experiences?

ii.i: Is there a statistically significant difference in the flow experience scores of higher education students using the 2D and 3D metaverse learning environments?

ii.ii: How do students describe the factors that enhance or hinder their flow experiences in 2D and 3D metaverse learning environments?

CHAPTER 3

METHOD

This section explains the research design, variables of the study, participants and sampling, context and setting of the study, data collection instruments, data collection procedure, data analysis, trustworthiness of the study, and the researcher's positionality.

3.1 Research design

The main purpose of this study was to examine the effects of 2D and 3D metaverse learning environments on students' cognitive load and flow experiences. Therefore, this study used an explanatory sequential mixed-method design (Creswell & Plano Clark, 2018) to provide a comprehensive understanding of the research topic. Explanatory sequential mixed methods consist of two sequential steps: (i) quantitative and (ii) qualitative data collection and analysis (Creswell, 2014). Firstly, quantitative data were collected and analyzed to determine whether the participants' learning experiences in the 2D and 3D metaverse learning environments lead to statistically significant differences in terms of cognitive load and flow experiences. Therefore, the cognitive load scale (see Appendix A) and flow experience scale (see Appendix B) were applied to participants to answer these quantitative research questions, and then the quantitative data were analyzed to create a general perspective and understanding of the research problem. After that, in order to provide more in-depth explanations of the findings obtained from the quantitative data, qualitative data were collected by means of reflection forms that contain open-ended questions (see Appendix C) and semi-structured interviews (for the protocol, see

Appendix D) to understand the possible factors or reasons that may affect the participants' cognitive load and flow experiences in 2D and 3D metaverse learning environments. Thanks to the integration and synthesis of these quantitative and qualitative data, this study aimed to create a general and complete understanding of the research problem by looking at it from various perspectives (Ivankova et al., 2006). The research design was summarized in Figure 1.

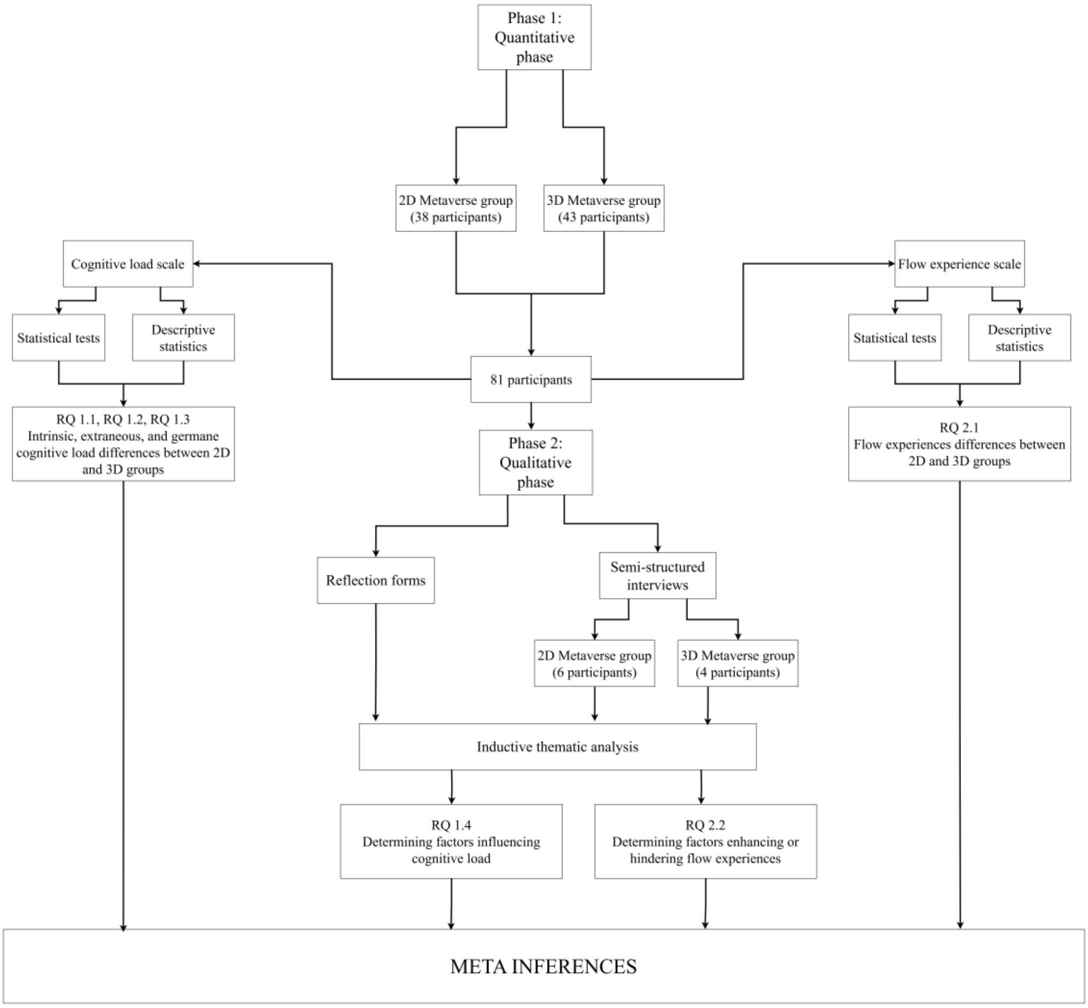

Figure 1. Research design of the study

3.2 Variables

In the context of this study, the independent variable is the type of metaverse learning environment (2D or 3D) in which participants take lessons. The dependent variables are participants' cognitive load scores measured using the cognitive load scale and their flow experience scores measured using the flow experience scale.

Additionally, in order to gain a deeper understanding of participants' experiences in 2D and 3D metaverse learning environments with respect to dependent variables, a qualitative data collection process was conducted. Through the reflection forms, including open-ended questions and semi-structured interviews, participants' cognitive load and flow experiences in the 2D or 3D metaverse learning environments were further explored. The variables of the study were summarized in Table 1.

Table 1. Variables of the Study

Variables	Description
Independent variable	Type of metaverse learning environment (2D or 3D)
Dependent variable 1	Cognitive load scores (measured by cognitive load scale)
Dependent variable 2	Flow experience scores (measured by flow experience scale)

3.3 Participants and sampling

In the 2024-2025 fall semester, the study was conducted with the participation of first-year, second-year, and third-year Computer Education and Educational Technology (CET) students at a public university in Istanbul, Türkiye. The target population to which the findings of the study may be generalized can be defined as higher education students who will attend lectures in metaverse-based learning environments. Purposive sampling, a non-probability sampling strategy, was used to select participants for this study. In order to eliminate the confounding variables and novelty effect in this research, participants' technological competencies should be at a certain level to better understand the impact of different metaverse-based learning environments on students' cognitive load and flow experiences, which increases the reliability of the study. For that reason, CET students were chosen as the most appropriate sample group for this study due to their inclination to use technology, experience with digital tools, and relatively high familiarity with innovative teaching/learning tools such as the metaverse. The criterion for purposive sampling was based on the selection of first, second, and third grade CET students who took the "Introduction to Educational Technology," "Education and Technology," and "Instructional Design" courses during the 2024-2025 fall semester. Although attending the lectures in these courses was compulsory, participating in the research was completely voluntary. The purpose, scope, data collection processes, and other details of the study were explained to participants in detail, and informed consent forms (see Appendix E) were filled out by the students who agreed to participate in the study. As mentioned before, participants were selected from the "Introduction to Educational Technology," "Education and Technology," and "Instructional Design" courses. The first two courses had two sections each. To ensure balance and minimize bias, one section of each course was randomly assigned to the 2D metaverse group and the other to the 3D metaverse group. Students remained in their original sections and did not select or switch between the 2D or 3D groups. The "Instructional Design" course had only one official section. However, to enable participation in both the 2D and 3D metaverse environments, students from this section were allowed to join the other course sections (previously assigned to either the 2D or 3D group) based on their availability. In other words, they attended whichever session (2D or 3D) best matched their schedule. This group assignment procedure was summarized in Table 2.

Table 2. The Procedure of the Group Assignment

Course	Number of Sections	Group Assignment
Introduction to Educational Technology	2	- One section randomly assigned to 2D group. - One section randomly assigned to 3D group.
Education and Technology	2	- One section randomly assigned to 2D group. - One section randomly assigned to 3D group.
Instructional Design	1	Students joined either 2D or 3D sessions of other courses based on their availability and whichever session best matched their schedule.

As a result, a total of 81 students participated in the study voluntarily. Based on the procedure explained in Table 2, the participants were divided into two groups: 2D and 3D metaverse groups. There were 38 students in the 2D metaverse group and 43 students in the 3D metaverse group. To gather information about the participants' previous metaverse experiences and gaming experiences that may affect the results of the study, a demographic information form (see Appendix F) was applied at the beginning of the study. Data related to the demographic information of groups and obtained from the participants' demographic form was used to determine whether the groups were equal in terms of gender, age, previous metaverse usage experiences, and their habits of playing digital games.

When the demographic information of the participants in the 2D and 3D metaverse groups was analyzed and compared, it appeared that both groups had almost similar characteristics. In terms of distribution of gender, age groups, grade level, previous metaverse experience, and gaming habits, there were no major differences between the groups. For example, in the 2D group, the majority of participants were male (65.8%), while the 3D group had a more balanced gender distribution (46.5% male, 48.8% female, and 4.7% other). Furthermore, the majority of participants in both groups—55.3% in the 2D group and 60.5% in the 3D group—reported having no prior experience with metaverse platforms, indicating a lack of familiarity with metaverse platforms. The majority of students (81.6% in the 2D group and 72.1% in the 3D group) reported playing video or computer games, and the majority had been playing for more than six years, with a preference for online multiplayer and simulation games. Detailed demographic information is provided in Appendix G (for the 2D group) and Appendix H (for the 3D group). The demographic similarity between the groups allowed comparing the participants' cognitive load and flow experiences between 2D and 3D metaverse groups objectively and equally. Since there were no major differences related to the other variables, this situation made it possible to interpret the findings of the study based only on the effect of 2D and 3D metaverse learning environments without the influence of novelty effect and any confounding demographic factors.

3.4 Context and setting of the study

The main purpose of this study was to examine the effects of 2D and 3D metaverse learning environments on students' cognitive load and flow experiences. In the context of this study, exactly the same two-hour lectures (see Appendix I for the detailed lesson plan) were reviewed by two experts and delivered in both 2D and 3D metaverse learning environments by the researcher. Since the participants' native language was Turkish, the lectures in both the 2D and 3D groups were delivered in Turkish to avoid language-related confounding variables that might affect students' cognitive load or flow experience. The design of the virtual classroom in both the 2D and 3D metaverse environments was also exactly the same to ensure consistency. As mentioned before, the participants took the lectures in those environments by dividing into two groups, namely, the 2D and 3D metaverse groups. While the participants in the 2D metaverse group took the lectures in the Gather.Town platform (Gather.Town, n.d.), the participants in the 3D metaverse group took the lectures in the 3D metaverse platform (MetaClass) developed by the researcher. For both lectures delivered in the 2D and 3D metaverse learning environments, the same instructor, who was the researcher, content, duration, and instructional strategies were employed, and all of them are explained in the "3.6 Data collection procedure" subsection in detail. In other words, all variables were the same except for the type of metaverse learning environments (2D and 3D) participants used. Their cognitive load level and flow experiences were compared with respect to the metaverse learning environments they used based on their experiences after participating in the lectures held in the 2D and 3D metaverse learning environments.

Also, with the help of the qualitative data, the reasons for the possible differences between 2D and 3D metaverse learning environments were examined in detail. The components of the study were explained in Table 3.

Table 3. The Components of the Study

Components	Details
Lecture content	- Introduction to the structure of the brain (First lecture – 60 minutes) - Cognitive load theory and cognitive theory of multimedia learning (Second lecture – 60 minutes)
Controlled variables	Same instructor, same content, same duration, and same instructional strategies across both groups
Group 1: 2D metaverse environment	Lectures delivered via Gather.Town platform
Group 2: 3D metaverse environment	Lectures delivered via MetaClass (3D metaverse platform developed by researcher)
Measured outcomes	- Cognitive load - Flow experience

In this study, in order to examine the students' cognitive load and flow experiences, two different metaverse learning environments were used: (i) a 2D metaverse learning environment (Gather.Town) and (ii) a 3D metaverse learning environment (MetaClass). Both of these environments offered participants interactive and collaborative learning. While the 2D metaverse learning environment (Gather.Town) provides students with a 2D pixelated, avatar-based, simplistic 2D interactive classroom environment, the 3D metaverse learning environment (MetaClass) provides students with a 3D avatar-based, immersive 3D interactive classroom environment. In the following subsections, the main features of both metaverse environments and their features used by the participants in the scope of this study were described.

3.4.1 2D metaverse learning environment: Gather.Town

Gather.Town is a web-based, 2D virtual metaverse environment (Gather.Town, n.d.). In the scope of this study, participants with their simplistic avatars were able to move in the virtual classroom environment, interact with the environment and objects, communicate with other participants either verbally or text-based, and also access the lecture materials. The features of the 2D metaverse learning environment used by the participants in the scope of this study are explained in detail in the following subsections.

3.4.1.1 Creating a virtual avatar and customization

By creating their own 2D pixel-art-style avatars, students were able to personalize their avatars with various clothes and accessories and move around the virtual environment with their avatars (see Figure 2). In this way, students were expected to reflect their identities in the virtual environment and participate more in the interaction.

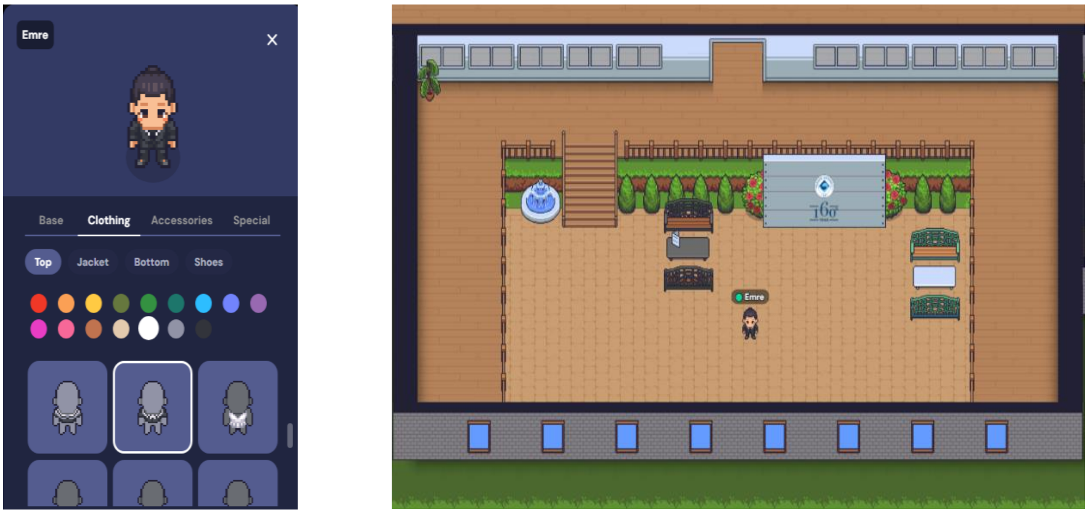

Figure 2. Avatar customization interface and 2D metaverse environment

3.4.1.2 2D virtual classroom environment

Students were able to move in the virtual classrooms and open spaces. Students were also able to attend the lectures and move freely around the virtual classrooms (see Figure 3).

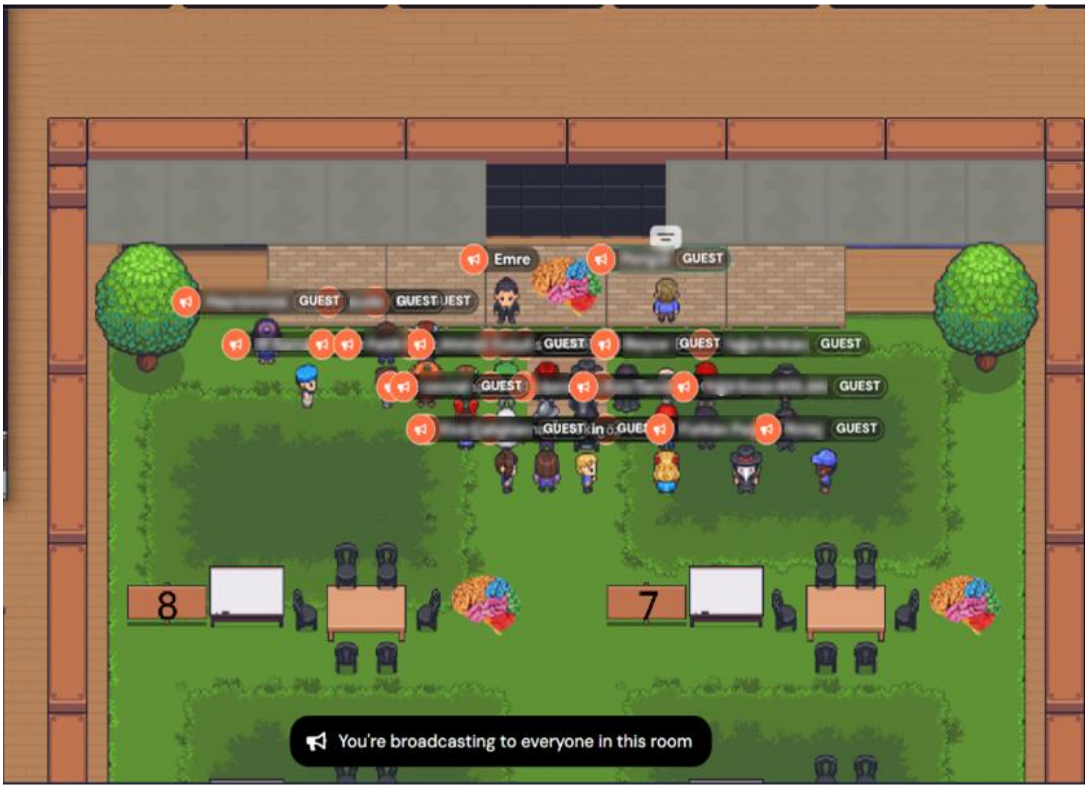

Figure 3. A screenshot from the lecture in the 2D metaverse environment

3.4.1.3 Voice and text-based communication

Students were able to make voice communication when they were in close proximity or use the text-based communication (see Figure 4). These features were important for group work and class discussions.

Figure 4. A screenshot from the voice and text-based communication

3.4.1.4 Screen sharing

Both instructors and students were able to share their computer screens during a lecture to make presentations or share materials (see Figure 5). This feature facilitated students' direct access to content related to the lectures.

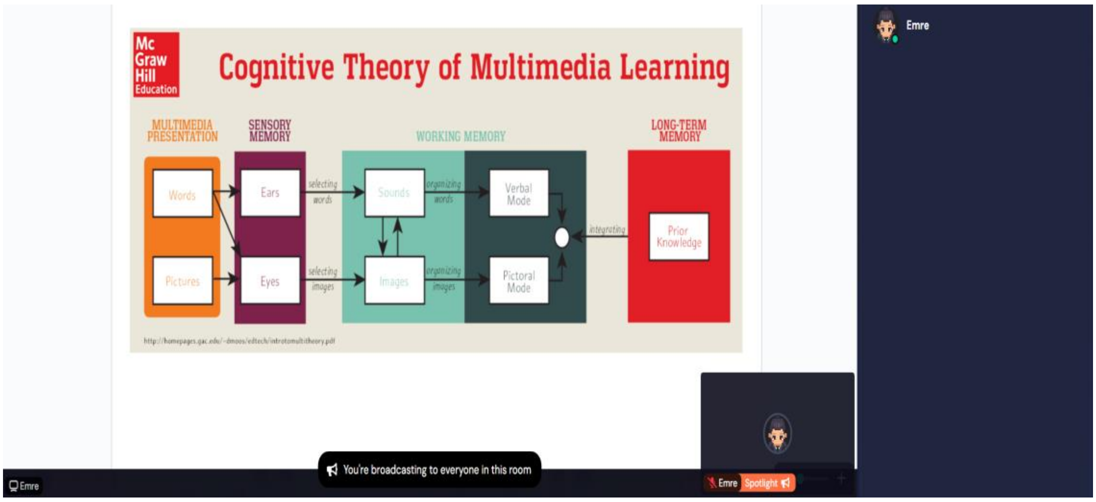

Figure 5. A screenshot from the screen-sharing function in the 2D metaverse environment
Note. Adapted from Learning Matters. (2018, June 10). *[Series: Influential Educators] Richard Mayer's cognitive theory of multimedia learning*. Medium. https://medium.com/learning-matters/series-influential-educators-richard-mayers-cognitive-theory-of-multimedia-learning-9c1db2f0805

3.4.1.5 Group work and whiteboard

Virtual classrooms had areas reserved for group work, and conversations within the group could not be heard outside the group (see Figure 6). In addition, thanks to the whiteboard feature, students were able to take notes, create concept maps, and work collaboratively.

Figure 6. A screenshot from the group works in the 2D metaverse environment

3.4.1.6 Use of simulation

In the scope of this study, a 2D brain simulation was developed and integrated into the 2D metaverse learning environment to be used in the lecture. It was aimed that participants could examine different regions of the brain through 2D simulation, learn the functions of each region, and comprehend them better with visual supports (see Figure 7).

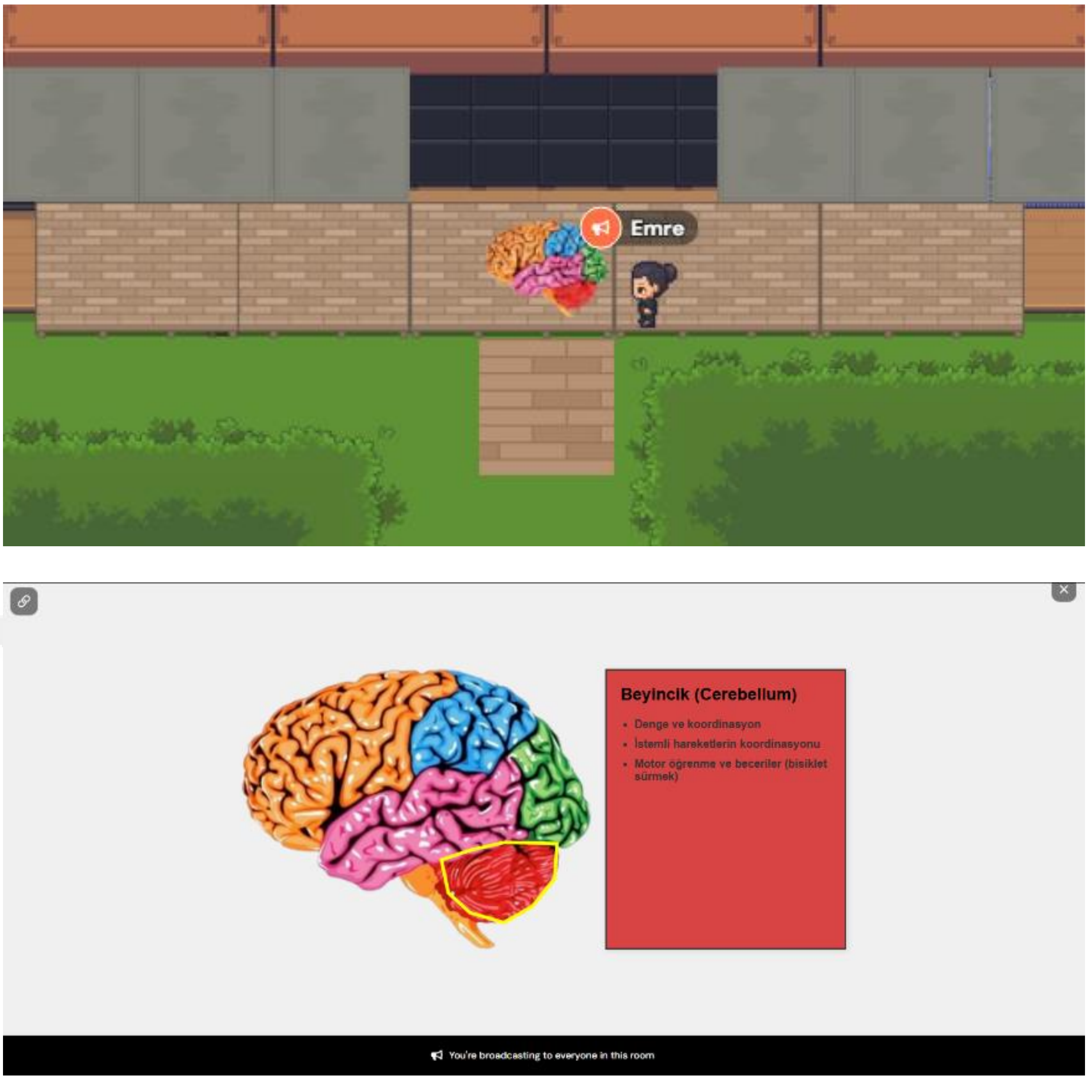

Figure 7. Screenshots from the brain simulation used in the 2D metaverse environment
Note. Adapted from Gorodetskiy, A. E., & Tarasova, I. L. (2023). Central Nervous System. In A. E. Gorodetskiy & I. L. Tarasova, *Introduction to the Theory of Smart Electromechanical Systems* (Vol. 486, pp. 89–177). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-36052-7_2

3.4.2 3D metaverse learning environment: MetaClass

For this study, a 3D metaverse learning environment titled MetaClass was developed by the researcher using the Unity game engine. MetaClass is a 3D DVR-based immersive classroom environment that does not require VR glasses. In MetaClass, participants were able to move freely in a 3D immersive classroom environment with their 3D personalized avatars, interact with objects and other users, communicate with other participants either verbally or text-based, and also access the lecture materials. In the scope of this study, the features of the 3D metaverse learning environment are explained in detail in the following subsections.

3.4.2.1 Creating a virtual avatar and customization

Participants were able to create their own 3D avatars and personalize them with different clothes, hairstyles, and accessories (see Figure 8). In this way, participants were expected to create their digital copy and express themselves more comfortably in the virtual environment.

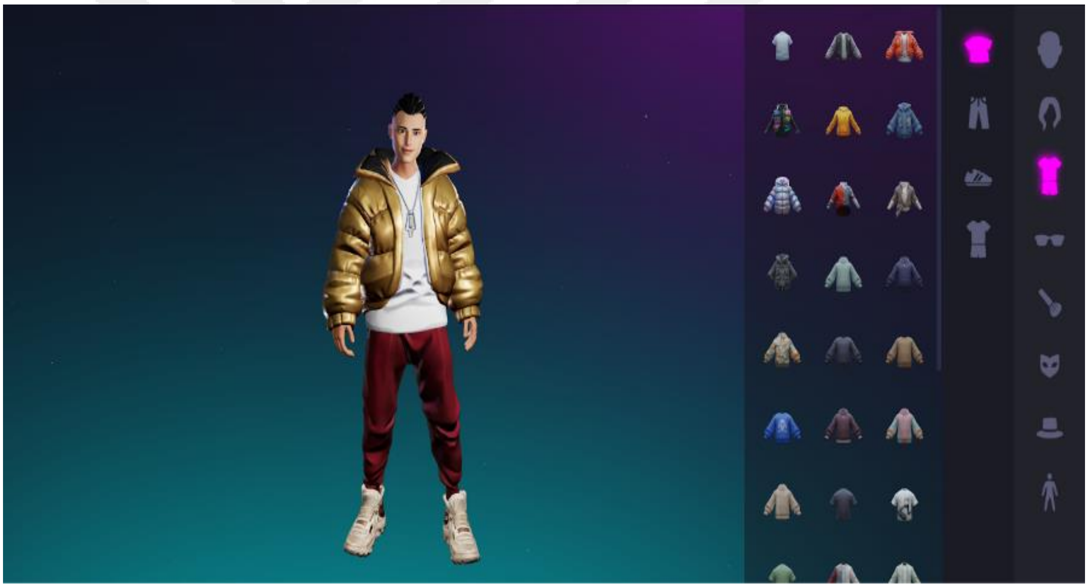

Figure 8. Avatar customization interface in the 3D metaverse environment

3.4.2.2 3D virtual classroom environment

The 3D metaverse environment consisted of immersive campus spaces and classrooms that mimic real-world classrooms. Students and instructors were able to come together in this immersive classroom environment to carry out individual or group work (see Figure 9). Therefore, MetaClass enabled users to move around in the classroom environment and participate in lectures and classroom discussions through their 3D avatars.

Figure 9. Screenshots from the lecture in 3D metaverse environment

3.4.2.3 Voice and text-based communication

Participants were able to communicate with text-based messaging or through the voice chat (see Figure 10). Thanks to the proximity-based voice feature, participants were able to hear conversations more clearly when they got closer.

Figure 10. A screenshot from the voice and text-based communication

3.4.2.4 Screen sharing

Both instructors and students were able to share their computer screens over large virtual screens during a lecture to make presentations or share materials (see Figure 11). This feature made presentations and access to lecture materials more effective.

Figure 11. A screenshot from the screen-sharing function in the 3D metaverse environment
Note. Adapted from Learning Matters. (2018, June 10). *[Series: Influential Educators] Richard Mayer's cognitive theory of multimedia learning*. Medium. https://medium.com/learning-matters/series-influential-educators-richard-mayers-cognitive-theory-of-multimedia-learning-9c1db2f0805c

3.4.2.5 Group work and whiteboard

Students were able to come together in specific group workspaces to make conversation that could not be heard outside the group and share ideas about the group work (see Figure 12). In addition, students were able to take notes, create concept maps, and work collaboratively through the whiteboard feature.

Figure 12. A screenshot from the group works in the 3D metaverse environment

3.4.2.6 Use of simulation

Students were able to explore the structure and functions of different brain regions by examining a full 3D brain model integrated into the 3D metaverse learning environment (see Figure 13). The simulation allowed students to gain a detailed understanding of brain structure, learn the functions of each region, and comprehend them better with real-like 3D visual supports.

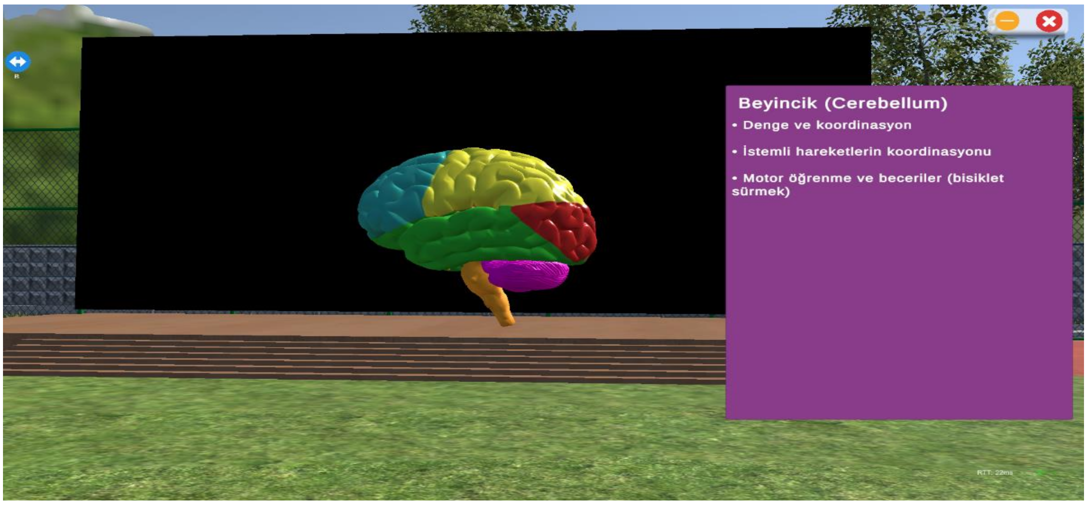

Figure 13. A screenshot from the brain simulation used in the 3D metaverse environment

3.5 Data collection instruments

In this study, both quantitative and qualitative data collection instruments were used. Quantitative data were gathered from the scales used to measure participants' cognitive load and flow experiences during the lectures in metaverse learning environments. Besides, qualitative data were obtained through the reflection form and semi-structured interviews to understand the participants' experiences in more detail.

All data collection instruments were selected or designed to assess and understand the participants' experiences in a comprehensive way. In addition, the scales and other data collection instruments used in the study were examined by two expert instructors in the field of educational technology, evaluated, and confirmed for content validity before they were applied in the study. All scales and forms were administered online via Google Form, and all data were collected digitally. In the following subsections, data collection instruments used in the study were described in detail. In Table 4, research questions and data collection instruments to answer them were summarized.

Table 4. Data Matrix of the Study

Research Question	Data Collection Instruments: Cognitive Load Scale	Flow Experience Scale	Reflection Form	Semi-structured Interviews	Data Analysis
i.i Is there a statistically significant difference in the intrinsic cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?	X				Descriptive and Inferential Statistics
i.ii Is there a statistically significant difference in the extraneous cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?	X				Descriptive and Inferential Statistics
i.iii Is there a statistically significant difference in the germane cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?	X				Descriptive and Inferential Statistics
i.iv How do students describe the factors influencing their cognitive load in 2D and 3D metaverse learning environments?			Q1, Q2	X	Inductive Thematic Analysis
ii.i Is there a statistically significant difference in the flow experience scores of higher education students using the 2D and 3D metaverse learning environments?		X			Descriptive and Inferential Statistics
ii.ii How do students describe the factors that enhance or hinder their flow experiences in 2D and 3D metaverse learning environments?			Q3, Q4	X	Inductive Thematic Analysis

3.5.1 Cognitive load scale

In this study, to measure the participants' cognitive load during VR instruction, the cognitive load scale was employed. In order to determine the cognitive load levels experienced by the participants during the lectures in the metaverse learning environment, this scale, whose validity and reliability have been proven, was applied at the end of the metaverse-based lectures. This scale was used in this study because it is aligned with the previous studies that examined the students' cognitive load in VR-based learning environments and has proven usability in the context of VR/metaverse-based education. The cognitive load scale used in the study was originally developed by Andersen and Makransky (2021) and modified by Li et al. (2023). The version of this scale created by Li et al. (2023) was used in the study. In addition, the scale was examined by two expert instructors in the field of educational technology, evaluated, and confirmed for content validity before they were applied in the study. The cognitive load scale was developed to measure the three main components of cognitive load during the VR instructions, which can be listed as (i) intrinsic cognitive load, (ii) extraneous cognitive load, and (iii) germane cognitive load.

The scale contains 13 items, and it is based on a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Items one through three are related to intrinsic cognitive load (e.g., the topic covered in the VR instruction was very complex), items four through 10 are related to extraneous cognitive load (e.g., the virtual environment was very effective in terms of learning), and items 11 through 13 are related to germane cognitive load (e.g., the simulation truly enhanced my understanding of the topics covered). Higher scores obtained from the scale indicate more cognitive load experienced by the participants during the VR instruction.

The scale includes some reverse-coded items. Since these items express the opposite of the cognitive load components, they were recoded in the scoring process in order to be interpreted correctly. Therefore, the scores of some items were reversed in the analysis process, which was explained in the data analysis section in detail. In addition, item 12 was adapted to the context of the study.

The reliability and the validity of the scale were confirmed in the study by Li et al. (2023). The overall Cronbach's alpha coefficient for the scale was reported as 0.819 (Li et al., 2023). This value shows that the internal consistency of the scale is high and that it can reliably measure cognitive load. In addition, in the scope of this study, reliability analysis was conducted with the data collected from 81 participants. Overall, Cronbach's alpha value was calculated as 0.85. This value also indicates that the scale has a high internal consistency and shows a reliability parallel to previous studies.

3.5.2 Flow experience scale

In order to measure participants' flow experiences during the learning process in the metaverse learning environments, the flow experience scale was used. This scale was originally developed by Pearce et al. (2005) to assess the students' flow experiences in online learning environments. In addition, the scale was examined by two expert instructors in the field of educational technology, evaluated, and confirmed for content validity before they were applied in the study. In this study, the modified version of this scale by Sung et al. (2015) was employed.

This scale assesses factors such as control, enjoyment, focus, and immersion during learning activities. This scale was used to measure participants' flow experiences during their learning process in 2D and 3D metaverse learning environments. It was used in this study because it is in line with previous studies examining the experience of flow in learning environments.

The scale consists of eight items and uses a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Sung et al. (2015) adapted the scale developed by Pearce et al. (2005) to eight items by removing the reverse-coded items from a total of 11 items. Examples of statements included in the scale are "I felt in control of what I was doing during the learning activity" (control) and "I was completely immersed in this learning activity" (enjoyment). The minimum score that can be obtained from the scale is eight, and the maximum score is 40, and higher scores indicate that participants experienced more flow experiences during the VR instruction.

The validity and reliability of both the Pearce et al. (2005) and Sung et al. (2015) versions of this scale were confirmed in previous studies. The overall Cronbach's alpha coefficient of the scale used in this study was reported as 0.82 (Sung et al., 2015). This value indicates that the internal consistency of the scale is high, and it is a reliable instrument for assessing the flow experience state. Also, Sung et al. (2015) stated that the scale was checked and controlled by the experienced researcher for the content validity. In addition, in the scope of this study, reliability analysis was conducted with the data collected from 81 participants. Cronbach's alpha value was calculated as 0.814. This value also indicates that the scale has a high internal consistency and shows a reliability parallel to previous studies.

3.5.3 Demographic information form

In this study, in order to determine whether the participants in the 2D and 3D metaverse groups have similar characteristics in terms of some variables that may affect the result of the study, a demographic information form developed by the researcher and examined by two experts in the field of educational technology was used. This form was used to collect information about participants' age, gender, academic level, previous metaverse experiences, and digital game-playing habits. Within the scope of the study, the demographic information form completed by the participants was used to ensure the comparability of the two groups without any confounding variables and to interpret the effect of independent variables more reliably. Since demographic information is important in terms of its possible effects on participants' cognitive load and flow experiences, demographic characteristics of the participants were examined to assess group similarity. No substantial differences were observed between the 2D and 3D metaverse groups. Therefore, this situation was considered a factor that increased the internal validity of the study.

3.5.4 Reflection form

In the study, a reflection form was used to better understand the reasons/factors for the differences that may occur between the 2D and 3D metaverse groups in terms of participants' cognitive load and flow experiences. The reflection form included four open-ended questions. To ensure content validity and the relevance of the questions, the items in the reflection form were developed by the researcher and reviewed by two experts to get their opinions. The reflection form helped to analyze in more detail the experiences of the students who participated in the learning process in 2D and 3D metaverse environments. The aim of the reflection form was to identify the factors that affect the cognitive load and flow experience levels of the participants and to understand how design or interaction elements contribute to or negatively affect the students' cognitive load and flow experiences. The reflection form includes open-ended questions such as "Which specific aspects of the 2D/3D metaverse environment or the sessions made you feel overwhelmed or made the information difficult to process?" and "Which specific aspects of the 2D/3D metaverse environment or the sessions contributed to feeling completely absorbed or deeply engaged in the environment or the learning activity?" The data gathered from the reflection form were used in the qualitative analysis phase of the study to prove more detailed understanding about the participants' cognitive load and flow experiences.

3.5.5 Semi-structured interviews

As a part of the process of qualitative data collection, semi-structured interviews were conducted with volunteer participants. The purpose of these interviews was to explore the factors influencing cognitive load and the factors that enhance or hinder flow experiences in 2D and 3D DVR-based metaverse learning environments, as described by the participants. Semi-structured interviews allowed the participants to share their experiences and the researcher to obtain more detailed information in alignment with the identified themes. The interviews were conducted with 10 volunteer participants. Interviews were conducted online through a video conference tool (e.g., Zoom). The participants were asked eight main questions about their cognitive load and flow experiences in the metaverse learning environments. These questions were developed to understand the difficulties students encountered during the course that may impact cognitive load and the factors that positively or negatively affected their flow experiences.

The data obtained from the semi-structured interviews were coded using thematic analysis to determine the factors that may impact participants' cognitive load and flow experiences in the metaverse learning environments.

3.6 Data collection procedure

Before starting the data collection procedure, the study was evaluated and confirmed by the Institutional Review Board in Social Sciences and Humanities of Boğaziçi University (SBINAREK), and the ethical approval (see Appendix J) that is necessary for conducting the study was obtained. Also, in the process of participation in the study, informed consent forms that included the aim of the study, the procedure of the study, and other important information related to the study were presented to the students, and the data collection process was started after their consent was obtained. The data collection procedure of the study mainly consists of four phases that took four weeks, which can be explained as follows:

3.6.1 Phase 1: Pilot study

Before starting the data collection process of the main study, during 90 minutes, a pilot study was conducted to evaluate the comprehensibility and clarity of the data collection instruments and also the technical functioning of the 2D and 3D metaverse learning environment used in the study. Different from the main participants, five higher education students participated in the pilot study. In this process, they filled out the scales and shared their opinions about whether the items and questions in the cognitive load scale, flow experience scale, reflection forms, and semi-structured interviews were clear and understandable. As a result of the interpretation of the data collection instruments by the pilot study participants, some statements were made clearer. For example, in the reflection form, the original open-ended questions were changed in a way that they more directly reveal responses related to cognitive load and flow experiences. Words such as “feel overwhelmed” and “difficult to process” were used to target cognitive load, and phrases such as “completely absorbed” and “deeply engaged” were used to reveal participants' reflections related to flow experiences. Through these adjustments, it was ensured that participants could better reflect the cognitive and emotional dimensions of their experiences in the 2D and 3D metaverse environments. Besides the data collection instruments, 2D and 3D metaverse learning environments were also tested. From a technical point of view, different scenarios such as communication, interactive materials, and navigation controls were tested in these environments with five participants to confirm that the metaverse learning environments worked without any problems and that the main participants were able to use the features of them effectively. According to the feedback from the pilot study, some adjustments in terms of both technical and content were made in order to conduct the main study without any problems or errors.

Furthermore, as a part of this phase, the lesson plans designed to be used in the lectures in 2D and 3D metaverse learning environments were reviewed and validated by two experts in the fields of educational technology and one expert from science teaching. These experts evaluated the lesson plan in terms of instructional design, suitability for metaverse-based teaching, and clarity and accuracy of the topics in the lesson plan. Based on experts’ feedback, some changes were made to optimize the lesson plan before the main study was conducted.

3.6.2 Phase 2: Preliminary application and metaverse environment training

Before the main application, training sessions on the use of metaverse learning environments during 120 minutes occurred with the main participants to familiarize them with these platforms. The main purpose of these training sessions is to minimize the novelty effect that may be caused by the use of a new digital learning environment. In this phase, both the 2D and 3D metaverse groups were given guidance on how to create avatars on these platforms, move and navigate in the virtual classroom, communicate with other participants in the environments through text-based or voice chat, share their computer screen, interact with objects, and access the lecture materials in the environment. In addition to this, participants were informed about how to connect to the metaverse environments and how to install these platforms on their computers. In this process, participants were allowed to test the features of the metaverse platforms freely, such as moving in the classroom environment, written and voice communication, using the whiteboards, and group work areas. Also, during this phase, technical support was provided to solve technical problems experienced by the participants in the metaverse environments, such as login or installation problems, audio/microphone malfunctions, connectivity issues, or challenges navigating within the virtual classrooms. At the end of this process, it was ensured that all participants were ready for the main application and could use the metaverse learning platforms for the lecture effectively without any problems.

At this phase, the demographic information form was also applied via Google Form. Information about participants' age, gender, academic level, previous metaverse experiences, and digital game-playing habits was collected, evaluated, and analyzed to determine whether the metaverse groups have similar characteristics.

3.6.3 Phase 3: Main application and data collection

The main application of this study included the implementation of a structured 120-minute lecture delivered in two sessions (60 minutes each) across two groups in either a 2D metaverse learning environment (see Figure 14) or a 3D metaverse learning environment (see Figure 15). As the lecture content was delivered in the metaverse environments, brain structure, cognitive load theory, and multimedia learning were chosen because they combine visual-spatial knowledge with abstract theoretical understanding, which allowed for examining the effect of different instructional approaches on students' cognitive load and flow experiences.

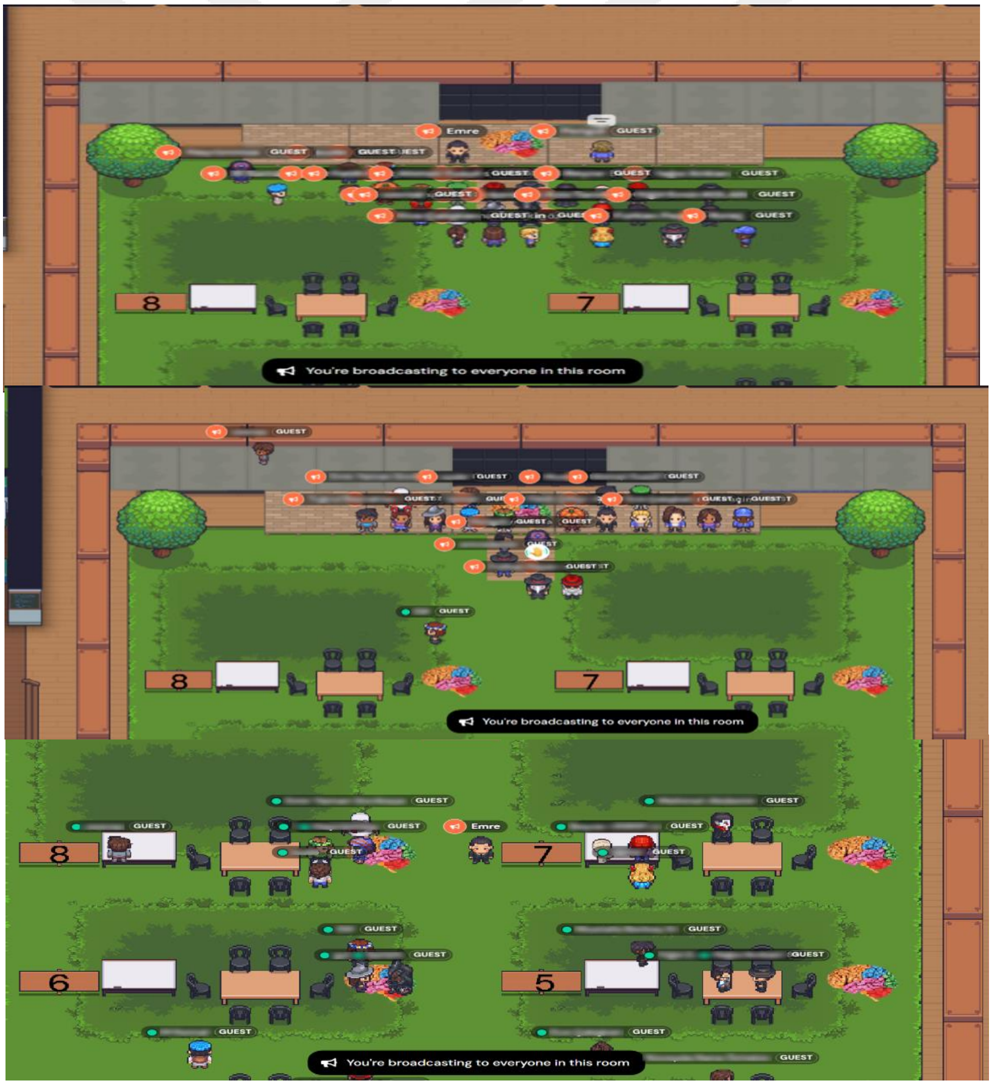

Figure 14. Screenshots from the lectures in 2D metaverse learning environment

Figure 15. Screenshots from the lectures in 3D metaverse learning environment

In the first lecture session (simulation-based lecture), participants were presented with interactive learning materials about brain structure and functions. In the 2D metaverse group, students explored the brain and its regions with explanations through a web-based 2D brain simulation. However, in the 3D metaverse group, participants interacted with and examined the brain and its different regions with their explanations through the 3D brain simulation integrated into the 3D metaverse environment. Also, in both 2D and 3D metaverse groups, through the same group work, each group was assigned to a specific brain region (e.g., frontal lobe, cerebellum), and they discussed its function, the role it plays in cognition or motor control, and potential consequences if it were damaged. Groups then summarized their findings and presented them to the class by using whiteboards and their avatars. Presentations were short (two–three minutes), interactive, and included both visual and verbal components.

In the second lecture session (verbal/theoretical), cognitive load theory and cognitive theory of multimedia learning were discussed. In both the 2D and 3D metaverse groups, the instructor explained the theoretical information using schematic diagrams and visuals. After the instructor’s lecture, participants worked in small groups to discuss how an ideal multimedia environment should be structured to optimize intrinsic, extraneous, and germane cognitive load. Students gave short group-based presentations discussing how design features (e.g., modality, signaling) could be used in real educational settings.

In this study, a mainly lecture-based instructional strategy was deliberately selected for both the 2D and 3D metaverse learning environments to compare the metaverse learning platforms that have different dimensions in terms of their effect on cognitive load and flow experiences. Lecturing is one of the most common ways in traditional higher education, and its integration into metaverse learning platforms is highly relevant and important, particularly in crisis situations such as pandemics or natural disasters, where institutions or instructors may need to replicate face-to-face instruction online. By applying the lecturing in metaverse settings, this study aimed to explore whether conventional teaching practices can be effectively transferred to immersive virtual environments and how such replication influences learners' cognitive load and flow experience. Furthermore, metaverse-based learning environments can enhance traditional lectures through immersive visual elements, avatar-based presence, and simulation, which have a strong effect on cognitive load and flow experiences. On the other hand, although different instructional strategies, such as flipped classrooms, may be well-suited for virtual environments, applying them in the context of this study would introduce instructional variability and make it harder to determine whether observed cognitive and affective differences were due to instructional design or the metaverse itself as the medium. Therefore, in the context of this study, lecturing was used in the metaverse-based lectures.

After the completion of the lectures, the cognitive load scale, flow experience scale, and reflection form were filled out by all participants to evaluate their learning experiences in the metaverse learning environment in terms of cognitive load and flow experiences. All data were collected online via Google Form. A summary of the actual lesson plan implementation for both metaverse groups is provided in Table 5.

Table 5. Structure and Activities of the 120-Minute Lesson in 2D and 3D Metaverse Environments

Time	Activity	Description
0-10 min	Introduction	The instructor gave an overview of the session and asked engaging questions about the brain's function.
10-35 min	Lecture 1: Brain structure	The instructor used 2D or 3D brain simulation to explain the structure and function of brain regions (e.g., the frontal lobe).
35-55 min	Group work 1: Brain simulation task	Each group was assigned to one brain region to explore. They discussed its function and what would happen if it was damaged in detail.
		Each group then presented their findings in two minutes briefly to the class via avatar speech or shared screen/whiteboard.
55-60 min	Question-and-answer session	The instructor answered questions to clarify students' understanding of brain structure and function.
60-85 min	Lecture 2: Cognitive load theory and cognitive theory of multimedia learning	Verbal lecture introducing intrinsic, extraneous, and germane load and cognitive theory of multimedia learning, with schematic diagrams.
85-105 min	Group Work 2: Multimedia design task	Groups discussed how to design a multimedia environment that reduces extraneous load and supports germane load.
		In five minutes, groups shared examples briefly with the class via avatar speech or shared screen/whiteboard, such as segmenting content, adding visuals, and using signaling.
105-110 min	Question-and-answer session	Follow-up questions were asked about cognitive load and multimedia principles.
110-120 min	Reflection and data collection	Students completed a cognitive load scale, a flow experience scale, and a reflection form via Google Forms.

3.6.4 Phase 4: Conducting semi-structured interviews

After the quantitative data collection process, semi-structured interviews were conducted with 10 volunteer participants to further explain the findings gathered from the quantitative data in detail. These interviews were conducted to collect more detailed data on the cognitive load and flow experiences of the students in the 2D and 3D metaverse groups. Six participants for the 2D metaverse group and four participants for the 3D metaverse group were included in the interviews, and one-to-one interviews were conducted via the Zoom platform. The participants for the semi-structured interviews were selected from among those who voluntarily agreed to participate after completing the quantitative phase of the study. Each interview lasted approximately 20–25 minutes and focused on participants' personal perceptions and experiences related to cognitive load and flow experiences during the metaverse-based lectures in the 2D and 3D metaverse environments. Participants were encouraged to reflect on which aspects of the 2D or 3D metaverse environment affected their cognitive load either positively or negatively. Also, they were encouraged to describe the specific elements that supported or hindered their ability to reach the flow experience state during the learning activities. All interviews were recorded as audio, transcribed, and coded in the context of thematic analysis, and themes were determined through inter-reliability. This process allowed the quantitative data to be interpreted in a more meaningful way and provided a stronger context for the overall results of the study. Also, the cognitive load and flow scores of the interview participants were examined. The data showed that the selected interviewees represented a diverse range of cognitive load and flow levels, and it included both higher and lower scorers of intrinsic, extraneous, and germane cognitive load scores and flow experience scores. This variation ensured a richer and more representative qualitative dataset and helped in capturing different perspectives and experiences within each metaverse learning condition. In Table 6, the distribution of the cognitive load and flow scores of the interview participants was presented. Also, the whole data collection procedure can be summarized in Figure 16.

Table 6. Cognitive Load and Flow Experience Scores of Interview Participants

Participant ID	Intrinsic Cognitive Load Scores (Over 15 points)	Extraneous Cognitive Load Scores (Over 35 points)	Germane Cognitive Load Scores (Over 15 points)	Flow Experience Scores (Over 40 points)
2D_Interview_#1	5	16	10	24
2D_Interview_#2	3	7	15	35
2D_Interview_#3	8	11	12	31
2D_Interview_#4	7	9	12	36
2D_Interview_#5	6	18	9	25
2D_Interview_#6	9	27	9	17
3D_Interview_#1	5	13	12	28
3D_Interview_#2	6	13	9	28
3D_Interview_#3	6	24	8	14
3D_Interview_#4	9	15	10	29

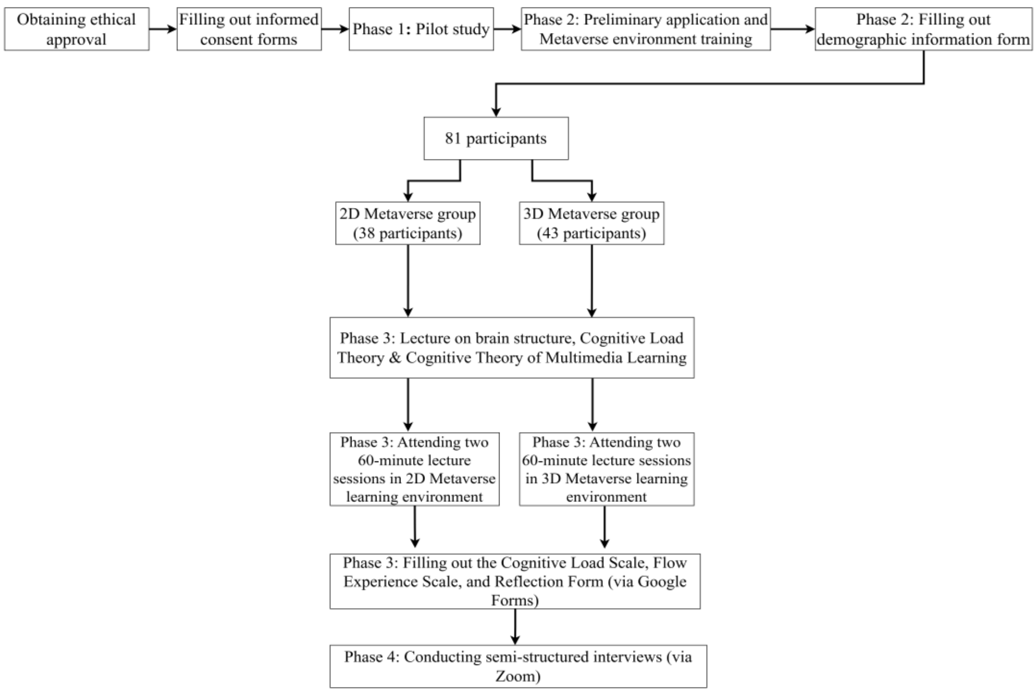

Figure 16. Summary of the data collection procedure

3.7 Data analysis

The collected data in the scope of this study was analyzed by using the IBM SPSS Statistics version 29.0.2.0 (IBM Corp., 2023) for quantitative analysis and MAXQDA 24 (VERBI Software, 2021) for qualitative analysis. For all data, pseudonyms (e.g., 2D_#1, 2D_#2, 3D_#1) were assigned to each participant to ensure the anonymity of the participants. The analysis process for each research question were explained in the following subsections.

3.7.1 Research question i (How do 2D and 3D DVR-based metaverse learning environments affect higher education students' cognitive load?)

3.7.1.1 Research question i.i (Is there a statistically significant difference in the intrinsic cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

For this research question, participants' intrinsic cognitive load scores gathered from the cognitive load scale scores were tabulated and calculated by summing the responses from items one, two, and three in the form of a five-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree nor Disagree, 4 = Agree, 5 = Strongly Agree). All items in the scale related to this research question were negatively stated, which means that higher scores indicate higher intrinsic cognitive load. Therefore, reverse coding was not performed for this research question. In order to test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. As a result of this process, it was concluded that since the distributions were not normal, the normality assumption was not met. Therefore, the Mann-

Whitney U test was conducted to determine whether there were differences in intrinsic cognitive load scores between 2D and 3D metaverse groups, and the effect size was calculated with the $r = Z / \sqrt{N}$ formula (Rosenthal, 1994).

3.7.1.2 Research question i.ii (Is there a statistically significant difference in the extraneous cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

Before conducting the statistical analysis for this research question, items five and eight, which were positively stated (indicating lower extraneous cognitive load), had to be reversed first to align with the other items in the cognitive load scale that measure the extraneous cognitive load. This process has ensured that higher scores indicate higher extraneous cognitive load across all items in this research question. After that, participants' extraneous cognitive load scores were tabulated and calculated by summing the responses from items four, five, six, seven, eight, nine, and 10 in the form of a five-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree nor Disagree, 4 = Agree, 5 = Strongly Agree). To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. After this process, it was concluded that the distributions were not normal; the normality assumption was not met. For that reason, the Mann-Whitney U test was run to determine whether there were differences in extraneous cognitive load scores between 2D and 3D metaverse groups.

3.7.1.3 Research question i.iii (Is there a statistically significant difference in the germane cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

For this research question, participants' germane cognitive load scores were tabulated and calculated by summing the responses from items 11, 12, and 13 in the form of a five-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree nor Disagree, 4 = Agree, 5 = Strongly Agree). All items in this research question were positively stated, which means that higher scores reflect higher germane cognitive load. Therefore, reverse coding was not performed for this research question. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. After this process, it was concluded that the distributions were not normal; the normality assumption was not met. For that reason, the Mann-Whitney U test was run to determine whether there were differences in germane cognitive load scores between 2D and 3D metaverse groups.

3.7.1.4 Research question i.iv (How do students describe the factors influencing their cognitive load in 2D and 3D metaverse learning environments?

To analyze this research questions, qualitative data collected from participants' responses to the reflection form and semi-structured interviews were analyzed through thematic analysis (see Table 7), as proposed by Braun and Clarke (2006). In the analysis phase, an inductive coding approach was employed (Thomas, 2006). In this approach, themes were identified based on the participants' responses to the reflection form and semi-structured interviews rather than the predetermined categories.

Table 7. Braun and Clarke's (2006) Six Steps of Thematic Analysis

Step	Process
1) Familiarization with the data	All responses were read and re-read to obtain an in-depth understanding.
2) Generating initial codes	Meaningful segments of the data were coded line by line.
3) Searching for themes	Codes were grouped into potential sub-themes and main themes.
4) Reviewing themes	The coherence of the themes was checked against the coded extracts and the entire dataset.
5) Defining and naming themes	Themes were clearly defined and named to reflect their core meaning.
6) Producing the report	The final analysis was written by using participant quotes that represent each theme.

At the beginning of the thematic analysis process, all responses were transcribed, cleaned, and anonymized. After that, a coding process was performed to reveal meaningful codes related to the factors that affect the participants' cognitive load in 2D and 3D metaverse learning environments. Then, the codes extracted from the responses were categorized into sub-themes. Based on the sub-themes, main themes were derived to comprehensively answer the research question i.iv. As a result, the final themes were used to provide a detailed interpretation of the main factors that increased cognitive overload or optimized cognitive load in 2D and 3D metaverse learning environments. An example codebook table for the cognitive load themes is presented in Table 8.

Table 8. An Example Codebook Table for Cognitive Load Themes

Main Theme	Description	Sample Codes	Example Quote
Verbal-based instruction increasing intrinsic cognitive load	Verbal/theoretical lectures increases mental effort.	Passive listening, Lack of visual support, Only listening to the teacher	" . . . it was very difficult to focus on the lesson especially when the instructor was lecturing and we didn't interactively participate in the lesson." (3D_#11)
Limited real interaction hindering germane processing	Absence of physical or face-to-face interaction hinders cognitive engagement.	Lack of eye contact, Not seeing gestures, No face-to-face group work	"Not being face to face becomes overwhelming after a while." (3D_#29)
Technical problems impairing germane cognitive processing	Technical and interface-related problems disrupt germane processing.	Audio cuts, Connectivity issues, Lags	"I experienced 6-7 audio disruptions lasting 3-4 seconds. These interruptions caused loss of focus and restricted my ability to follow and understand the topic." (3D_#15)
Enhancing germane cognitive processing through visualization and simulation	Visual materials and simulations help in understanding the lecture content by increasing germane processing.	Brain model, Clickable visuals, Interactive objects	"Examining the brain lobes one by one through visual elements and then discussing them with my friends was quite memorable." (2D_#2)
Digital learning tools and collaborative learning as mediators of germane cognitive processing	Tools such as whiteboards and shared spaces enhance group learning through the schema construction.	Whiteboards, Shared digital space, Breakout rooms	"Being able to have group chats, access a notebook, and use interactive whiteboards in group work made the learning process more efficient." (3D_#12)
Interactivity fostering germane cognitive processing	Learners benefit cognitively from actively engaging with content and environment.	Interactive material, Real-time engagement, Avatar-based interaction	"Being able to move around and explore different parts of the brain through 3D simulation helped me process the details better." (3D_#41)

3.7.2 Research question ii (How do 2D and 3D DVR-based metaverse learning environments affect higher education students' flow experiences?)

3.7.2.1 Research question ii.i (Is there a statistically significant difference in the flow experience scores of higher education students using the 2D and 3D metaverse learning environments?)

For this research question, participants' flow experience scores were tabulated and calculated by summing the responses from all eight items in the form of a five-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree nor Disagree, 4 = Agree, 5 = Strongly Agree). All items in this research question were positively stated, which means that higher scores reflect higher flow experience scores. Therefore, reverse coding was not performed for this research question. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. After this process, it was concluded that the distributions were not normal; the normality assumption was not met. For that reason, the Mann-Whitney U test was run to determine whether there were differences in flow experience scores between 2D and 3D metaverse groups.

3.7.2.2 Research question ii.ii (How do students describe the factors that enhance or hinder their flow experiences in 2D and 3D metaverse learning environments?)

To analyze this research question, qualitative data collected from participants' responses to the reflection form and semi-structured interviews were analyzed through thematic analysis, as proposed by Braun and Clarke (2006). In the analysis phase, an inductive coding approach was employed (Thomas, 2006). In this approach, themes were identified based on the participants' responses to the reflection form and semi-structured interviews rather than the predetermined categories. At the beginning of the thematic analysis process, all responses were transcribed, cleaned, and anonymized. After that, a coding process was performed to reveal meaningful codes related to the factors that affect the participants' flow experiences in 2D and 3D metaverse learning environments. Then, the codes extracted from the responses were categorized into sub-themes. Based on the sub-themes, main themes were derived to comprehensively answer the research question ii.ii. As a result, the final themes were used to provide a detailed interpretation of the main factors that enhanced or hindered participants' flow experiences in 2D and 3D metaverse learning environments. An example codebook table for the flow experience themes is presented in Table 9.

Table 9. An Example Codebook Table for Flow Experience Themes

Main Theme	Description	Sample Codes	Example Quote
Collaborative learning and interaction as a facilitator of flow experience	Working with peers and engaging in collaborative group activities enhances flow experiences.	Group work, Peer interaction, Shared whiteboards	"Splitting into groups, discussing the topics there and making presentations in front of everyone made me feel like I was immersed in the learning activity." (2D_#4)
Interactive environment facilitating flow experience	Interactive features and student control over content increase flow experiences.	Exploring with avatars, Interacting with content, Real-time engagement	"The interactive nature of the environment made me feel fully involved." (2D_#14)
Immersive visual elements supporting flow experience	3D simulations and visually rich content improve flow experiences.	3D brain model, Visual detail, Immersive environment	"The immersive visuals and interactive simulations in the 3D metaverse environment made me feel deeply engaged and completely absorbed in the learning activity." (3D_#17)
Digital distractions and reduced control as barriers to flow	Online distractions and lack of monitoring hinder flow experiences.	Phone use, Browsing unrelated sites, Informal settings	"It's easier to access distracting content (like social media or games) compared to a physical classroom." (2D_#29)
Passive instructional delivery hindering flow experiences	Verbal-only and non-interactive instruction hinders flow experiences.	Verbal lecture format, No visuals, Passive listening	"During the second part of the class, when we were just listening passively, I felt like I was attending like a Zoom session and lost some interest." (2D_Interview_#1)
Visual complexity as an obstacle for flow experiences	Overcrowded visual design and excessive elements can overwhelm learners and disrupt their flow experiences.	Too many visual objects, lots of avatars in the environment, Complexity of the environment	"Since there were many objects of interest in the virtual environment, I was occasionally distracted while exploring the environment." (2D_#17)

3.8 Trustworthiness

In line with Lincoln and Guba's (1985) framework, trustworthiness in the qualitative part of this study was addressed through the four main criteria, which are (i) credibility, (ii) transferability, (iii) dependability, and (iv) confirmability. Credibility, which refers to the confidence in the truth of the findings, was supported through methodological triangulation by using the qualitative data analysis to elaborate on and explain the quantitative findings (Lincoln & Guba, 1985). In addition, to enhance credibility and reduce potential researcher bias, a peer debriefing process in which an independent researcher reviewed and cross-checked the codes was conducted. As a peer, a graduate student in the educational technology master's program currently works as a research assistant at the Robotics and Artificial Intelligence Education laboratory involved in the coding process. AI literacy and the integration of AI and AI-based learning environments into education are the focus of their academic works. Because of their experience regarding the educational technology, they were able to offer insightful, constructive, and technically based comments on the coding process and creating new themes in the qualitative analysis phase. Through the intercoder agreement with the peer before finalizing the main themes, it was ensured that the main themes accurately reflected participants' cognitive load and flow experiences in 2D and 3D metaverse learning environments. Transferability, which refers to the extent to which the findings can be applied to other contexts, was supported through the detailed and thick descriptions of participants, metaverse learning environments, and procedures of this study (Lincoln & Guba, 1985). The transferability allows readers to determine the relevance of this study to their own settings. Dependability, which refers to the consistency and reliability of the research process over time, was established through clear and detailed documentation. This included the procedures followed throughout the study, such as data collection instruments, coding steps, and the development of main themes (Lincoln & Guba, 1985). Finally, confirmability, which refers to the degree to which the findings are shaped by the participants rather than researcher bias, was supported through an audit trail, which involved maintaining clear records of each step taken throughout the research process from data collection to theme development to ensure transparency (Lincoln & Guba, 1985). In addition, methodological triangulation contributed to the objectivity of the analysis. These strategies together improved the overall trustworthiness of the qualitative part of this study.

3.9 Researcher's positionality

The researcher holds a Bachelor of Science degree in CET. He continued his master's education in educational technology. By also working as a research assistant in the department of CET, the researcher has contributed to various undergraduate courses, particularly those focusing on instructional design and the development of multimedia applications. The researcher also has been actively involved in research projects and took part in many scientific studies and the development of innovative technologies related to the immersive 3D metaverse environments. The researcher has a solid foundation in the design and assessment of metaverse-based learning environments thanks to these experiences.

In this study, the researcher had several intersecting roles, which were instructional designer, platform developer (particularly for the 3D metaverse environment called MetaClass), course instructor, and principal investigator. These roles made the researcher not only an observer but also an active participant in the instructional and technological implementation of the study. Especially, MetaClass

(3D metaverse learning environment) was fully designed and developed by the researcher, which included its instructional content, user interface, visual simulations, and interactive tools. This level of involvement allowed for a coherent alignment between the instructional goals and technological capabilities of the environment.

From a pedagogical perspective, the researcher was also responsible for designing and delivering the lectures in both 2D and 3D metaverse learning environments, ensuring consistency and equality of the lecture content, instructional strategy, timing, and interaction. Being the instructor of both groups helped control for instructor-related differences and increase the internal validity of the findings. Also, the researcher was actively involved as a teaching assistant in the courses from which the participants came. This role contributed to a better understanding of the learner profiles, technological readiness of them, and learning needs of the participants.

However, the researcher's positionality also introduced possible limitations. For instance, since the researcher was also a teaching assistant in the courses from which the participants selected, participants may have perceived the researcher as a figure of authority. Therefore, this situation may have influenced their engagement, responses to self-report instruments, or participation in qualitative interviews.

In order to minimize these risks, several strategies were used. Firstly, an expert-reviewed and approved lesson plan was followed strictly in both environments to ensure equivalence of the instruction during the metaverse-based lectures. In addition, the content validity of all instruments was established through expert reviews. Furthermore, during the qualitative analysis stage, intercoder agreement procedures with a peer explained in the trustworthiness section were followed to reduce interpretation bias. Lastly, participants were informed that their academic grades would not be affected by their participation or responses, and they were encouraged to provide honest feedback and responses.

All in all, while the researcher's multiple roles in this study enriched the authenticity, feasibility, and technical integrity of the study, it also required a reflective awareness of potential bias related to the study. By explicitly explaining this researcher's positionality, the study aims to provide transparency and enhance its methodological trustworthiness.

CHAPTER 4

RESULTS

This chapter contains the answers of each research question in the study.

4.1 Research question i.i (Is there a statistically significant difference in the intrinsic cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

To answer research question i.i, descriptive statistics for participants' intrinsic cognitive load scores in 2D and 3D metaverse learning environments were calculated and presented in Table 10. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. According to the results, intrinsic cognitive load scores were not normally distributed for 2D and 3D metaverse groups, as assessed by Shapiro-Wilk's test ($p < .05$) (see Table 11). Therefore, the results indicated that the normality assumption was not met, and it was concluded that the Mann-Whitney U test was run to analyze this research question.

Table 10. Descriptive Statistics of Intrinsic Cognitive Load Scores of Groups

	N	*M*	*SD*	*Mdn*	Min	Max	Skewness	Skewness z-value	Kurtosis	Kurtosis z-value
2D Metaverse Group	38	4.84	1.516	5	3	9	.527	1.376	.097	.129
3D Metaverse Group	43	6.05	1.927	6	3	12	.371	1.028	1.035	1.460

Table 11. Shapiro-Wilk Result of Intrinsic Cognitive Load Scores of Groups

	W	*df*	*p*
2D Metaverse Group	.894	38	.002
3D Metaverse Group	.903	43	.002

A Mann-Whitney U test was run to determine if there were differences in intrinsic cognitive load scores between 2D and 3D metaverse groups. Distributions of the intrinsic cognitive load scores for 2D and 3D metaverse groups were not similar, as assessed by visual inspection. Intrinsic cognitive load scores for 3D metaverse groups (mean rank = 48.37) were statistically significantly higher than for 2D metaverse groups (mean rank = 32.66), $U = 1134$, $z = 3.094$, $p = .002$. According to Rosenthal (1994), the effect size was calculated using the $r = Z / \sqrt{N}$ formula, which results in $r \approx 0.34$. Therefore, this result suggests a medium effect size according to Cohen (1992). As a result, these findings suggest that participants in the 3D metaverse environment experienced a significantly higher intrinsic cognitive load compared to participants in the 2D environment. Descriptive statistics related to intrinsic cognitive load items in the scale are presented in Table 12 to provide a more detailed view of participants' perceptions across individual items.

Table 12. Descriptive Statistics Related to Intrinsic Cognitive Load Items

Item No	Statement	2D Group *M*	2D Group *SD*	3D Group *M*	3D Group *SD*
1	The topic covered in the VR instruction was very complex.	1.58	.642	2.02	.740
2	The VR instruction covered procedures that I perceived as very complex.	1.63	.589	1.95	.722
3	This VR instruction covered concepts and definitions that I perceived as very complex.	1.63	.541	2.07	.737

4.2 Research question i.ii (Is there a statistically significant difference in the extraneous cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

To answer research question i.ii, descriptive statistics for participants' extraneous cognitive load scores in 2D and 3D metaverse learning environments were calculated and presented in Table 13. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. According to the results, extraneous cognitive load scores were normally distributed for the 3D metaverse group but not the 2D metaverse group, as assessed by Shapiro-Wilk's test ($p < .05$) (see Table 14). Therefore, the results indicated that the normality assumption was not met, and it was concluded that the Mann-Whitney U test was run to analyze this research question.

Table 13. Descriptive Statistics of Extraneous Cognitive Load Scores of Groups

	N	*M*	*SD*	*Mdn*	Min	Max	Skewness	Skewness z-value	Kurtosis	Kurtosis z-value
2D Metaverse Group	38	13.34	4.180	13	7	27	1.058	2.762	2.164	2.885
3D Metaverse Group	43	13.12	3.666	13	7	24	.657	1.820	.593	.836

Table 14. Shapiro-Wilk Result of Extraneous Cognitive Load Scores of Groups

	W	*df*	*p*
2D Metaverse Group	.928	38	.017
3D Metaverse Group	.959	43	.126

A Mann-Whitney U test was run to determine if there were differences in extraneous cognitive load scores between 2D and 3D metaverse groups. Distributions of the extraneous cognitive load scores for 2D and 3D metaverse groups were similar, as assessed by visual inspection. The extraneous cognitive load score was not statistically significantly different between the 2D metaverse group (*Mdn* = 13) and the 3D metaverse group (*Mdn* = 13), $U = 796$, $z = -.200$, $p = .842$. As a result, the findings indicate that there was no statistically significant difference in extraneous cognitive load between the 2D and 3D metaverse groups, and both metaverse learning environments led to a similar level of extraneous cognitive load. Descriptive statistics related to extraneous cognitive load items in the scale are presented in Table 15 to provide a more detailed view of participants' perceptions across individual items.

Table 15. Descriptive Statistics Related to Extraneous Cognitive Load Items

Item No	Statement	2D Group *M*	2D Group *SD*	3D Group *M*	3D Group *SD*
4	The instruction and/or explanation used in the VR material were very unclear.	1.79	.905	1.67	.892
5	The instructions and explanations used in the VR material were very effective for learning.	3.82	.834	3.77	.841
6	The instructions and/or explanations used in the VR material were full of unclear content.	1.55	.760	1.67	.715
7	The elements in the virtual environment made learning very unclear.	1.82	1.062	1.63	.618
8	The virtual environment was very effective in terms of learning.	3.45	.921	3.63	.874
9	The virtual environment was full of irrelevant content.	1.74	.891	1.77	.751
10	It was difficult to find the relevant learning information in the virtual environment.	1.71	.694	1.77	.841

4.3 Research question i.iii (Is there a statistically significant difference in the germane cognitive load scores of higher education students using the 2D and 3D metaverse learning environments?)

To answer research question i.iii, descriptive statistics for participants' germane cognitive load scores in 2D and 3D metaverse learning environments were calculated and presented in Table 16. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-Wilk test was conducted. According to the results, germane cognitive load scores were not normally distributed for 2D and 3D metaverse groups, as assessed by Shapiro-Wilk's test ($p < .05$) (see Table 17). Therefore, the results indicated that the normality assumption was not met, and it was concluded that the Mann-Whitney U test was run to analyze this research question.

Table 16. Descriptive Statistics of Germane Cognitive Load Scores of Groups

	N	*M*	*SD*	*Mdn*	Min	Max	Skewness	Skewness z-value	Kurtosis	Kurtosis z-value
2D Metaverse Group	38	11.34	2.363	11	6	15	.085	0.222	-.506	-.675
3D Metaverse Group	43	11.07	2.501	12	4	15	-.801	-2.219	.983	1.386

Table 17. Shapiro-Wilk Result of Germane Cognitive Load Scores of Groups

	W	*df*	*p*
2D Metaverse Group	.927	38	.017
3D Metaverse Group	.927	43	.009

A Mann-Whitney U test was run to determine if there were differences in germane cognitive load scores between 2D and 3D metaverse groups. Distributions of the germane cognitive load scores for 2D and 3D metaverse groups were similar, as assessed by visual inspection. The germane cognitive load score was not statistically significantly different between the 2D metaverse group (*Mdn* = 11) and the 3D metaverse group (*Mdn* = 12), $U = 811$, $z = -.058$, $p = .954$. As a result, the findings indicate that there was no statistically significant difference in germane cognitive load between the 2D and 3D metaverse groups, and both metaverse learning environments led to a similar level of germane cognitive load. Descriptive statistics related to germane cognitive load items in the scale are presented in Table 18 to provide a more detailed view of participants' perceptions across individual items.

Table 18. Descriptive Statistics Related to Germane Cognitive Load Items

Item No	Statement	2D Group *M*	2D Group *SD*	3D Group *M*	3D Group *SD*
11	The simulation truly enhanced my understanding of the topics covered.	3.63	.883	3.60	.903
12	The simulation truly enhanced my understanding of the parts of the brain and their functions.	3.95	.804	3.81	.958
13	The simulation truly enhanced my understanding of concepts and definitions.	3.76	.852	3.65	.973

4.4 Research question i.iv (How do students describe the factors influencing their cognitive load in 2D and 3D metaverse learning environments?)

In this research question, the results of the thematic analysis of the participants' responses to the open-ended questions and semi-structured interviews related to the factors influencing their cognitive load in 2D and 3D metaverse learning environments are presented. For inter-rater reliability, the responses to reflection forms and transcripts of semi-structured interviews were independently coded by two researchers. Themes were identified through a consensus process where similar and different codes were compared and edited. This approach helped in ensuring that the process of categorization was objective. The original Turkish versions of participants' quotations in semi-structured interviews conducted in Turkish were presented in Appendix K.

The participants' responses were coded using Braun and Clarke's (2006) thematic analysis approach, and then sub-themes and main themes were identified. In addition, the frequency of sub-themes that indicate how many participants gave responses about this particular sub-theme was denoted with "f" in the parentheses. Besides that, the main themes that emerged as a result of the analysis of the answers of the participants in the 2D and 3D groups, how many participants in each group gave answers related to these themes, and the percentage within the group are summarized in Table 19, Table 20, and Table 21.

Table 19. Main Themes Leading to Cognitive Overload in 2D and 3D Metaverse Learning Environments

Condition	Main Theme	Frequency (f)	Within-group Percentage (%)
2D Metaverse Group (n = 38)	1) Verbal-based instruction increasing intrinsic cognitive load	5	13.2%
	2) Limited real interaction hindering germane processing	3	7.9%
	3) Technical problems impairing germane cognitive processing	3	7.9%
	4) Visual complexity elevating extraneous cognitive load	3	7.9%
3D Metaverse Group (n = 43)	1) Technical problems impairing germane cognitive processing	14	32.6%
	2) Verbal-based instruction increasing intrinsic cognitive load	4	9.3%
	3) Limited real interaction hindering germane processing	3	7.0%

Table 20. Main Themes Contributing to Cognitive Load Optimization in 2D and 3D Metaverse Learning Environments

Condition	Main Theme	Frequency (f)	Within-group Percentage (%)
2D Metaverse Group (n = 38)	1) Enhancing germane cognitive processing through visualization and simulation	24	63.2%
	2) Digital learning tools and collaborative learning as mediators of germane cognitive processing	8	21.1%
	3) Interactivity fostering germane cognitive processing	5	13.2%
3D Metaverse Group (n = 43)	1) Enhancing germane cognitive processing through visualization and simulation	32	74.4%
	2) Digital learning tools and collaborative learning as mediators of germane cognitive processing	13	30.2%
	3) Interactivity fostering germane cognitive processing	7	16.3%

Table 21. Main Themes Derived from Semi-Structured Interviews Regarding Cognitive Load in 2D and 3D Metaverse Learning Environments

Theme Category	Main Theme	2D Metaverse Group f (%) (n = 6)	3D Metaverse Group f (%) (n = 4)
Cognitive overload	Verbal-based instruction increasing intrinsic cognitive load	2 (33.3%)	4 (100%)
Cognitive load optimization	Optimizing cognitive processing through simplicity of environment	2 (33.3%)	-
	Enhancing germane cognitive processing through visualization and simulation	6 (100%)	4 (100%)
	Digital learning tools and collaborative learning as mediators of germane cognitive processing	-	2 (50%)

4.4.1 Factors leading to cognitive overload in 2D metaverse environment

In this section, the responses to the open-ended question “What were the specific elements that made you feel overwhelmed or made it difficult to process information in the 2D metaverse environment or sessions?” and semi-structured interviews were analyzed by Braun and Clarke’s (2006) thematic analysis method. The responses obtained as a result of this analysis were grouped under four main themes, which are “verbal-based instruction increasing intrinsic cognitive load,” “limited real interaction hindering germane processing,” “technical problems impairing germane cognitive processing,” and “visual complexity elevating extraneous cognitive load.” Findings regarding these themes are explained in the following subsections.

Main theme 1: Verbal-based instruction increasing intrinsic cognitive load

In this theme, several participants indicated that the second lecture session, which was based mainly on verbal explanations, led to their feeling of being overwhelmed (f = 5). For instance, one participant (2D_#4) stated that “While the second topic was being explained, I felt overwhelmed after a while when I did not see the presentation screen and only listened to the teacher.” Similarly, others reported that “In the theoretical lecture, just looking at a screen negatively affected my concentration on the lesson” (2D_#34) and “less use of presentations by the instructor while explaining the theoretical subject created distraction” (2D_#7). As a result, especially in the theoretical lectures in the metaverse learning environments, the lack of visualization and reliance on verbal explanations made it harder for students to process information, which may have led to increased intrinsic cognitive load and not supported germane cognitive load.

Similarly, in the semi-structured interviews, several participants stated that the second lecture in the metaverse environment, which was mostly theoretical and had less interactivity, was the major reason for the increased intrinsic cognitive load (f = 2). One student (2D_Interview_#1) stated that “During the second part of the class, when we were just listening passively, I felt like I was attending like a Zoom session and lost some interest.” Similarly, another student (2D_Interview_#3) stated that “Listening to the lecture without any interaction in the second class led to distraction and disengagement.” The findings from these responses suggest that the lectures in the metaverse environment in which there is overly verbal or theoretical-based instruction may increase the intrinsic cognitive load by decreasing the germane cognitive load.

Based on the quantitative results, the qualitative results suggest that although the 2D group had lower intrinsic load compared to the 3D group, lectures based on theoretical and verbal instruction increased cognitive demands, and this supports the overall inference that instructional strategy rather than metaverse platform alone affects intrinsic cognitive load negatively.

Main theme 2: Limited real interaction hindering germane processing

In this theme, some participants mentioned the lack of real face-to-face interaction in the 2D metaverse learning environment and how this situation distracted their focus and communication during the lectures (f = 3). For instance, a participant (2D_#20) stated that “when we were asked to work together in groups during the lectures, there was a communication problem because we were not face to face with the people in the group,” while another participant (2D_#29) stated that “When I cannot make face to face contact with the teacher, I may not be able to focus. This causes me to get distracted.” Also, one participant (2D_#33) shared that “not being able to see the instructor gestures and reflexes” made it difficult to stay engaged. Based on the participants’ response, the lack of face-to-face interaction may have created a sense of distraction from the learning environment, which may have reduced their level of concentration and not supported germane cognitive load during the learning process.

These statements show how reduced real social interaction and physical presence can lower germane cognitive load, as students are less likely to build meaningful schema through interactive engagement. This contradicts the quantitative results, which indicate a relatively high germane cognitive load overall in the 2D group thanks to the interactive simulations. However, despite the interactive environments and visuals, the qualitative findings suggest that some students still struggled to stay concentrated on the lecture due to the lack of real social interaction.

Main theme 3: Technical problems impairing germane cognitive processing

In this theme, some participants mentioned the technical problems that they faced in the 2D metaverse learning environments during the lectures. For instance, a participant (2D_#36) reported that due to the “connection problem,” they experienced difficulties in the 2D metaverse environments (f = 1). Besides, some participants mentioned the complexity of the user interface elements in the 2D metaverse learning environment (f = 2). For example, a participant (2D_#6) stated that “I experienced user interface and user experience problems such as not being able to see the screens when necessary and not being able to go back to the environment.”

In this manner, the problems or complexity of the user interface and accessibility issues due to the network connections may lead to the distraction of students' attention, cause extraneous cognitive load, and reduce the germane cognitive load during the lectures in the metaverse learning environments. Therefore, this finding indicates one of the reasons why the 2D group may have experienced some level of extraneous cognitive load as revealed in the quantitative data.

Main theme 4: Visual complexity elevating extraneous cognitive load

Some participants stated that the 2D metaverse environment was visually complex and crowded (f = 2). This situation may have led to difficulty in focusing on the lectures. For example, a participant (2D_#3) stated that "the abundance of visual elements made it hard to focus on key information." Another student (2D_#31) stated that "there are many things on the environment." These responses indicated that too many visual objects or stimuli in the metaverse learning environment may distract learners and contribute to extraneous cognitive load.

In addition, a participant (2D_#8) stated that "Generally, being in a gaming environment can be distracting for most people, but to be honest, I was happy." (f = 1). This response suggests that if the metaverse environments are perceived as a gaming environment rather than a learning environment due to their design and structure, this may decrease some students' focus towards the lecture and create additional cognitive overload.

In this manner, while the quantitative results did not show high extraneous load scores in the 2D group, these qualitative findings show that individual perceptions of visual complexity did exist, especially among those sensitive to the design of the environment. This suggests variability within the group and highlights the need for user-centered visual design in virtual learning environments.

4.4.2 Factors leading to cognitive overload in 3D metaverse environment

This section presents the results of the thematic analysis of the responses to the question “What were the specific elements that made you feel overwhelmed or made it difficult to process information in the 3D metaverse environment or sessions?” and the semi-structured interviews. The findings were categorized under three main themes, which are “technical problems impairing germane cognitive processing,” “verbal-based instruction increasing intrinsic cognitive load,” and “limited real interaction hindering germane processing.” Findings regarding these themes are explained in the following subsections.

Main theme 1: Technical problems impairing germane cognitive processing

Similar to the 2D metaverse group, some participants mentioned the technical difficulties or problems they experienced in the 3D metaverse learning environment. A prominent problem was network problems, which included audio disruptions and connection problems (f = 8). For example, some participants stated that “I experienced 6-7 audio disruptions lasting 3-4 seconds. These interruptions caused loss of focus and restricted my ability to follow and understand the topic.” (3D_#15), “ . . . encountering problems such as audio and connection losses at certain times caused me to be distracted from the lecture and the content covered.” (3D_#5), “The most overwhelming aspect of the 3D metaverse environment for me was the audio dropouts and freezes caused by internet connection issues." (3D_#17). Some participants stated that they experienced these difficulties due to unstable internet connections in public settings such as schools. A participant (3D_#10) stated that "internet related connection problems in public settings such as school" led to feelings of overwhelm in the metaverse learning environment. Another participant supported this idea by stating that:

> Although it was not directly caused by the metaverse environment, problems such as sound interruption due to the unstable internet connection, disconnecting from the lesson, not loading the 3D shape, etc., were quite difficult for me, and in general, I am a person who gets distracted very quickly due to environmental factors in online courses, so even a slight disruption in the sound can reduce my interest in the lesson. (3D_#27)

Besides network issues, some participants mentioned user interface problems related to the metaverse learning environment (f = 6). For instance, one participant (3D_#1) stated that "using the whiteboard was quite difficult," and another participant (3D_#10) stated that "the zoom in and zoom out settings were very difficult to use." These technical difficulties may have led to distractions, which made it more difficult for students to process the presented information effectively because of the increased intrinsic cognitive load and reduced germane cognitive load.

This qualitative finding in which the 3D group reported more technical problems than the 2D group is consistent with the quantitative data. The technical issues in a more immersive 3D metaverse environment seem to have increased the cognitive effort needed to navigate and process instruction, which supports the quantitative result that 3D metaverse students reported significantly higher intrinsic cognitive load than 2D students.

Main theme 2: Verbal-based instruction increasing intrinsic cognitive load

Similar to the 2D metaverse group, some participants found the instructional strategy used in the second part of the lecture based on verbal and theoretical lecture cognitively demanding in the 3D metaverse learning environment (f = 4). For instance, some participants stated that “the lecture part where we were just passively listening was difficult for me.” (3D_#33), “ . . . it was very difficult to focus on the lesson especially when the instructor was lecturing and we didn’t interactively participate in the lesson.” (3D_#11) and “I found it difficult to maintain my focus during the theoretical lecture.” (3D_#35). These responses from the participants suggest that the strategy and delivery of content, when mainly based on verbal or theoretical information, could make it harder for students to process information and stay cognitively engaged in 3D metaverse learning environments because of higher intrinsic cognitive load and lower germane cognitive load.

Based on the semi-structured interviews, all participants stated that the shift from more interactive (first session) to verbal/theoretical lecture (second session) increased their mental effort to stay attentive towards the lecture (f = 4). Related to this, one participant (3D_Interview_#1) stated that “The second part of the class was more theoretical and harder to follow. I lost focus more easily.” Similarly, other participants stated that “The theoretical part lacked visuals, and I think that made it less helpful. The part with the brain visuals was much more effective” (3D_Interview_#3) and “Verbal content is more difficult in this environment. The session with brain visuals was far better than the second session” (3D_Interview_#4). As a result, these responses align with cognitive load theory, in which passive instruction increases mental effort without supporting understanding.

These statements align with the quantitative finding that the 3D group experienced significantly higher intrinsic cognitive load. In this manner, the qualitative evidence strongly suggests that the verbal-based lecture design, more than the metaverse environment itself, led to higher intrinsic cognitive load.

Main theme 3: Limited real interaction hindering germane processing

In this theme, some participants mentioned the lack of physical engagement during the lectures in the 3D metaverse environment. For example, the lack of face-to-face interaction was mentioned as a reason for cognitive overload (f = 2). One participant (3D_#29) stated that "not being face to face becomes overwhelming after a while." Similarly, another participant stated that:

> The environment is quite static, so it is difficult to pay attention to the lesson for a long time. For example, while the teacher is explaining something in the classroom environment, his gestures and mimics and his walking in the classroom make it easier for us to pay attention to him, but in metaverses it was very difficult to focus on the lesson especially when the instructor was lecturing and we didn't interactively participate in the lesson." (3D_#11)

Furthermore, another participant (3D_#40) stated the negative physical effects of prolonged screen time by stating that "looking the computer screen for a long time hurt my eyes." (f = 1) These factors may have contributed to difficulties in engagement with the lectures due to the lower germane cognitive load. While quantitative results showed similar germane load levels across both groups, these findings reveal that interaction quality, not quantity, may shape cognitive processing and affect the germane cognitive load.

4.4.3 Factors contributing to cognitive load optimization in 2D metaverse environment

Thematic analyses presented in this section were based on the participants' responses to the question "Which specific aspects of the 2D metaverse environment or the sessions made the information easier to understand or process?" and semi-structured interviews. The responses were classified into four main themes, which are "enhancing germane cognitive processing through visualization and simulation," "digital learning tools and collaborative learning as mediators of germane cognitive processing," "interactivity fostering germane cognitive processing," and "optimizing cognitive processing through simplicity of environment." Findings regarding these themes are explained in the following subsections.

Main theme 1: Enhancing germane cognitive processing through visualization and simulation

A majority of participants in the 2D metaverse learning environment stated that the use of visual materials and simulations significantly contributed to easier understanding and cognitive processing of the lecture (f = 24). Based on the participants' response, it was concluded that visuals and simulations about the brain structure and its lobes helped them to concretize abstract information, which made the information in the lecture more memorable. For instance, one participant (2D_#2) stated that "examining the brain lobes one by one through visual elements and then discussing them with my friends was quite memorable." Similarly, another participant (2D_#1) noted that "The visual parts were very striking. The lobes of the brain are active in my mind even now. It was memorable." Another participant (2D_#4) shared that "Clicking on the brain object, examining the brain concept in parts, and changing the part interactively made it easier to understand the information." Similarly, a participant (2D_#11) expressed that "the fact that the concepts were visualized increased their memorability for me." Furthermore, another participant (2D_#14) stated that "Visuals and interactions helped make the information easier to understand." This finding suggests that the use of visualization and simulation helped learners to integrate and retain information more effectively, which may have led to optimized cognitive load by increasing germane cognitive load.

In semi-structured interviews, participants stated that the brain simulation and interactive visual elements in the metaverse environment were factors leading to lower cognitive load (f = 6). In this manner, one participant (2D_Interview_#1) stated that "Having direct access to the brain simulation was a great way to stay focused." Likewise, another participant (2D_Interview_#4) stated that "The visual and interactive elements, especially the simulation and whiteboard activities, made the class more enjoyable and easier to understand than traditional lectures." It could be concluded that these features may have increased students' germane cognitive load by encouraging them to build mental schemas about the topic by delivering dynamic content.

This theme supports the quantitative finding that germane load scores were moderately high in both groups. The qualitative evidence clarifies that in the 2D group, concrete visual elements were key to supporting meaningful and active cognitive processing.

Main theme 2: Digital learning tools and collaborative learning as mediators of germane cognitive processing

This theme was focused on the positive impact of digital learning tools and group-based learning activities on optimizing cognitive load in the metaverse learning environments. The participants mentioned the practical advantage of the interactive whiteboards (f = 3) and the convenience of working in breakout rooms or group areas (f = 5). For instance, one participant (2D_#10) stated that:

> I liked the place created when we were divided into groups during the lesson because it was very practical. We were able to split into groups without any effort, and it was also very impressive that we had a common workspace with our group. It can be very useful.

Similarly, another participant (2D_#2) expressed that “unlike in a physical classroom, in a metaverse environment we completed the group formation process quickly and this is a great feature.” Another participant (2D_#19) mentioned the value of built-in collaboration tools by stating that “probably the tools inside of the app are like the whiteboard.” Similarly, one more participant (2D_#12) said that “When we divided students into groups, having a whiteboard that could be used collectively by the group was very useful.” Also, another participant stated that:

> Interactive whiteboard, easy and aesthetic access to chat and speak with members, real-time and visual grouping in the place, not just like a classic 2D chat box like in Zoom or Slack. All of them increase the students' enthusiasm, and it feels more educational, as opposed to the classical class. (2D_#37)

These responses suggest that the collaborative features of the 2D metaverse environment helped to easily carry out group activities and increase task-focused interaction during the lectures, which may have an effect on optimizing cognitive load through the germane cognitive load.

Although the quantitative results showed no significant difference in germane cognitive load between 2D and 3D, these responses suggest that interactive digital tools compensated for the lack of physical presence and played a major role in optimizing cognitive processing in the 2D group.

Main theme 3: Interactivity fostering germane cognitive processing

In this theme, interactivity was mentioned as one of the key factors that contribute to optimized cognitive load (f = 5). Participants found it beneficial to be able to interact with the elements in the metaverse environment and also interact with the instructional content in real-time. For example, one participant (2D_#5) stated that "being able to interact directly with the instructional material during the lesson helped me engage more." Also, another participant (2D_#15) stated that " . . . system was interactive prevented boredom and allowed me to think directly about the topic." The participants' responses indicate that the higher interactivity and learner engagement in the metaverse environment made the learning experience more dynamic, and they supported active learning processes during the lectures in the metaverse environment. Therefore, this situation may have resulted in optimizing the cognitive load by increasing the germane cognitive load. This finding indicates that interactivity can serve as a positive factor against other factors that hinder the germane cognitive processing in metaverse-based environments.

Main theme 4: Optimizing cognitive processing through simplicity of environment

In semi-structured interviews, participants commonly stated that the simplicity of the 2D metaverse environment was a factor reducing cognitive overload and enhancing concentration (f = 2). They stated that the minimalist and basic design helped them focus more effectively on instructional content. For example, a participant (2D_Interview_#4) stated that “The 2D environment felt like a balanced space—neither too plain like Zoom nor too playful like a game. Because it didn’t contain too many visual distractions, I could concentrate better on the lecture.” Similarly, another participant (2D_Interview_#5) noted that “I believe the simplicity of the 2D environment, compared to 3D, made it easier to follow the lesson and understand the content.” The simplistic/pixel-based design of the 2D metaverse learning environment may have led to optimized cognitive load by letting students process information more efficiently and maintain attention. While quantitative scores did not reveal significant differences in extraneous load, these responses suggest that perceived visual simplicity can still enhance germane cognitive processing, even in low-fidelity environments.

4.4.4 Factors contributing to cognitive load optimization in 3D metaverse environment

This section’s thematic analyses were based on participants’ responses to the question “Which specific aspects of the 3D metaverse environment or sessions made the information easier to understand or process?” and semi-structured interviews.

The responses were divided into three main themes, which are "enhancing germane cognitive processing through visualization and simulation," "digital learning tools and collaborative learning as mediators of germane cognitive processing," "interactivity fostering germane cognitive processing." Findings regarding these themes are explained in the following subsections.

Main theme 1: Enhancing germane cognitive processing through visualization and simulation

This theme includes the participants' responses about how the 3D metaverse learning environment, which is both immersive and visually rich, assists them in understanding the lecture content in a better way. A significant part of the participants mentioned that the integration of 3D visual elements and interactive simulations into the 3D metaverse learning environment enriched their understanding of abstract or complex concepts, which may have contributed to increasing the germane cognitive load (f = 32). According to many students, seeing and interacting with the 3D brain model and other 3D objects enhanced their comprehension of the lecture content. For example, one participant stated that:

> The 3D visuals and hands-on interactions in the metaverse made the information easier to understand because I could see concepts in action. Being able to move around and explore different parts of a topic helped me process the details better. The immersive experience made complex ideas feel more real and clear. (3D_#41)

Another participant (3D_#43) stated that "The activity was easier to understand with the colorful and interesting materials used." Similarly, a participant (3D_#36) noted that "The visualization of brain regions created a richer learning environment visually."

Another student (3D_#35) explained that "being able to click on parts of the brain model and instantly access information about that part made learning much easier for me." Participants also found it beneficial to access the information whenever they want. A participant noted that:

> It was very helpful to have the brain regions in front of me and to see the relevant information pop up when I clicked them. Unlike slides that are sometimes skipped in traditional classes, I could visit the content easily. (3D_#24)

Furthermore, students mentioned how the 3D experience made abstract ideas more concrete. One participant (3D_#29) stated that "three-dimensional objects made it easier to understand the concepts visually." Another student (3D_#9) said that "being able to see the brain lobes in 3D made it easier to understand their functions. It was much more engaging and comprehensible compared to just seeing them in a picture or textbook." In addition, student (3D_#8) expressed that "The way concepts that are difficult to visualize in the real world were presented in 3D could potentially make them easier to understand." Also, another participant summarized this impact by stating that:

> The use of simulations in the 3D metaverse environment made learning much easier for me. By allowing me to interact with concepts in a visual and immersive way, it helped solidify complex ideas that might have been harder to grasp through traditional methods. The visual representations and interactive elements, such as 3D models, also enhanced my understanding and made the information more engaging and easier to retain. (3D_#17)

The immersive nature of the 3D metaverse experience was also mentioned by participants as a feature that eased the learning process. One participant (3D_#41) stated that " . . . the immersive experience made complex ideas feel more real and clear." The responses provided by the participants indicate that the virtual classroom environment, which is similar to a real classroom environment, enhanced their comprehension of the lesson more effectively. In other words, the higher similarity between the virtual environment and real-world contexts also helped students to process information in the lecture content more easily. A participant (3D_#8) noted that "the way concepts that are difficult to visualize in the real world were presented in 3D could potentially make them easier to understand." These types of responses indicate that when virtual learning environments present real-world conceptual structures or objects, they support students in making meaningful connections and facilitate deeper understanding. As a result, these responses suggest that using visualization and simulation within the immersive nature of the 3D metaverse environment supported cognitive processing (germane cognitive load) of the lecture content by letting students make abstract content concrete and visual. This situation not only improved students' comprehension but also increased attention and retention of the content, which ultimately optimized the cognitive effort required to learn.

In semi-structured interviews, the combination of the interactive visualizations and the simulations was noted as a most liked characteristic of the 3D metaverse learning environment, especially in the first session in which participants employed a 3D brain model (f = 4). Participants stated that these visual elements enhanced their understanding, increased their cognitive engagement, and resulted in improved retention of the content. One participant (3D_Interview_#2) stated that "Listening to the lecture while exploring the simulation helped me focus more. I could combine what I was hearing with what I was seeing." Similarly, another participant (3D_Interview_#4) mentioned that "When I could touch the parts of the brain and information would appear, it made learning much easier and more enjoyable." In addition, a third participant (3D_Interview_#1) highlighted that "The metaverse allowed for excellent visualization tools that really helped simplify complex content." From the participants' responses, it could be concluded that immersive visuals and simulations likely may have supported germane cognitive load by enabling students to allocate mental resources toward meaningful learning.

These findings support the similar germane cognitive load levels in the quantitative analysis. In this manner, the use of interactive visualization and simulation in both 2D and 3D metaverse platforms appeared to increase germane cognitive load equally.

Main theme 2: Digital learning tools and collaborative learning as mediators of germane cognitive processing

The participants mentioned that digital tools and group work in the 3D metaverse environment were one of the main factors for making the learning process easier and more effective by optimizing the cognitive load. According to the participants, besides the individual understanding, the digital learning tools also helped them enhance group engagement and peer learning. Some participants stated the usefulness of the various digital tools provided in the 3D metaverse platforms (f = 3). For instance, one participant (3D_#12) stated that "being able to have group chats, access a notebook, and use interactive whiteboards in group work made the learning process more efficient." Another student (3D_#16) mentioned that "In metaverse, the materials were easily accessible at all time." Similarly, another student (3D_#36) emphasized that "Having a notebook tool that we could open anytime and take notes made it easier for me to learn important points." These responses illustrate that easily accessible digital learning materials and tools supported learners in processing and organizing the lecture content more efficiently.

The integration of interactive whiteboards into the metaverse environment was also found to be beneficial by participants for making abstract information more concrete (f = 4). A student (3D_#35) explained that "being able to see the information and visuals on the whiteboard in group work helped visualize the content." This suggests that the use of digital whiteboards in metaverse learning environments helped the understanding and retention of information, which led to optimizing cognitive effort.

In addition, participants stated that collaborative activities, such as group work, enriched their comprehension of the topic (f = 6). One participant (3D_#39) stated that "the group work we did in between made it easier to understand the topic." Another participant (3D_#40) added that "Doing group work at the end of the lesson reinforced my learning process." These findings indicate that group discussion and group work not only contributed to engagement but also may have helped in optimizing the cognitive load through the germane cognitive load.

In semi-structured interviews, participants mentioned that in the 3D metaverse environment, being able to use the digital tools like collaborative whiteboards and note-taking features increased their interaction and supported active learning by increasing the germane cognitive load (f = 2). Related to this theme, one participant (3D_Interview_#1) stated that "It was great that everyone could write on the whiteboard and work together in the same space. I also used the notes section a lot—it helped me stay organized." Similarly, another participant (3D_Interview_#4) said that "the whiteboard and our discussions as a group were very productive. These tools definitely helped." From these quotes, it could be said that such digital learning tools may have enhanced students' engagement while minimizing unnecessary cognitive effort. Therefore, this situation may have provided students with an efficient learning experience through the increased germane cognitive load.

Since digital learning tools and collaborative learning activities were similar in both 2D and 3D groups, these findings are also similar to those in the 2D group, and they suggest that collaborative activities and digital learning tools across platforms consistently helped optimize cognitive effort, contributing to germane load without increasing extraneous demands.

Main theme 3: Interactivity fostering germane cognitive processing

Participants indicate that the ability to interact with the environment and having control over the pace of learning positively affected their understanding (f = 3). For instance, one participant (3D_#2) expressed that “In the brain simulation, it helped us to understand that we could look at all parts individually and that we were in general control.” Another student (3D_#5) stated that “The interaction. Being able to explore the content without needing to shift my attention using my own mouse and not wasting time with the teacher writing or drawing made the lesson more efficient than a traditional classroom.” These comments indicate that interactive control over the lecture content led to better cognitive engagement and reduced passive learning and cognitive overload.

The movement with avatars within the 3D metaverse environment was also found to be supportive of learning by the participants (f = 3). For example, a participant (3D_#41) noted that “Being able to move around and explore different parts of the brain through 3D simulation helped me process the details better.” Another participant (3D_#6) stated that “The ability to explore spaces at my own pace helped in understanding the content.” These experiences indicate that spatial exploration in 3D metaverse environments can contribute to deeper comprehension and optimized cognitive load by aligning with students' learning pace.

Also, the psychological comfort provided by the online metaverse environment was found to improve classroom participation and focus (f = 1). A participant (3D_#24) explained that:

> My motivation to participate increased because, unlike in a physical classroom where I feel shy to speak, in a virtual environment I felt more comfortable and more willing to respond. I felt like I was playing The Sims, so I didn't get bored and actually enjoyed the class.

This response suggests that the virtual classroom environment may reduce social pressure and anxiety. Therefore, this situation may result in supporting cognitive engagement and optimizing cognitive load.

All in all, these qualitative findings confirm and enrich the quantitative outcomes by showing that while germane load scores were statistically similar, the mechanisms supporting optimized cognitive load varied between environments (e.g., visual immersion in 3D and simplicity in 2D). Both environments, when well-designed, can support effective cognitive processing through different but complementary ways.

4.5 Research question ii.i (Is there a statistically significant difference in the flow experience scores of higher education students using the 2D and 3D metaverse learning environments?)

To answer research question ii.i, descriptive statistics for participants' flow experience scores in 2D and 3D metaverse learning environments were calculated and presented in Table 22. To test the normality assumption for both groups (2D metaverse and 3D metaverse groups), histograms and normal Q-Q plots were visually inspected, skewness and kurtosis z-values were computed, and the Shapiro-

Wilk test was conducted. According to the results, flow experience scores were normally distributed for the 2D metaverse group but not the 3D metaverse group, as assessed by Shapiro-Wilk's test ($p < .05$) (see Table 23). Therefore, the results indicated that the normality assumption was not met, and it was concluded that the Mann-Whitney U test was run to analyze this research question.

Table 22. Descriptive Statistics of Flow Experience Scores of Groups

	N	*M*	*SD*	*Mdn*	Min	Max	Skewness	Skewness z-value	Kurtosis	Kurtosis z-value
2D Metaverse Group	38	29.11	5.280	29.5	15	40	-.543	-1.418	1.142	1.523
3D Metaverse Group	43	28.93	4.657	29	14	37	-.663	-1.837	1.543	2.176

Table 23. Shapiro-Wilk Result of Flow Experience Scores of Groups

	W	*df*	*p*
2D Metaverse Group	.949	38	.085
3D Metaverse Group	.945	43	.038

A Mann-Whitney U test was run to determine if there were differences in flow experience scores between 2D and 3D metaverse groups. Distributions of the flow experience scores for 2D and 3D metaverse groups were similar, as assessed by visual inspection. The flow experience score was not statistically significantly different between the 2D metaverse group (*Mdn* = 29.50) and the 3D metaverse group (*Mdn* = 29), $U = 786.500$, $z = -.290$, $p = .772$. As a result, the findings indicate that there was no statistically significant difference in participants' flow experience between the 2D and 3D metaverse groups, and both groups demonstrated similar median flow experience scores (*Mdn* = 29.50 for 2D, *Mdn* = 29 for 3D), which indicates that neither metaverse learning environment provided a significantly greater sense of flow experience than the other. Although there was no statistically significant difference between the two groups in terms of flow experience, both groups showed relatively high median flow scores (*Mdn* = 29.50 for 2D, *Mdn* = 29 for 3D) on a scale ranging from eight to 40. This finding shows that, overall, participants in both environments experienced a high level of flow experience during the metaverse-based lectures in 2D and 3D metaverse learning environments. Descriptive statistics related to flow experience items in the scale are presented in Table 24 to provide a more detailed view of participants' perceptions across individual items.

Table 24. Descriptive Statistics Related to Flow Experience Items

Item No	Statement	2D Group *M*	2D Group *SD*	3D Group *M*	3D Group *SD*
1	I felt in control of what I was doing during the learning activity.	3.66	.966	3.74	.875
2	I was absorbed intensely by the activity.	3.34	.937	3.30	.914
3	I found the activity enjoyable.	3.84	1.001	4.02	.963
4	I found the activity interesting.	3.79	.935	3.95	.975
5	I was completely immersed in this learning activity.	3.26	.891	3.21	.833
6	During the learning activity, time seemed to pass fast.	3.39	1.028	3.35	1.193
7	The activity excited my curiosity.	3.76	.998	3.53	.909
8	I knew the right thing to do in the learning activity.	4.05	.733	3.81	.764

4.6 Research question ii.ii (How do students describe the factors that enhance or hinder their flow experiences in 2D and 3D metaverse learning environments?)

In this research question, the results of the thematic analysis of the participants' responses to the open-ended questions and semi-structured interviews related to the factors enhancing or hindering their flow experiences in 2D and 3D metaverse learning environments are presented.

For inter-rater reliability, the responses to reflection forms and transcripts of semi-structured interviews were independently coded by two researchers. Themes were identified through a consensus process where similar and different codes were compared and edited. This approach helped in ensuring that the process of categorization was objective.

The participants' responses were coded using Braun and Clarke's (2006) thematic analysis approach, and then sub-themes and main themes were identified. In addition, the frequency of sub-themes that indicate how many participants gave responses about this particular sub-theme was indicated with "f" in the parentheses. Besides that, the main themes that emerged as a result of the analysis of the answers of the participants in the 2D and 3D groups, how many participants in each group gave answers related to these themes, and the percentage within the group are summarized in Table 25, Table 26 and Table 27.

Table 25. Main Themes Contributing to Increased Flow Experiences in 2D and 3D Metaverse Learning Environments

Condition	Main Theme	Frequency (f)	Within-group Percentage (%)
2D Metaverse Group (n = 38)	1) Collaborative learning and interaction as a facilitator of flow experience	14	36.8%
	2) Interactive environment facilitating flow experience	9	23.7%
	3) Familiarity and presence in virtual space fostering flow experience	7	18.4%
3D Metaverse Group (n = 43)	1) Immersive visual elements supporting flow experience	19	44.2%
	2) Collaborative learning and interaction as a facilitator of flow experience	19	44.2%
	3) Perceived realism and avatar presence enhancing flow experience	15	34.9%
	4) Interactive environment facilitating flow experience	7	16.3%
	5) Gameful learning and functional features enhancing emotional involvement in flow	7	16.3%

Table 26. Main Themes Contributing to Decreased Flow Experiences in 2D and 3D Metaverse Learning Environments

Condition	Main Theme	Frequency (f)	Within-group Percentage (%)
2D Metaverse Group (n = 38)	1) Digital distractions and reduced control as barriers to flow	6	15.8%
	2) Game elements hindering flow experience	5	13.2%
	3) Passive instructional delivery hindering flow experiences	4	10.5%
	4) Visual complexity as an obstacle for flow experiences	3	7.9%
3D Metaverse Group (n = 43)	1) Technical problems as barriers to maintaining flow experiences	17	39.5%
	2) Visual complexity as an obstacle for flow experiences	6	14.0%
	3) Passive instructional delivery hindering flow experiences	3	7.0%

Table 27. Main Themes Derived from Semi-Structured Interviews Regarding Flow Experiences in 2D and 3D Metaverse Learning Environments

Theme Category	Main Theme	2D Metaverse Group f (%) (n = 6)	3D Metaverse Group f (%) (n = 4)
Increased flow experiences	Collaborative learning and interaction as a facilitator of flow experience	5 (83.3%)	2 (50%)
	Emotional and motivational comfort enabling flow experience	1 (16.7%)	1 (25%)
	Realism as a facilitator or obstacle for sustained flow experience	3 (50%)	4 (100%)
	Minimalist design promoting flow experience	3 (50%)	-
Decreased flow experiences	Digital distractions and reduced control as barriers to flow	2 (33.3%)	1 (25%)
	Passive instructional delivery hindering flow experiences	2 (33.3%)	4 (100%)

4.6.1 Factors increasing flow experiences in 2D metaverse environment

This section's thematic analyses were based on participants' responses to the question "Which specific aspects of the 2D metaverse environment or the sessions contributed to feeling completely absorbed or deeply engaged in the environment or the learning activity?" and semi-structured interviews. The responses were divided into six main themes, which are "collaborative learning and interaction as a facilitator of flow experience," "interactive environment facilitating flow experience," "familiarity and presence in virtual space fostering flow experience," "emotional and motivational comfort enabling flow experience," "realism as a facilitator of sustained flow experience," and "minimalist design promoting flow experience." Findings regarding these themes are explained in the following subsections.

Main theme 1: Collaborative learning and interaction as a facilitator of flow experience

Group work was the most frequently mentioned factor contributing to flow experiences ($f = 11$). For example, one student (2D_#29) stated that "doing tasks together in small groups felt me I was in a classroom." Another student (2D_#10) noted that "When we moved directly from the lecture area to group rooms, it felt like a real class and helped me get more into the lesson." Similarly, (2D_#4) said that "Splitting into groups, discussing the topics there and making presentations in front of everyone made me feel like I was immersed in the learning activity." Similarly, another participant (2D_#1) mentioned that "Being able to collaborate with classmates contributed to my engagement."

As a result, collaborative learning in the metaverse environment increased students’ involvement, motivation, and social presence which are key components that facilitated reaching the flow experience state.

Being able to communicate with other students in the metaverse environment was also seen as a factor that improves engagement (f = 3). A student (2D_#2) mentioned that “Being able to chat and share ideas in audio and written helped me to be involved in the lesson.” The opportunity to communicate with other students in real time allowed students to stay connected and focused. Therefore, this situation may have reduced feelings of isolation and enhanced flow experiences.

In semi-structured interviews, according to participants, group activities and digital tools that were used together, like interactive whiteboards in the 2D metaverse, played a significant role in increasing students’ sense of immersion and active participation (f = 5). For example, one student (2D_Interview_#2) stated that “When we divided into groups and worked together on the whiteboard, I truly felt like I was in a physical classroom.” Another student (2D_Interview_#4) stated that “Those shared digital tools made me feel more connected and excited about the class, especially being able to manipulate content with others.” As indicated in the participants’ responses, collaborative environments and tools helped students develop social presence and engagement that were aligned with the characteristics of the flow experience state.

These qualitative findings support the quantitative results by explaining why both groups scored similarly high on flow experience. The presence of collaborative elements in both 2D and 3D groups appears to have strongly contributed to positive flow experience states.

Main theme 2: Interactive environment facilitating flow experience

The participants mentioned that the interactive features of the 2D metaverse environment had a significant impact on their deep engagement with the lectures (f = 6). For example, one student (2D_#14) stated that "The interactive nature of the environment made me feel fully involved." Another participant (2D_#13) stated that "Being able to interact with the visual material indeed contributed to my learning progress." Similarly, a participant (2D_#3) stated that "In the 2D metaverse environment, the immersive visuals and interactive features contributed to my deep sense of involvement. It allowed me to adapt immediately to interact with the content." These statements indicate that the ability to interact with learning materials in the metaverse environment allowed students to take an active role in their learning. Therefore, this situation led to increasing their sense of control and focus, which are two main components of the flow experience.

Several students mentioned that active participation in the sessions rather than passive observation made them feel more engaged (f = 3). For instance, one student said that:

> When I participated in the class, I really felt like I was part of the class. I could talk to other students with my avatar in the virtual environment and we could do tasks together. I focused more on the lesson and learned more because I took an active role in the lesson instead of just being a passive spectator. (2D_#20)

Another participant (2D_#29) stated that "Being in a classroom environment prevented us from just being in viewer mode like during remote education." Being active in the metaverse environment during the learning process increased students' involvement and maintained their attention and engagement.

These are important factors in increasing the students’ flow experiences to immerse students in the learning activity. These findings align with the quantitative results by showing that 2D environments were capable of inducing high flow experiences, particularly when designed with interactive features.

Main theme 3: Familiarity and presence in virtual space fostering flow experience

Students expressed that since the design of the virtual classroom is similar to a real classroom, this situation enhanced their feeling of presence in the lectures (f = 3). A student (2D_#26) explained that “The designed metaverse environment was a good experience in terms of feeling like a real classroom.” Another student stated that:

> When I participated in the lesson, I truly felt like I was part of the class. In the virtual environment, I could talk to other students through my avatar and complete tasks together. Since I was no longer just a passive observer and instead took an active role in the lesson, I was more focused and learned more. (2D_#20)

The presence due to being in a well-known, realistic classroom environment helped students foster their emotional and cognitive presence and, thus, promote the immersion state, which is the characteristic of flow experiences. In addition, the use of avatars helped simulate physical presence and social interaction (f = 3). A participant (2D_#5) stated that “Going to the class with my character made me feel as if I was really attending class in real life.” The integration of these social elements into the metaverse contributed to the creation of an interactive and realistic learning environment, and this provided the experience with a higher level of authenticity, which helped in reaching the flow experience state by maintaining the students’ engagement.

The gamified design of the 2D metaverse setting also contributed to the flow experiences (f = 1). As one student (2D_#15) stated that "Just like video games can easily capture attention, this virtual environment did the same especially for people already used to computer games." Fun and the game-like environment fostered maintained focus and participation, and as a result of that, the students may have been deeply absorbed in both the lecture and the environment and reached the state of flow experience.

While the quantitative data did not show a significant difference between groups, these qualitative findings suggest that specific design aspects of the 2D platform helped enhance flow experience, explaining the relatively high flow experience scores despite having simpler visuals.

Main theme 4: Emotional and motivational comfort enabling flow experience

In semi-structured interviews, a student mentioned that they felt more relaxed and had less anxiety in the metaverse learning environment compared to face-to-face lectures (f = 1). The student (2D_Interview_#2) stated that "Compared to real-life classes, I felt more relaxed attending in the metaverse. I don't know exactly why, but being behind a computer and doing things together as a group helped increase my motivation and focus." The collaborative and interactive metaverse environment in which students feel relaxed supported flow experiences by lowering emotional obstacles to participation in the lectures.

Although this theme had lower frequency, it still contributes to explaining the overall positive flow levels in both groups. Emotional comfort likely served as a condition that supported some students' flow experiences.

Main theme 5: Realism as a facilitator or obstacle for sustained flow experience

This theme was derived from participants in the 2D metaverse group in response to a hypothetical question posed during the semi-structured interviews: “What would happen if you had taken the lecture in a 3D metaverse environment instead of a 2D environment?” These participants did not actually experience the 3D environment. Therefore, their statements reflect imagined perceptions and expectations rather than direct experience. In this manner, participants’ opinions were different in terms of the appropriateness of a realistic 3D metaverse environment for lecturing. While some participants had an idea that 3D might be distracting for lectures (f = 3), others viewed it as more realistic and motivating (f = 3). For instance, one student (2D_Interview_#3) stated that “In a 3D environment, I might get too distracted by the characters and surroundings and lose focus on the lecture.” However, another participant (2D_Interview_#6) stated that “I would have preferred to take the course in a 3D setting because it feels more realistic and engaging.” The distinction between these preferences suggests that different metaverse environments can have the dual effect of either improving or decreasing the level of flow experience based on the characteristics of the learner and the instructional context.

Main theme 6: Minimalist design promoting flow experience

Participants commonly stated that the simplicity of the 2D metaverse environment was a factor enhancing flow experiences (f = 2). They stated that the minimalist and basic design helped them focus more effectively on instructional content. For example, a participant (2D_Interview_#4) stated that “The 2D environment felt like a balanced space—neither too plain like Zoom nor too playful like a game. Because it didn’t contain too many visual distractions, I could concentrate better on the lecture.”

Similarly, another participant (2D_Interview_#5) noted that “I believe the simplicity of the 2D environment, compared to 3D, made it easier to follow the lesson and understand the content.” The simplistic/pixel-based design of the 2D metaverse learning environment may have led to maintained attention by increasing the flow experiences.

These findings support the lack of a significant group difference found in the quantitative data. They suggest that even though 2D environments lack immersive visuals, minimalist design can still support strong flow experiences through cognitive focus and clarity.

4.6.2 Factors increasing flow experiences in 3D metaverse environment

This section’s thematic analyses were based on participants’ responses to the question “Which specific aspects of the 3D metaverse environment or the sessions contributed to feeling completely absorbed or deeply engaged in the environment or the learning activity?” and semi-structured interviews. The responses were divided into seven main themes, which are “immersive visual elements supporting flow experience,” “collaborative learning and interaction as a facilitator of flow experience,” “perceived realism and avatar presence enhancing flow experience,” “interactive environment facilitating flow experience,” “gameful learning and functional features enhancing emotional involvement in flow,” “emotional and motivational comfort enabling flow experience,” and “realism as a facilitator of sustained flow experience.” Findings regarding these themes are explained in the following subsections.

Main theme 1: Immersive visual elements supporting flow experience

According to the answers given by the participants, one of the key elements identified for improving the students’ flow experiences in the 3D metaverse learning environment was the use of visually engaging objects (f = 6), immersive environments (f = 6), and 3D simulations (f = 7). A majority of participants mentioned that interacting with 3D models, such as the 3D brain simulation, significantly increased their level of flow experiences and also enhanced their focus and attention. For instance, one participant stated that:

> It was really visually interesting. The activities provided the opportunity to examine the lobes of the brain in 3D and made the lesson more impressive. Being able to examine the brain structure in detail both contributed to the learning process and kept my interest in the lesson alive and prevented me from being distracted. Working with three dimensional visuals helped me to master the subject in more depth. (3D_#9)

Another participant (3D_#40) stated that “The use of visual and auditory multimedia resources more effectively than traditional classrooms made me feel more connected to the environment.” The immersive environment that includes 3D simulation and objects helped participants to better visualize abstract concepts and provided a more engaging learning experience. One participant (3D_#17) stated that “The immersive visuals and interactive simulations in the 3D metaverse environment made me feel deeply engaged and completely absorbed in the learning activity.” Similarly, another participant (3D_#34) stated that “3D modelling helped me a lot to memorize.” The findings suggest that realistic 3D visuals and 3D simulation-based content have a significant effect on increasing cognitive and emotional engagement; as a result, users experience the flow experience in a stronger way.

These findings clarify that while the minimalist design of the 2D environment may enhance flow experience, the immersive design features in the 3D environment also have the power to enhance flow experiences. This situation may explain one of the reasons why no difference was found in quantitative results.

Main theme 2: Collaborative learning and interaction as a facilitator of flow experience

The most frequently mentioned factor that contributed to flow experience in the 3D metaverse environment was group work (f = 19). Students mentioned that being part of a group in the metaverse environment enhanced their involvement and allowed them to feel deeply immersed in the learning process. For example, one student (3D_#36) stated that "Taking lessons in a space larger than a real classroom helped us stay better isolated from other groups and focus more effectively on our own group and the tasks." Another participant mentioned that:

> I felt that I had a lot of fun in the part where we were divided into groups. The fact that we all went to a place, sat there and started talking made me feel like we were on a panel and made me think more on the subject. This grouping experience, which I usually get bored doing in the rooms via Zoom, was very pleasant for me in this way. I talked more comfortably with my friends there. (3D_#24)

Additionally, students mentioned that this type of collaboration improved their sense of presence. A student (3D_#18) said that "When we worked in teams, I found myself inside the learning environment." Similarly, another student (3D_#1) said about the efficiency of the process by stating that "Doing group work in the metaverse environment was quite efficient. Despite having 7–8 groups, the absence of overlapping voices helped us maintain focus."

These experiences show that social collaboration in the metaverse learning environment contributed to immersion, attention, and emotional involvement, which are important factors in flow experiences.

In semi-structured interviews, group-based and collaborative tasks in the 3D metaverse learning environment were frequently mentioned as factors that improved participants' engagement during the lectures (f = 2). These activities contributed to flow experiences by focusing them into the lectures and providing a sense of social presence. For example, while a participant (3D_Interview_#1) stated that "During group work, I felt more focused and active. It was much more efficient and engaging than passive learning," another participant (3D_Interview_#4) similarly mentioned that "group work really made it feel like a real classroom. We thought and discussed as a team, and that helped me understand the content better." From these responses, it can be concluded that collaborative tasks may have enriched the flow experiences of participants by maintaining their attention through the social interaction.

This theme confirms that collaboration strongly supports flow in both environments, helping explain the similar quantitative scores. In terms of flow experiences, effective instructional design may have more importance than the platform differences.

Main theme 3: Perceived realism and avatar presence enhancing flow experience

Several participants mentioned that since the 3D metaverse learning environment is closely similar to a real-classroom environment, it contributed to their sense of presence and flow experiences (f = 11). For instance, a student (3D_#18) said that "During the Metaclass session I felt like I was in a real classroom." Another participant (3D_#5) noted that "Being in a space with my friends created for the lesson even if virtual environment made me feel more engaged."

According to the students' responses, the use of avatars contributed to a sense of social presence (f = 4). A student (3D_#30) stated that "Seeing my friends next to me on screen even though it was virtual felt more real." Another participant (3D_#5) explained that "Having my own character gave me the feeling that I was actually going to class in real life." This integration of immersive environmental design, personal representation through the avatars, and social interaction played an important role in enriching students' engagement and maintaining the flow experiences throughout the lectures.

These qualitative results help explain why 3D scores were not significantly higher despite their richer and immersive features because many of the same flow experience-enhancing elements (presence, realism) were effectively simulated in 2D as well.

Main theme 4: Interactive environment facilitating flow experience

Interactivity was another important factor in reaching the flow experience state during the lectures. Students stated that being able to explore the environment and interact with learning materials/objects helped them feel more involved in the lectures (f = 4).

For example, a participant (3D_#41) stated that "Being able to explore the environment and interact with objects made the lessons feel more like real-life experiences." Another student (3D_#19) mentioned that "Everyone contributing interactively to the lesson accelerated the learning process."

Distance-based communication and private group areas also supported this interactivity (f = 3). A student (3D_#14) explained that " . . . voices were heard depending on our position in the space made it feel like a real environment." Similarly, another student (3D_#11) emphasized that "Not hearing others during our own discussions helped us focus and made the discussion process more productive." According to the participants' responses, dynamic interactions and responsive learning environments were the factors that were primarily responsible for the encouragement of maintained attention, the feeling of control, and the engagement of tasks, which are all related to the flow experience.

Like the 2D group, these findings support the view that interactivity rather than dimensionality was the significant factor in flow experiences. This helps interpret the statistical equivalence in quantitative results.

Main theme 5: Gameful learning and functional features enhancing emotional involvement in flow

Several participants reported that the 3D metaverse environment's enjoyable and game-like design contributed to their sustained focus and engagement (f = 3). One student (3D_#41) stated that " . . . the activities felt more like a game, which kept my attention and made learning more fun." These game-like experiences during the lectures in the metaverse environments increased the participants' motivation and helped in turning the lecture process into an enjoyable process. Especially, the students who were already familiar with the digital games may have benefited more from the environment, which may have led to fostering curiosity and immersion of the participants. Therefore, this process may have supported the emotional involvement that is the key element of the flow experience.

In addition to game-like elements, students mentioned the functional features of the metaverse environment, such as screen sharing (f = 4) and interactive whiteboards (f = 3), which made the learning process effective. For instance, one student (3D_#21) stated that “being able to view screen sharing in full screen made the platform more practical,” while another participant (3D_#3) simply noted, “Screen sharing was good.” Another student (3D_#2) mentioned that “It was nice to be able to use the whiteboard” These digital tools helped in following the lecture content effectively by reducing the distractive elements or processes. Therefore, the combination of game-like design and supportive digital learning tools played a crucial role in helping students stay engaged with both the content and the metaverse environment. As a result, by balancing functionality with enjoyment, the 3D metaverse platform increased learners’ attention, reduced mental effort, and facilitated a more immersive learning experience, which supports the stronger state of flow experiences during the lectures.

Main theme 6: Emotional and motivational comfort enabling flow experience

In semi-structured interviews, one participant mentioned that unlike the traditional face-to-face classroom, which mostly triggers anxiety for some students, the online nature of the 3D metaverse environment made them feel more comfortable and relaxed (f = 1). The participant (3D_Interview_#4) stated that “I have some anxiety, so I actually feel more comfortable learning in this environment than in a real classroom. It helps me respond to questions more easily.” Emotional comfort is often a precondition for flow experience and an efficient learning process. For that reason, the response from the participant emphasizes the potential of metaverse learning environments to meet diverse learner needs. This theme was also mentioned in the 2D group, and this supports the no difference between groups based on the quantitative data in terms of flow experiences.

Main theme 7: Realism as a facilitator or obstacle for sustained flow experience

A hypothetical question was posed during the semi-structured interviews: “What would happen if you had taken the lecture in a 2D metaverse environment instead of a 3D environment?” These participants did not actually experience the 3D environment. Therefore, their statements reflect imagined perceptions and expectations rather than direct experience. In this manner, all participants stated that the 3D metaverse environment looked and felt more realistic and immersive compared to possible 2D settings (f = 4). This sense of realism may have contributed positively to their sense of presence, and this situation may have led to enhanced motivation and flow experience. One participant (3D_Interview_#4) stated that “Compared to the 2D environment, 3D was better for me. It felt more real and closer to a real classroom. I think learning in 2D would have been more difficult.” Likewise, another participant (3D_Interview_#2) expressed that “In a 2D metaverse, I’d feel like I’m just watching a screen. In 3D, I felt like I was inside the classroom.” In addition, another participant (3D_Interview_#1) noted that “Why would I learn in a 2D world when we live in a 3D one? A 2D environment would be harder to take seriously.”

Based on the participants' responses, it can be concluded that the immersive nature of the 3D metaverse environment may have supported deeper engagement, which is in line with conditions that facilitated flow experiences.

4.6.3 Factors decreasing flow experiences in 2D metaverse environment

This section's thematic analyses were based on participants' responses to the question "Which specific aspects of the 2D metaverse environment or the sessions made it difficult to stay focused or engaged in the environment or the learning activity?" and semi-structured interviews. The responses were divided into four main themes, which are "digital distractions and reduced control as barriers to flow," "game elements hindering flow experience," "passive instructional delivery hindering flow experiences," and "visual complexity as an obstacle for flow experiences." Findings regarding these themes are explained in the following subsections.

Main theme 1: Digital distractions and reduced control as barriers to flow

Many students expressed that the ease of access to other digital distractions while attending the lectures in the 2D metaverse environment, such as phones or other websites that are not related to the lectures, reduced their flow experiences (f = 5). For instance, one student noted that:

> Since we access the environment through devices that can also perform other functions, my eyes often look at other things during the lecture. Just like how we might look at our phones in a physical classroom. The biggest problem of the system is that you have no option but to self monitor. (2D_#30)

Similarly, another participant (2D_#29) emphasized that "It's easier to access distracting content (like social media or games) compared to a physical classroom." Likewise, a student (2D_#24) stated that "Rather than being specific to the 2D metaverse, I experienced the general attention issues that come with online learning. From time to time, my attention inevitably shifted to other things." One more participant (2D_#16) stated that "Since no one can see you, you don't feel like you're in a classroom, so you might not feel like looking at the lesson much." From these responses, it can be concluded that one of the most important factors that reduced students' engagement in the 2D metaverse environment was the abundance of distractions and lack of control compared to traditional classroom settings. These responses indicate that the absence of supervision and the presence of different external distractions in the online setting made it easier for students to lose their focus. Therefore, this situation may have led to interrupting the students' immersion in the lecture, which is necessary for the flow experience state.

A student also mentioned a problem like being too physically relaxed in the environment in which they connected to the metaverse environment (f = 1). For instance, one student (2D_#11) stated that "Being able to attend while I'm lying on my bed." This response suggests that extreme physical comfort may reduce the psychological readiness that is required for flow experience in the lecture in the metaverse environment.

In semi-structured interviews, according to some participants, attending the lectures in the metaverse environment from a personal computer made them vulnerable to digital distractions and reduced their ability to self-regulate, which disrupted their focus and flow experience state (f = 2). For example, one participant (2D_Interview_#6) stated that "Because I was using my personal computer, I occasionally found myself browsing the internet or getting distracted by messages. The lack of supervision in metaverse made it easier to lose focus." As well, another participant (2D_Interview_#1) noted that "I sometimes drifted away from the computer and leaned back, which made me mentally distant from the class. Since it's the same device I use for entertainment, staying engaged was harder." These findings indicate that although the metaverse learning environment is flexible thanks to its online nature, it may also have negatively contributed to the students' flow experience state due to the other digital distractions.

These responses help explain why some participants may have experienced lower individual flow scores, even if the median was high. However, since similar themes appeared in the 3D group, these factors likely influenced both groups comparably, which helps in explaining the non-significant statistical difference.

Main theme 2: Game elements hindering flow experience

Although gamification is typically associated with increased motivation for some students, one student mentioned this could also lead to interruption in the focus (f = 1). A student stated that:

> It felt like a game was in front of me and I was walking around with my character for fun, so it prevented the seriousness of the lesson. The environment has many different options which force you to try them. For example, you wonder what would happen if you click a certain button. This causes distraction. (2D_#21)

This statement shows that while game elements may increase flow experiences for some students, they can also lead to some behaviors that are not related to the learning process and reduce the seriousness of the learning context. Therefore, this may make it harder to achieve a focused, flow experience state.

In addition, the digital and online format of the class itself emerged as another factor reducing flow experiences (f = 4). A student (2D_#3) stated that " . . . it was online made it hard for me to stay focused. Sometimes, I found myself looking the social media." Another participant (2D_#32) shared that "It is online. That's why I have to use a computer to connect to the system, and I cannot focus using the computer." Lecturing in an online environment may be flexible. However, at the same time, the responses from the participants indicated that online environments can cause distractions. These distractions may reduce the emotional and cognitive involvement, which are two main critical factors for reaching the flow experience state.

This theme reveals an important point, which is that design elements intended to enhance flow can affect some learners negatively. Yet, since this was a minority experience, it did not significantly lower the overall flow experience scores, and this aligns with the quantitative result of no significant difference.

Main theme 3: Passive instructional delivery hindering flow experiences

Another commonly mentioned reason for disengagement from the lecture was related to passive instruction and theoretical lecture styles (f = 4). Several students indicated that lectures that are lacking interactivity or visual support and mainly based on verbal/theoretical parts led to reduced flow experiences. For example, one student (2D_#5) stated that "There was nothing specific about the metaverse environment that would make learning difficult. The parts where the Direct Instructional Model was used were one of the possible reasons for disengagement from learning." Another student (2D_#7) added that "One point where I lost focus was during the part where we only listened to the lecture without any screen sharing. I even felt the need to check if anything was being shared on the screen." Similarly, a student (2D_#35) stated that "During the second topic, we were required to sit and just listen to the teacher, but since I was at the computer, I had to press a key. Not pressing anything and staying still caused my attention to fade."

These responses show that since there were not enough dynamic and interactive elements in the second part of the lecture, students felt like passive spectators themselves. The lack of engagement and control in the learning process prevented them from reaching a flow experience state.

In semi-structured interviews, several participants stated that the second lecture in the metaverse environment, which was mostly theoretical and had less interactivity, was the major reason for the decrease in participation and flow experiences (f = 2). One student (2D_Interview_#1) stated that “During the second part of the class, when we were just listening passively, I felt like I was attending like a Zoom session and lost some interest.” Similarly, another student (2D_Interview_#3) stated that “Listening to the lecture without any interaction in the second class led to distraction and disengagement.” The findings from these responses suggest that the lectures in the metaverse environment in which there is overly verbal or theoretical-based instruction may increase the cognitive overload, and the state of flow experiences may be decreased.

Passive instructional delivery hindered flow experience in both groups, which may have balanced any potential difference between 2D and 3D flow scores in the quantitative data.

Main theme 4: Visual complexity as an obstacle for flow experiences

Some participants mentioned the visual complexity of the 2D metaverse environment (f = 3). One student (2D_#17) stated that “Since there were many objects of interest in the virtual environment, I was occasionally distracted while exploring the environment.” Another student (2D_#19) mentioned that “overcrowded spaces . . .” For some students, the abundance and complexity of the visuals in the metaverse environment made it hard to focus attention and engagement in the lectures. This situation may have interrupted their sense of flow experience. While the minimalist design helped some learners, as mentioned before, others found visual complexity overwhelming. This variability in experience may have balanced out in the statistical data, and this resulted in no group difference in flow scores.

4.6.4 Factors decreasing flow experiences in 3D metaverse environment

This section's thematic analyses were based on participants' responses to the question "Which specific aspects of the 3D metaverse environment or the sessions made it difficult to stay focused or engaged in the environment or the learning activity?" and semi-structured interviews. The responses were divided into four main themes, which are "technical problems as barriers to maintaining flow experiences," "visual complexity as an obstacle for flow experiences," "passive instructional delivery hindering flow experiences," and "digital distractions and reduced control as barriers to flow." Findings regarding these themes are explained in the following subsections.

Main theme 1: Technical problems as barriers to maintaining flow experiences

Several participants reported that technical problems significantly reduced their ability to stay engaged during the lessons (f = 12). These problems included frequent network connection problems, audio delays, and lagging. For example, one student (3D_#17) stated that "The technical issues, like lagging and audio dropouts, made it difficult to stay focused in the 3D Metaverse environment." Besides, another participant (3D_#18) also added that "Sometimes I couldn't hear or heard voices late due to the internet. The app even crashed a few times, and these issues made it hard to stay engaged with the lesson." Also, a student (3D_#27) stated that "Even though the issue wasn't directly related to the metaverse platform, things like audio cutting out or 3D elements not loading due to poor internet really disrupted my focus." Based on the responses, these technical problems reduced the students' focus and attention during the lecture. Therefore, this situation may have prevented the immersion and made it difficult to maintain a focus, which is required for the flow experience state.

The nature of attending online to the metaverse environment also contributed to difficulties in maintaining focus (f = 3). Student (3D_#11) stated that "not seeing the instructor or other students in the classroom distracted me." Similarly, student (3D_#28) mentioned that "Connecting from the computer makes it harder to stay focused." Additionally, one student (3D_#37) noted that "I was sitting on the computer so some times I want to just chill on web." These experiences point out the challenge of being disconnected from peers and instructors in a virtual environment, which may have resulted in decreasing the flow experiences.

In addition, extended exposure to the computer screen was another challenge for some students (f = 2). A student (3D_#29) simply said that "looking at the screen constantly." made it difficult to stay focused. Another student (3D_#40) stated that "Since I had to look the screen for a long time during the lesson, I felt more tired than I usually would in a physical class. Reducing the duration of computer-based lessons could make them more efficient." Based on the participants' responses, prolonged digital engagement with the metaverse environment contributed to mental fatigue and disrupted their attention required to sustain flow experiences in the metaverse environment.

These technical challenges may have reduced the effect of the immersive nature of the 3D environment and their impact on flow experiences. Despite its richer design, flow was hindered for some learners due to technical problems, and this situation helps in explaining why 3D did not lead to statistically higher flow experience scores than 2D.

Main theme 2: Visual complexity as an obstacle for flow experiences

Another factor that limited students' flow experiences was caused by the complexity of the environment and overstimulation in the 3D environment. Some students found having freedom in the metaverse environment distracting rather than beneficial (f = 3). One student stated that:

> To be honest, I was in a constant state of movement while listening to the lecture and most of the time involuntarily. In some parts of the lecture, since there was nothing else to do but listen and I saw people moving around, I started to turn around and move left and right and sometimes I realized that I missed what was being said. (3D_#13)

Another student (3D_#24) said that " . . . everyone suddenly moving their characters around sometimes made me laugh, but it was also a bit distracting." Similarly, another student (3D_#36) stated that "It was distracting to have other users walking around randomly during the lesson." Based on the participants' responses, the ability to move freely within the metaverse environment sometimes may have resulted in reduced attention and flow experiences for some students.

Furthermore, the complexity of the virtual environment and simultaneous interactions led to an overloaded learning space for some students (f = 3). A participant (3D_#6) stated that "Too many simultaneous interactions made it difficult to maintain focus." The results show that too much and simultaneous visual interactivity in the environment can overwhelm both the learner and other learners, which may result in reduced immersion and attention, and this situation may lead to a decrease in the flow experience state. This theme aligns with the visual complexity issues mentioned in the 2D group. Although the 3D metaverse environment had greater immersive capacity, its overstimulation became an obstacle for maintaining the flow experience like in the 2D group, which is consistent with the quantitative finding of no significant difference.

Main theme 3: Passive instructional delivery hindering flow experiences

The instructional strategy was also indicated as a limiting factor for flow experiences. Especially, participants stated that more passive and verbal/theoretical parts of the lecture reduced their attention and focus (f = 3). A student (3D_#35) noted that “the verbal topic we covered in the second part of the lesson made it harder for me to stay focused.” Besides, another student (3D_#2) indicated that “The first lesson was more engaging because we had visual elements to focus on. In the second lecture, we were just sitting and listening to the instructor, and it made me feel a bit too relaxed.” From these responses, it can be concluded that when students are only passive recipients of information in the lecture in the metaverse environment, they often struggle to stay mentally engaged. Therefore, this situation interrupts the deep immersion and flow experience state.

In semi-structured interviews, all participants stated that the shift from more interactive (first session) to verbal/theoretical lecture (second session) decreased their engagement and increased their mental effort to stay attentive towards the lecture (f = 4). Related to this, one participant (3D_Interview_#1) stated that “The second part of the class was more theoretical and harder to follow. I lost focus more easily.” Similarly, other participants stated that “The theoretical part lacked visuals, and I think that made it less helpful. The part with the brain visuals was much more effective" (3D_Interview_#3) and "Verbal content is more difficult in this environment. The session with brain visuals was far better than the second session" (3D_Interview_#4). As a result, these responses align with cognitive load theory, in which passive instruction increases mental effort without supporting understanding and also leads to decreasing the flow experience.

As in the 2D group, this suggests that instructional strategy rather than the platform itself is an important factor for flow experiences. Flow experience scores were similar between groups because both environments experienced the same instructional strategy.

Main theme 4: Digital distractions and reduced control as barriers to flow

Despite the benefits of the 3D metaverse learning environment, a student stated the difficulties in maintaining focus due to environmental and physical factors such as screen fatigue, lack of physical supervision, or connecting to the metaverse from informal settings like dorm rooms (f = 1). As an example, a participant (3D_Interview_#1) stated that "Being in my dorm and not needing to turn on my camera made it harder to stay focused. I also felt more tired after class because of screen time." Also, they added that:

> Spending too much time on the computer was obviously more tiring than the classroom environment. We did 2-60 minutes, but I was more tired to do 2-60 minutes on the computer than 2-60 minutes in the classroom. I mean, my eyes hurt a lot, for example, I felt much more tired afterwards. (3D_Interview_#1)

As a result, these distractions may have reduced students' ability to stay fully immersed and absorb the environment efficiently. Despite being less frequently reported than in the 2D group, digital distractions and physical disengagement were still present in 3D settings. These shared challenges further support the finding of statistical similarity in flow scores between both groups.

4.7 Integration of findings

This study used an explanatory sequential mixed-methods design to examine how 2D and 3D metaverse learning environments affected students' cognitive load and flow experiences. Quantitative analysis indicated a statistically significant difference in intrinsic cognitive load between the two groups, and the 3D metaverse environment led to a significantly higher intrinsic load than the 2D environment (U = 1134, z = 3.094, p = .002, $r \approx 0.34$ (medium effect size)). However, there were no significant differences in extraneous cognitive load (U = 796, z = -.200, p = .842), germane cognitive load (U = 811, z = -.058, p = .954), and flow experience scores (U = 786.500, z = -.290, p = .772).

The qualitative results supported and extended these findings. In the 3D group, the primary contributors to cognitive overload were technical problems (32.6%), verbal instructional strategy (9.3%), and lack of physical engagement (7.0%). On the contrary, 74.4% of 3D metaverse participants stated immersive visualization and simulation as optimizing cognitive load, followed by digital learning tools (30.2%) and interactive engagement (16.3%). In the 2D group, cognitive overload was mostly associated with the verbal instructional strategy (13.2%), lack of social interaction (7.9%), and technical problems (7.9%). However, cognitive load was reported to optimize due to the use of visualization and simulation

(63.2%), collaborative tools (21.1%), and interactive engagement (13.2%). In particular, the high frequency of technical problems reported by participants in the 3D group (32.6%) may partially explain the significantly higher intrinsic cognitive load experienced in the 3D metaverse learning environment.

Regarding flow experiences, although no statistical difference was found between groups, qualitative findings revealed that both environments provided distinct flow-enhancing elements, and this balanced the flow experiences between the groups. For the 3D group, immersive and visually rich environments (44.2%), collaborative tasks (44.2%), and realism (34.9%) were the main factors that enhanced flow experiences. However, technological barriers (39.5%) and environmental complexity (14%) were indicated as obstacles for the flow experiences. Similarly, in the 2D group, collaborative learning (36.8%), interactivity (23.7%), and realism (18.4%) enhanced flow experiences, while digital distractions (15.8%) and verbal instruction (10.5%) hindered flow experiences.

The findings were further supported by the data acquired from the semi-structured interview. In terms of cognitive efficiency, every interviewee (100%) from both the 2D and 3D groups mentioned the benefits of interactive and visual learning tools. Simplicity (33.3%) and group work (83.3%) were cited as contributing factors to optimized cognitive load and higher flow experiences in the 2D metaverse group. In addition, 3D participants highlighted immersive realism (100%) and digital tool integration (50%) as crucial elements. Verbal or theoretical lectures were reported to decrease flow experiences and lead to cognitive overload in both groups, with 100% of 3D participants and 33.3% of 2D participants expressing disengagement in such lectures.

When combined with both quantitative and qualitative findings, the integration of findings showed that while the 3D metaverse learning environment provides immersive features that enhance flow experiences, it may also increase intrinsic cognitive load due to technical problems. In this perspective, technological issues may have an indirect impact on intrinsic cognitive load in some circumstances, even if they are mostly linked to extraneous cognitive load. In this way, technological issues (such as simulations that do not load correctly, content that seems distorted or incomplete, or students who are constantly interrupted by network issues) might make the environment or learning materials seem more complicated than they actually are. In these situations, students must use more mental effort to understand the lecture even when the learning content is the same. Technical issues might make the information seem more complex, which causes an increase in the intrinsic cognitive load. On the other hand, the 2D metaverse learning environment, although cognitively less demanding and easier to navigate, may not always be enough to maintain flow experiences due to its lack of immersiveness and realism compared to the 3D metaverse environment. These results highlight the importance of designing metaverse-based learning environments with active instructional strategies, collaboration, interaction, and robust technical infrastructure.

CHAPTER 5

DISCUSSION AND CONCLUSION

This study was aimed at examining the higher education students' cognitive load and flow experiences in 2D and 3D metaverse learning environments. In the scope of this study, participants took the same two-hour lectures in 2D and 3D metaverse learning environments as separate two groups, and their cognitive load and flow experiences during the metaverse-based lectures were investigated through both quantitative and qualitative methods. Quantitative results indicated that there was a statistically significant difference between the 2D and 3D metaverse groups in terms of intrinsic cognitive load scores, and the 3D metaverse environment brought about more intrinsic cognitive load compared to the 2D metaverse environment. However, for the extraneous cognitive load, germane cognitive load, and flow experiences, there were no statistically significant differences between the 2D and 3D metaverse groups. These results show that while the immersive 3D metaverse learning environment resulted in more inherent task complexity for learners (intrinsic load), it did not necessarily cause more distracting elements (extraneous load) and enhance the beneficial processing for learning (germane load) compared to the 2D metaverse learning environment. Similarly, despite the different metaverse environments, participants in both groups reached similar levels of flow experiences (optimal engagement towards the lecture) during the metaverse-based lectures.

Qualitative findings also highlighted and enriched the quantitative findings by providing in-depth explanations related to the main factors that influenced participants' cognitive load and flow experiences during the Metaverse-based lectures. In both environments, participants reported that some factors, such as technical challenges (e.g., audio disruptions or network lag), verbal/theoretical instruction formats (e.g., one-way lecturing or lack of interactivity), a lack of physical engagement, visual complexity, and digital distractions, led to cognitive overload. Conversely, immersive visuals, simulations, interactive tools, and collaborative group activities were mentioned by participants as factors that help them understand the learning material and optimize cognitive load by increasing the germane load. In terms of flow experiences, participants mentioned that factors such as being supported by interactive and game-like features, digital learning tools, realism and a sense of presence, similarity to a real classroom, teamwork opportunities, and a visually engaging metaverse environment resulted in increased flow experiences. However, they also mentioned that their flow experiences were disrupted by technical issues, verbal/theoretical lecture-style sessions, external distractions, and complex visual environments.

This section discussed the results of six research questions with the literature, along with the implications and recommendations for future research and limitations of the study.

5.1 Cognitive load in 2D and 3D metaverse learning environments

Intrinsic cognitive load can be defined as the mental effort or work that is caused by the inherent complexity of the content or the learning task (Sweller, 1994). Some studies in the literature stated that compared to 2D environments, 3D virtual reality environments can decrease the cognitive overload experienced by learners (Dan & Reiner, 2017; Sudar & Csapó, 2024). However, as a finding of this study, the significantly higher intrinsic cognitive load in the 3D metaverse environment suggests that although the 3D environment is more immersive due to its nature, it also made the learning task inherently more complex for students. According to the cognitive load theory, intrinsic cognitive load itself cannot be altered by instructional method because intrinsic cognitive load is based on the specific task or the learning materials (De Jong, 2010; Sweller et al., 2011). However, some researchers have stated that while intrinsic cognitive load is based on the inherent complexity of the content, instructional strategies can still affect how learners experience this load. By progressively increasing the number of interacting elements that students must manage simultaneously, sequencing strategies such as simple-to-complex or part-whole teaching can help manage the perception of difficulty (Pollock et al., 2002; Van Merriënboer & Sweller, 2005). These strategies do not change the inherent complexity of the task, but they change how and when this complexity is presented, thus supporting learners in managing cognitive resources more efficiently.

In this context, the significantly higher intrinsic cognitive load experienced by students in the 3D metaverse environment may not stem solely from the instructional method but also from the interaction between the learning task and the medium, which is the point that Kozma (1994) defended in the media-method debate. According to Kozma (1994), media are not mere delivery vehicles; rather, they interact with instructional methods to shape learning outcomes. In contrast to Clark's (1983) claim that media do not influence learning directly, the findings of this study suggest that the visual-spatial demands and navigation complexity inherent to 3D platforms may have increased the element interactivity of the same learning task, and this situation led to increasing intrinsic cognitive load. In other words, a 3D learning environment may impose a higher intrinsic cognitive load than a 2D one, much like reading a cursive, scribbly font increases a reader's cognitive load compared to plain, legible handwriting (Main, 2022). Therefore, learners may need to split their focus between processing the environment and comprehending the content due to the additional spatial complexity, navigation, and visual elements in 3D. On the other hand, 2D's simplicity eliminates unnecessary cognitive effort by enabling a more direct focus on the educational content.

The finding of this study associated with the higher intrinsic cognitive load in the 3D metaverse learning environment is also supported by the studies in the literature, which suggested that immersive or complex virtual environments can cause more mental effort from learners and higher cognitive load. In the scope of this study, students who took the lectures in the 3D metaverse learning environment may have needed to allocate additional mental resources and effort in navigating, locating, and orienting their avatars in the immersive and complex virtual classroom instead of solely allocating their mental resources towards the learning material. However, this situation may not be the case in the 2D Metaverse learning environment since it has a simplistic and basic nature. In parallel with that, a recent study similarly found that a 360° VR simulation caused significantly higher intrinsic cognitive load than a comparable 2D video, likely due to the "complex virtual environment" and additional stimuli (Chao et al., 2023). It also noted that increased cognitive effort in the immersive environment may affect students' performance adversely if it is not managed well (Sewell et al. 2019). In addition, due to the higher levels of presence and depth perception in 3D environments, they may bring about a greater cognitive overload (Roettl & Terlutter, 2018). Other studies on immersive VR environments and their effects on cognitive load also supported the findings of this study. According to these studies, participants who were in the immersive VR group and performing tasks in immersive VR simulation generally experienced higher cognitive overload compared to other participants who used other instruction methods (Breves

& Stein, 2023; Makransky et al., 2019; Makransky & Petersen, 2021; Petersen et al., 2020). Similarly, Yin et al. (2023) and Liu et al. (2024) stated that participants experienced higher cognitive overload through 3D visual stimuli than 2D visual stimuli based on the analysis of cognitive load with EEG. As a result, authors concluded their study by stating that 3D visual stimuli may lead to more cognitive activities in the brain by inducing higher cognitive load (Liu et al. 2024; Yin et al., 2023). Similarly, Slobounov et al. (2015) stated that immersive 3D VR environments require more brain and sensory resources for cognitive and motor control compared to 2D VR environments. In parallel with this study, findings highlight that the immersive nature of the 3D metaverse environment may provide students with realism and interactivity, which may be potentially beneficial, but it may also bring about some difficulties and complexities (e.g., spatial navigation, orientation in 3D space, and interface controls) that may increase the mental effort during the metaverse-based lectures. In the scope of this study, the medium effect size ($r \approx .34$) for the intrinsic load difference suggests a moderate impact. It can be concluded that because of the complex nature of the 3D Metaverse learning environment, the 3D environment made the learning task and lecture inherently more challenging for students, although the instructional content was equivalent in both 2D and 3D Metaverse groups.

Secondly, participants' extraneous cognitive load in 2D and 3D metaverse groups did not significantly differ. Extraneous cognitive load may stem from the unnecessary or poorly designed elements either in the learning process or learning environment (Sweller et al., 2019). In this study, both groups have similar and relatively low extraneous cognitive load mean scores of approximately 13 points out of 35 points. The similarity of the scores in terms of extraneous cognitive load between the groups indicates that both 2D and 3D Metaverse learning environments were similarly effective in minimizing the external and extraneous distractions during the Metaverse-based lectures. The result of no significant difference in extraneous cognitive load between 2D and 3D environments also supports Clark's (1983) view that media alone do not determine learning effectiveness. Generally, it may be highly expected that the immersive and realistic nature of the 3D Metaverse environment may include more distracting or confusing elements compared to the simplistic characteristics of the 2D Metaverse environment (Richards & Taylor, 2015). For instance, since learners have a larger visual field of view in immersive environments like 3D, which usually increases complexity, studies indicate that immersive environments may increase extraneous cognitive load (Makransky et al., 2021). However, in contrast, the results of this study indicated that participants in the 3D Metaverse environment did not report significantly more mental effort due to the extraneous cognitive load than those in the 2D Metaverse environment. Lee and Wong (2014) stated that by having control over the learning activities thanks to engaging with the dynamic visualizations, students may reduce extraneous cognitive load by adapting the course content to their cognitive abilities. This statement supports the finding of this study in which students used dynamic simulations in both 2D and 3D Metaverse groups. Similar to this study, a study that compared an immersive VR headset, an augmented reality headset, and a standard 2D screen for a training task reported that both participants experienced similar cognitive load in different visualization technologies (Wenk et al., 2023). In that study, participants who used the VR system experienced more motivation and presence; however, they did not experience extra cognitive effort relative to 2D (Wenk et al., 2023). The study by Wenk et al. (2023) supports the idea that the complexity of immersive VR environments can be balanced and compensated through good design and user support. As a result, when the environment is well-designed, the environments, including immersive, traditional, and simplistic, can lead to a similar overall cognitive load (Wenk et al., 2023). In other words, if the 3D environment is designed well based on the design principles, it is possible to decrease the extraneous cognitive load experienced by students in the 3D environment (Sudár & Csapó, 2024). The finding of this study contributes to the literature by highlighting that the immersive environment itself does not necessarily lead to extraneous cognitive load. However, the design and implementation of this environment and support determine the extraneous load experienced by students (Sewell et al., 2019; Sudár & Csapó, 2024; Wenk et al., 2023).

Thirdly, there was no significant difference in participants' germane cognitive load scores between the 2D and 3D metaverse learning environments. Germane cognitive load can be defined as the cognitive effort that a learner devotes to processing and understanding the material (Sweller, 2010). Both groups have similar and relatively high germane cognitive load mean scores of approximately 11 points out of 15 points. The result of no significant difference in germane cognitive load between 2D and 3D environments also supports Clark's (1983) view that media alone do not determine learning effectiveness. These similar germane cognitive load scores between the groups suggest that both the 2D and 3D metaverse learning environments allowed participants to allocate a comparable amount of their mental capacity to constructive learning processes during the lectures. In other words, although 3D metaverse groups experienced higher intrinsic cognitive load, they were able to allocate as much germane effort to learning as the 2D group. This finding may be explained by some aspects of metaverse learning environments, such as being immersive, interactive, and allowing for active participation. For example, 3D visuals and simulation may have helped participants understand the complex topics more clearly, which may balance the high mental effort due to the intrinsic cognitive load. Jian and Abu Bakar (2024) stated that art students training spatial abilities in a VR immersive learning environment had significantly lower cognitive load and better performance compared to those learning via slides and 2D media. In that case, 3D visualization of the VR environment alleviated and eased the cognitive processing that is needed to mentally construct, which shows how immersive technologies can lower cognitive load. Similarly, being able to interact with the multiple representations of the information in learning environments, such as using simulations, may also be the reason for increased germane cognitive load (Bodemer et al., 2004). Besides, the higher social presence due to the immersive nature of metaverse learning environments is aligned with the higher germane cognitive load (Costley, 2019). As a result, the similar germane cognitive load between the Metaverse groups is a positive indication that the 3D environment did not hinder students' ability to engage in deep learning strategies. All in all, with the help of visualizations and simulations, both environments allowed students to focus on understanding the content (germane processing).

Qualitative responses about cognitive load also provide insight into the factors that affected students' cognitive load either positively or negatively. Based on the thematic analysis, participants also reported additional factors such as technical challenges (e.g., audio disruptions, UI problems, and network lag), verbal/theoretical instruction formats, and digital distractions increased their cognitive load.

Due to its relatively high system requirements and realistic graphics, a 3D metaverse learning environment is more likely to create technical problems. In parallel with that, based on the thematic analysis, the participants in the 3D metaverse learning environment mentioned the technical problems more than the 2D metaverse groups, and the quantitative results indicated that the participants in the 3D metaverse learning environments also experienced higher intrinsic cognitive load. As mentioned before, while technical problems are primarily associated with extraneous cognitive load, they may also indirectly affect intrinsic cognitive load in certain situations. In this manner, technical problems (e.g., simulations not loading properly, content appearing incomplete or distorted, or students being interrupted frequently due to connectivity problems) can make the learning material or environment appear more complex than it actually is. In such cases, although the learning content or material remains unchanged, students need to devote more mental effort to comprehend it. Therefore, technical problems can increase the perceived difficulty of the content, which indirectly leads to intrinsic cognitive load. According to Goktas et al. (2015), technical problems experienced in virtual learning environments can influence the pedagogical effectiveness of the environment, which may lead to increased cognitive overload. Therefore, the finding by Goktas et al. (2015) explains another reason for why the participants in the 3D metaverse group experienced more intrinsic cognitive load.

Also, as indicated in this study, other empirical studies mentioned that digital distractions (e.g., multitasking on devices or notifications) significantly increase cognitive processing demands and become an obstacle for retention of the information (Pérez-Juárez et al., 2023). In addition, a passive and verbal lecture format can also increase cognitive overload by making it difficult to retain abstract concepts in memory without interactive support or visual aids. Therefore, social-interactive learning factors are important for positive and active learning experiences in metaverse platforms (Hwang et al., 2023). This situation suggests that solely verbal or theoretical instruction without using any interactive materials in the metaverse learning environment may increase the intrinsic difficulty of complex content, which may lead to cognitive overload.

On the other hand, in addition to visuals, simulations, and interactive tools, collaborative group activities were mentioned by participants as a factor that optimized their cognitive load through the germane load. This finding is also supported by some studies. For example, collaborative group work in a virtual learning environment is in line with higher germane cognitive load, and the amount of collaboration in group work has a positive impact on germane cognitive load (Costley, 2021; Lange et al., 2021). These findings suggest that for better learning outcomes, metaverse-based lectures should mostly be oriented based on collaborative learning.

5.2 Flow experience in 2D and 3D metaverse learning environments

There was no statistically significant difference in participants' flow experience scores between the 2D and 3D metaverse learning environments. Both groups have similar and relatively high flow experience mean scores of approximately 29 points out of 40 points. The result of no significant difference in flow experiences between 2D and 3D environments supports Clark's (1983) view that media alone do not determine learning effectiveness. Generally, compared to a 2D environment, it might be expected that the 3D metaverse learning environment might create a stronger sense of "being there" and engagement due to its realistic similarity to the real classroom environment, and this situation may trigger a higher flow experience state. Yet, quantitative and qualitative findings of this study indicated that participants in both 2D and 3D metaverse learning environments experienced similar and higher flow experience states. This result showed that the 3D metaverse environment itself does not necessarily lead to a higher flow experience state.

From the findings, it could be concluded that the 2D metaverse learning environment could also trigger a higher flow experience state, likely through collaborative activities and interactive elements integrated into the metaverse environment. In the scope of this study, metaverse-based lectures were designed in a way that they included collaborative group tasks and clear objectives, which allowed participants to become absorbed in the lectures. Like metaverse learning environments, including simulations and visuals, in a multimodal learning environment, collaborative activities do provide a sense of flow experiences (Vasiliou et al., 2014). Similarly, according to Van Schaik et al. (2012), immersive virtual environments can induce flow experiences during collaborative learning tasks. Likewise, Nah and Eschenbrenner (2015) found that dyads working collaboratively in virtual worlds achieved higher states of flow experiences compared to individuals working alone. In line with these findings, the collaborative group tasks and interactive tools used in this study likely contributed positively to the participants' flow experience state in both groups in a similar way.

Based on the qualitative data gathered from this study, participants in both 2D and 3D metaverse groups experienced a sense of presence, deep engagement, and enjoyment when the collaborative group activities that were somehow challenging, interactive, and engaging were performed in the lectures. The flow theory supports this finding. According to Csikszentmihalyi (1990), the flow experience emerges when there is an optimal balance between challenge and skill, clear goals, immediate feedback, and unbroken concentration. Likewise, it was stated in an empirical study that the quality of flow experience in 3D environments was shaped by three major factors: the availability of necessary skills to meet challenges, the perception of interactivity within the learning experience, and the degree of presence sensed by learners (Huang et al., 2010). Similar to other studies, Ardura and Artola (2017) also stated that flow experience states in e-learning environments are caused by a sense of control, focused attention, and presence, leading to positive emotions, improved performance, and maintained engagement. Similarly, virtual world environments can promote high levels of interactivity, presence, and flow experiences, particularly in preservice teacher education (Badilla-Quintana & Sandoval-Henríquez, 2021). Also, Ha and Im (2020) stated that interactive visual learning tools in online learning activities can improve students' flow experience and performance. The findings support the results of this study in which participants in both the 2D and 3D metaverse environments mentioned higher flow experiences. Due to its nature, the 3D metaverse environment may bring about high immersion and realism. However, interactive tools, collaborative tasks, and clearly structured learning activities in both 2D and 3D environments have a significant impact on increasing a strong sense of engagement and presence, which are main components of flow experience. On the contrary, if the lectures in metaverse-based learning environments lack collaborative and interactive tasks and are mainly based on verbal/theoretical lecture style, this situation may lead to a decrease in the flow experiences, as participants stated in this study.

Additionally, other studies in the literature provide additional insight into the importance of media characteristics such as avatar usage and immersion on students' flow experience in virtual learning environments. Choi and Baek (2011) stated that media characteristics such as interactivity and representational fidelity in virtual worlds influence students' flow experiences. Forte et al. (2011) similarly stated that interactivity, exploratory behavior, and telepresence are important factors that contributed to students' flow experience in 3D virtual learning environments like Second Life. In addition, Guerra-Tamez (2023) stated that immersion through virtual reality positively impacts the flow experience of art and design students, which mediated their learning experiences. Furthermore, Alblehai (2022) showed that avatar homophily in virtual environments can enhance flow experiences and exploratory behaviors. As a result, these findings provide another perspective about why participants experienced similar and relatively high flow experiences in both 2D and 3D metaverse environments.

Although both 2D and 3D metaverse learning environments led to higher levels of flow experience states, participants also stated several factors that decreased their flow experience states. Firstly, technical issues, such as network problems or platform-related lags, were one of the most commonly mentioned problems in maintaining the flow experience state. This finding is consistent with a prior study that stated technical issues experienced by students negatively affect their motivation and pedagogical guidance within virtual worlds (Coban et al., 2015). Similarly, Alabbasi (2022) mentioned that technical difficulties significantly decrease students' engagement and satisfaction in online learning environments. Furthermore, external distractions were another significant factor that decreased flow experiences, especially in online settings. In this study, participants mentioned that environmental and digital distractions, such as notifications from other applications or easy access to other websites or applications during the lectures, negatively affected their ability to stay focused. In parallel with that, some studies stated external distractions during online lectures can significantly harm students' attention and adversely affect learning performance, even if they are in immersive settings (Adhani & Remijn, 2023; Fisher & Kulshreshth, 2024). Additionally, the visual complexity of the metaverse environment was also mentioned as a disruptive element that decreases flow experience state. While an environmental richness can enhance immersion to some extent, excessive or unnecessary visual elements can overload students' cognitive resources, which may cause decreased flow experiences (Kiluk et al., 2023; Liu & Wang, 2024). Participants in this study similarly stated lots of visuals and crowded virtual spaces distracted them from the learning content, which suggests that minimalistic and purposeful design should be considered in metaverse-based lectures for better flow experiences. All in all, these findings highlight that in order to maintain higher levels of flow experiences in metaverse learning environments, technical reliability, active learning design, minimal visual distractions, and strategies to reduce external distractions must be carefully considered.

5.3 Implications and recommendations for future research

The results of this study showed that some important factors should be considered when 2D and 3D metaverse learning environments will be used for lectures. As indicated in the discussion, the higher intrinsic cognitive load experienced by students in 3D metaverse environments may be due to the complex nature of immersive 3D environments and multiple stimuli in the environment. This situation highlights the importance of the well-designed 3D environment and greater familiarity process of navigation, interaction, and orientation in the immersive learning environment before attending the lectures in the 3D metaverse environment.

In addition, technical problems (such as network or user interface problems) in both 2D and 3D environments increased the students' cognitive overload and disrupted the flow experience. This result shows that instructors who will use metaverse-based education have to make sure that their students have good internet connections when connecting to the metaverse-based lectures and that their systems or computers meet the requirements needed to use the metaverse platforms with realistic graphics without any problems. More importantly, developers must also optimize the metaverse-based learning environments as much as possible to make them smoothly and fluently usable on any computer or system without high system requirements. Therefore, technical support mechanisms, user-friendly interfaces and environments, and also easily accessible platforms should be provided in the Metaverse-based learning environments. These are critical for better learning experiences with lower cognitive load and higher flow experiences during the metaverse-based lectures.

On the other hand, the immersive simulations, visual elements, and sense of social presence thanks to metaverse environments supported a higher flow experience state for both 2D and 3D metaverse groups. Especially, tools such as visualization, interactive whiteboards, simulation, and group work increased germane cognitive load by supporting active cognitive processing for learning. This finding suggests that when designing a metaverse-based lecture, not only visuality but also interaction and collaboration should be the core of the lecture.

One of the important findings of this study is related to the lecture format. The findings showed that in both 2D and 3D metaverse learning environments, verbal and theoretical lectures increased students' cognitive overload and decreased their flow experience in the metaverse-based lectures. Therefore, in the metaverse-based lectures, it is recommended to avoid prolonged passive lecture methods. Instead, interactive elements (e.g., simulations, visuals, quizzes, and group discussions) should be integrated frequently into some parts of the lecture to support students' active participation and optimize cognitive load. Also, dividing the theoretical content into small pieces and presenting them interactively can help students maintain their attention and process information more effectively. In addition, turning theoretical knowledge into problem-based, case-based, or discovery-based learning activities can make the abstract concepts concrete by using the experiential advantages of metaverse learning environments. As a result, besides the technical facilities, the pedagogical design of the lecture in metaverse environments had a direct impact on flow experiences and cognitive load. In conclusion, it is important to balance verbal lecture with interactive and experiential learning strategies to support students' flow experience state and optimize cognitive load in metaverse environments.

In terms of future research about this topic, longitudinal and repeated-measures studies should be conducted to see the effects of 2D and 3D metaverse learning environments on cognitive load and flow experiences in long-term use. Also, the generalizability of the findings should be tested by using larger samples from various disciplines and age groups. In addition, objective measurement methods (e.g., eye tracking, behavioral analysis, physiological measurements) should be used to measure cognitive load and flow experiences not only based on self-reports but also behaviorally. Also, the effects of metaverse learning environments on cognitive load and flow experiences should be compared in different disciplines (e.g., between more visual and spatial courses such as chemistry, physics, and mathematics and more abstract and theoretical courses such as philosophy and law). Future research could be conducted in more standardized and technically adequate settings in which the risk of performance problems (e.g., lags, disconnections) is minimized. In this way, it might be possible to more effectively isolate the effects of the learning environment itself by using optimal and ideal technical setups for each participant. Finally, studies comparing different metaverse platforms (e.g., 2.5D, fully immersive with VR headset) should be conducted, and the technical and pedagogical effects of these different platforms should be investigated in detail.

5.4 Limitations of the study

This study had some limitations. There were 38 participants in the 2D metaverse group and 43 participants in the 3D metaverse group, which may be considered a limited sample size. Additionally, the participants were selected from one university and one department. Therefore, this situation may narrow the generalizability of the findings to different demographic groups or other disciplines. Furthermore, since both participants connected to the metaverse platforms online from their personal computers, there was not full control over the learning environment, and participants were more likely to encounter external distractions during the lectures. There are some technical limitations in this study. The differences of the devices used by the participants (such as computer hardware and internet connection speed) were not systematically controlled. Therefore, due to the differences in devices and internet connection, some participants may have experienced performance or network problems (e.g., lags, disconnections) compared to other participants. Another limitation is that cognitive load and flow experiences were measured with self-report instruments. These instruments are based on the subjective perceptions of the participants and may not always accurately reflect the changes or differences in cognitive load and flow experiences. Also, the study used Gather.Town (a 2D metaverse platform) and MetaClass (a 3D metaverse platform) developed by the researcher. Different results may be obtained when using different platforms (e.g., more advanced VR systems or simpler 2D environments) because different platforms offer different levels of immersion, interactivity, usability, and technical stability, and all of them can influence cognitive load and flow experiences. Therefore, the findings obtained in the scope of this study were based on these two metaverse learning platforms. Finally, the duration of the study was short-term. Students' cognitive load and flow experiences were measured based on two-hour lectures in the metaverse learning environments. Therefore, the results may change with long-term use of these platforms. Considering these limitations, it is important for future studies to deepen this research topic with larger samples, long-term designs, and multiple and objective measurement methods.

APPENDIX A

THE COGNITIVE LOAD SCALE

Please read each statement below carefully and choose the most appropriate option for you.

For each statement, you will choose one of the following options:

1. Strongly Disagree – You completely disagree with the statement.
2. Disagree – You mostly disagree with the statement.
3. Neither Agree nor Disagree – You neither agree nor disagree, or you are neutral.
4. Agree – You mostly agree with the statement.
5. Strongly Agree – You completely agree with the statement.

Statement	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)
1. The topic covered in the VR instruction was very complex.					
2. The VR instruction covered procedures that I perceived as very complex.					
3. This VR instruction covered concepts and definitions that I perceived as very complex.					
4. The instruction and/or explanation used in the VR material were very unclear.					
5. The instructions and explanations used in the VR material were very effective for learning.					
6.The instructions and/or explanations used in the VR material were full of unclear content.					
7. The elements in the virtual environment made learning very unclear.					
8. The virtual environment was very effective in terms of learning.					
9. The virtual environment was full of irrelevant content.					
10. It was difficult to find the relevant learning information in the virtual environment.					
11. The simulation truly enhanced my understanding of the topics covered.					
12. The simulation truly enhanced my understanding of the parts of the brain and their functions.					
13. The simulation truly enhanced my understanding of concepts and definitions.					

APPENDIX B

THE FLOW EXPERIENCE SCALE

Please read each statement below carefully and choose the most appropriate option for you based on your experience in the metaverse learning environment.

For each statement, you will choose one of the following options:

1. Strongly Disagree – You completely disagree with the statement.
2. Disagree – You mostly disagree with the statement.
3. Neither Agree nor Disagree – You neither agree nor disagree, or you are neutral.
4. Agree – You mostly agree with the statement.
5. Strongly Agree – You completely agree with the statement.

Statement	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)
1. I felt in control of what I was doing during the learning activity.					
2. I was absorbed intensely by the activity.					
3. I found the activity enjoyable.					
4. I found the activity interesting.					
5. I was completely immersed in this learning activity.					
6. During the learning activity, time seemed to pass fast.					
7. The activity excited my curiosity.					
8. I knew the right thing to do in the learning activity.					

APPENDIX C

REFLECTION FORM

This reflection form is designed to help you express your experiences during the learning sessions in the 2D/3D metaverse learning environment. Please reflect on your cognitive and emotional experiences based on your experience in the 2D/3D metaverse learning environment.

1) Which specific aspects of the 2D/3D metaverse environment or the sessions made you feel overwhelmed or made the information difficult to process?

2) Which specific aspects of the 2D/3D metaverse environment or the sessions made the information easier to understand or process?

3) Which specific aspects of the 2D/3D metaverse environment or the sessions contributed to feeling completely absorbed or deeply engaged in the environment or the learning activity?

4) Which specific aspects of the 2D/3D metaverse environment or the sessions made it difficult to stay focused or engaged in the environment or the learning activity?

APPENDIX D

SEMI-STRUCTURED INTERVIEW PROTOCOL

Time of interview:

Date:

Interviewee:

Interviewer: Emre Yıldırım

Position of interviewee: One-on-one

English Version	Turkish Version
Hello, My name is Emre Yıldırım. First of all, thank you very much for agreeing to participate in this interview. As part of my master's thesis, I will ask you questions about your experience in the 2D/3D metaverse-based learning environment. The aim of this interview is to better understand your cognitive load and flow experience during the lesson. Your responses will only be used for research purposes and your identity will remain confidential. The interview will last approximately 20–25 minutes. I would also like to audio-record this interview. Is that okay for you? Thank you! I will begin by asking some questions about the moments you found difficult during the lesson.	Merhaba, ben Emre Yıldırım. Öncelikle bu mülakata katılmayı kabul ettiğiniz için çok teşekkür ederim. Yüksek lisans tezim kapsamında sizlere, 2D/3D Metaverse tabanlı bir öğrenme ortamında gerçekleştirilen ders deneyiminizle ilgili sorular yönelteceğim. Bu görüşmenin amacı, ders sırasında yaşadığınız bilişsel yük ve akış (flow) durumlarını daha iyi anlamaktır. Paylaşacağınız görüşler yalnızca araştırma kapsamında değerlendirilecek ve kimlik bilgileriniz gizli tutulacaktır. Görüşme yaklaşık 20-25 dakika sürecek. Konuşmalarımızı sesli olarak kaydetmek istiyorum. Sizin için uygun mudur? Teşekkürler! İlk olarak, ders sırasında zorlandığınız anlarla ilgili bazı sorularla başlayacağım.

[Cognitive Load – Bilişsel Yük]

1. Can you describe moments during the 2D/3D metaverse-based lesson when you had difficulty understanding the topic or found it complicated?
   → *2 boyutlu/3 boyutlu Metaverse ortamında yaptığımız derste benim anlattığım konuları anlamakta zorlandığın veya anlattıklarımı karmaşık bulduğun anlardan bahsedebilir misin?*

2. What factors in the 2D/3D environment do you think contributed to those difficulties? What made you feel this way?
   → *2 boyutlu/3 boyutlu öğrenme ortamında bu zorluklar üzerinde etkili olduğunu düşündüğün faktörler nelerdi? Neler bu hisse kapılmanda etkili oldu?*

3. What changes in the environment or content do you think could help reduce the difficulties or confusion you experienced?
   → *Bu yaşadığın zorluk ya da karmaşıklık hissine kapılmamak için ortamda veya içerikte nasıl bir değişiklik yapılması gerektiğini düşünüyorsun?*

4. Did you feel as if you were in a real classroom during the 2D/3D metaverse lesson?
   → *2 boyutlu/3 boyutlu* metaverse ortamındaki ders sırasında kendini gerçek bir sınıf ortamında hissedebildin mi?

5. Do you think taking this lesson in a simpler/immersive 2D/3D metaverse environment would help overcome these difficulties? Why or why not?
   → *Daha basit/gerçekçi 2 boyutlu/3 boyutlu bir metaverse ortamında bu dersi almak, bu zorlukların üstesinden gelmende fark yaratır mıydı? Neden?*

[Flow – Akış Durumu]

6. Can you describe moments during the 2D/3D metaverse lesson when you felt completely focused? What features of the environment or activity contributed to those moments?
   → 2 boyutlu/3 boyutlu *metaverse ortamında yaptığımız ders sırasında kendini tamamen derse odaklanmış hissettiğin anlardan bahseder misin? Bu anlara katkı sağlayan ortamdaki veya etkinlikteki özellikler nelerdi?*

7. What features should be added or changed in the 2D/3D metaverse environment to help you concentrate better during the lesson?
   → *2 boyutlu/3 boyutlu metaverse ortamında anlatılan derse daha çok odaklanmanı sağlamak için hangi özelliklerin eklenmesi veya değiştirilmesi gerektiğini düşünüyorsun?*

8. How would taking the same lesson in a simpler/immersive 2D/3D metaverse environment affect your focus and interest? Why?
   → *Daha basit/gerçekçi 2 boyutlu/3 boyutlu bir Metaverse ortamında bu dersi almak, odaklanmanı ve derse olan ilgini sürdürmeni nasıl etkilerdi? Neden?*

APPENDIX E

INFORMED CONSENT FORM

Research sponsoring institution: Boğaziçi University
Title of the research project: Examining Higher Education Students' Cognitive Load and Flow in 2D and 3D Metaverse Learning Environments
Thesis Advisor: Assist. Prof. Oğuz Ak
Researcher: Emre Yıldırım

Dear Students,

Assist. Prof. Oğuz Ak and Emre Yıldırım from the Department of Computer Education and Educational Technology at Boğaziçi University are carrying out a scientific research project. The research aims to examine higher education students' cognitive load and flow in 2D and 3D metaverse learning environments.

As Computer Education and Educational Technology students, you will engage in lessons and learning activities that explore the students' cognitive load and flow experiences during the use of 2D and 3D Metaverse learning environments. If you volunteer for this research, your participation will include attending lessons and completing activities within these platforms as part of your regular course schedule for 2 hours. You will also be asked to complete forms and scales assessing your cognitive load and flow experiences. Additionally, with volunteer participants, semi-structured interviews will also be conducted on the Zoom platform to gather qualitative insights into your experiences. Audio recording will be taken during the semi-structured interviews. Your participation in the study is entirely voluntary, and your identities will be kept confidential throughout the research process. At any time, without penalty, you are free to choose not to participate or to withdraw from the study. If you choose to stop participating, your demographic information form, cognitive load scale, flow experience scale, reflection form, interview recordings, and all the related materials or data related to you will be removed from the data. There will be no fee, extra credit, or any kind of reward for participation; however, your involvement will contribute significantly to research aimed at improving educational technology practices and understanding the impact of VR-based metaverse learning environments. Upon completion of the study, all stored data will be completely destroyed. There are no known risks or inconveniences associated with this study.

Please ask if you have any questions about the study before signing this form. If you have any questions later, you can ask the thesis advisor Assist. Prof. Oğuz Ak or the researcher Emre Yıldırım. You can also consult Boğaziçi University Social and Human Sciences Human Research Ethics Committee regarding your rights in this study.

I have read the text above and understood the scope and purpose of the research I was asked to participate in. I realized that I could quit this study whenever I wanted, without giving any reason, and that I would not encounter any negativity if I quit.

Participant Name-Surname: ………………………………….. I approve to participate in the study. YES ☐ NO ☐ I volunteer to participate in the semi-structured interview, and I give permission for the audio recording of the interview session. YES ☐ NO ☐ Date (day/month/year): ..../........./........	Researcher Name-Surname: Emre Yıldırım

APPENDIX F

DEMOGRAPHIC INFORMATION FORM

This form aims to gather information about your background and experience with the metaverse and computer gaming habits.

Age: ________

Gender:
Male ☐
Female ☐
Other ☐

Grade Level:
1st Year (Freshman) ☐
2nd Year (Sophomore) ☐
3rd Year (Junior) ☐

Have you ever used a metaverse platform (e.g., Second Life, Gather.town, Decentraland)?
Yes ☐
No ☐

If yes, which metaverse platform(s) have you used? (Select all that apply)
Second Life ☐
Gather.town ☐
Decentraland ☐
Roblox ☐
Others (Please specify): ____________________

How frequently do you use metaverse platforms?
Daily ☐
Weekly ☐
Monthly ☐
Rarely ☐
Never ☐

Do you play computer or console games?
Yes ☐
No ☐

If yes, how often do you play video/computer games?
Daily ☐
Several times a week ☐
Weekly ☐
Several times a month ☐
Rarely ☐
Never ☐

How many hours do you spend playing video/computer games per day on average?
0-1 hour ☐
1-2 hours ☐
2-4 hours ☐
4-6 hours ☐
More than 6 hours ☐
Never ☐

What type of games do you usually play? (Select all that apply)
First-Person Shooter (FPS) ☐
Role-Playing Games (RPG) ☐
Simulation Games ☐
Puzzle/Strategy Games ☐
Multiplayer Online ☐
Sports Games ☐
Adventure/Exploration Games ☐
Educational Games ☐
Others (Please specify): ____________________

How long have you been playing computer/video games?
Less than 1 year ☐
1-3 years ☐
4-6 years ☐
More than 6 years ☐

APPENDIX G

DEMOGRAPHIC INFORMATION (2D GROUP)

2D Metaverse Group	Number	Percentage (%)
Gender		
Male	25	65.8
Female	13	34.2
Age		
18-20	10	26.3
21-23	23	60.5
24+	5	13.2
Grade Level		
1st Year (Freshman)	9	23.7
2nd Year (Sophomore)	19	50.0
3rd Year (Junior)	10	26.3
Have participants ever used a Metaverse platform?		
Yes (Roblox, Second Life, Decentraland, VR Chat, Minecraft, Habbo)	17	44.7
No	21	55.3
How frequently do participants use Metaverse platforms?		
Never	21	55.3
Rarely	16	42.1
Daily	1	2.6
Do participants play computer or console games?		
Yes	31	81.6
No	7	18.4
How often do participants play video/computer games?		
Daily	3	7.9
Several times a week	8	21.1
Weekly	5	13.2
Several times a month	9	23.7
Rarely	6	15.8
Never	7	18.4
How many hours do participants spend playing video/computer games per day on average?		
0-1 hour	17	44.7
1-2 hours	8	21.1
2-4 hours	4	10.5
4-6 hours	1	2.6
More than 6 hours	1	2.6
Never	7	18.4
What type of games do participants usually play? (Multiple answers possible)		
First-Person Shooter (FPS)	15	13.4
Role-Playing Games (RPG)	12	10.7
Simulation Games	20	17.9
Puzzle/Strategy Games	14	12.5
Multiplayer Online	20	17.9
Sports Games	12	10.7
Adventure/Exploration Games	13	11.6
Educational Games	4	3.6
Moba	1	0.9
Card Games	1	0.9
How long have participants been playing computer/video games?		
Less than 1 year	6	15.8
1-3 years	3	7.9
More than 6 years	29	76.3

APPENDIX H

DEMOGRAPHIC INFORMATION (3D GROUP)

3D Metaverse Group	Number	Percentage (%)
Gender		
Male	20	46.5
Female	21	48.8
Other	2	4.7
Age		
18-20	14	32.6
21-23	26	60.5
24+	3	7.0
Grade Level		
1st Year (Freshman)	12	27.9
2nd Year (Sophomore)	25	58.1
3rd Year (Junior)	6	14.0
Have participants ever used a Metaverse platform?		
Yes (Roblox, Second Life, Decentraland, Minecraft)	17	39.5
No	26	60.5
How frequently do participants use Metaverse platforms?		
Never	26	60.5
Rarely	17	39.5
Do participants play computer or console games?		
Yes	31	72.1
No	12	27.9
How often do participants play video/computer games?		
Daily	5	11.6
Several times a week	9	20.9
Weekly	4	9.3
Several times a month	7	16.3
Rarely	6	14.0
Never	12	27.9
How many hours do participants spend playing video/computer games per day on average?		
0-1 hour	14	32.6
1-2 hours	10	23.3
2-4 hours	7	16.3
Never	12	27.9
What type of games do participants usually play? (Multiple answer possible)		
First-Person Shooter (FPS)	19	15.3
Role-Playing Games (RPG)	18	14.5
Simulation Games	15	12.1
Puzzle/Strategy Games	17	13.7
Multiplayer Online	23	18.5
Sports Games	10	8.1
Adventure/Exploration Games	19	15.3
Educational Games	3	2.4
How long have participants been playing computer/video games?		
Less than 1 year	9	20.9
1-3 years	3	7.0
4-6 years	4	9.3
More than 6 years	27	62.8

APPENDIX I

LESSON PLAN

Grade Level: First-year, second-year, and third-year university students

Duration: 120 minutes

Topic: Introduction to the Structure of the Brain, Cognitive Load Theory, and Cognitive Theory of Multimedia Learning

Objectives:

- Students will be able to identify the major parts of the brain.
- Students will be able to describe the basic functions of the major parts of the brain.
- Students will be able to explain the three types of cognitive load.
- Students will be able to differentiate the three types of cognitive load from each other.
- Students will be able to explain how to optimize cognitive load based on the cognitive load type.
- Students will be able to describe the key assumptions of the cognitive theory of multimedia learning.

Materials used in the metaverse learning environment:

- For 2D Metaverse Group:
  - 2D web-based simulation of the brain integrated into the 2D Metaverse environment.
  - Schematic representation of the cognitive theory of multimedia learning integrated into the 2D Metaverse environment.
- For 3D Metaverse Group:
  - 3D brain simulation integrated into the 3D Metaverse environment.
  - Schematic representation of the cognitive theory of multimedia learning integrated into the 3D Metaverse environment.

Body of the Lesson

1. Introduction (10 minutes):

- Overview:
  - The instructor will provide an outline of the lesson, explaining that the first hour will focus on understanding the structure of the brain through simulation and modeling, while the second hour will focus on the Cognitive Load Theory and Cognitive Theory of Multimedia Learning.
  - The instructor will briefly introduce the topic of the brain and its importance in human cognition.

- Engagement:
  - The instructor will ask some questions to catch students' attention towards the lesson:
    - What are some major parts of the brain you know of?
    - Can you think of any functions that the brain performs that are crucial for our daily lives?

2. Part 1: Brain Structure and Its Function (Simulation/Modeling-based Lecture) (50 minutes):

- Lecture (25 minutes):
  - In the first part of the lecture, the instructor will begin with a detailed explanation of the brain's anatomy using brain simulation:
    - For 2D Metaverse Group: The instructor will use a 2D web-based brain simulation to teach students the different parts of the brain (e.g., frontal lobe, cerebellum, parietal lobe) and their respective functions.

        - For 3D Metaverse Group: The instructor will use a 3D brain model to teach students the different parts of the brain (e.g., frontal lobe, cerebellum, parietal lobe) and their respective functions.
- Interactive Group Activity (20 minutes):
    - After the lecture part, the instructor will want students to divide into small groups in the metaverse and give a task:
        - Task: Each group will explore a specific part of the brain using the 2D brain simulation or 3D brain model, discuss its function and discuss what health problems or consequences may occur if this specific part of the brain is damaged.
    - After the group discussion, each group will share their findings with the class to foster collaborative and active learning in the metaverse learning environment.
- Q&A Session (5 minutes):
    - The instructor will allow students to ask questions about the brain structure and its functions to ensure that students understand the structure of the brain and its functions before moving on to cognitive load theory and cognitive theory of multimedia learning.

3. Part 2: Cognitive Load Theory, and Cognitive Theory of Multimedia Learning (Verbal/Theoretical Lecture) (60 minutes):

- Lecture (25 minutes):
    - In the second part of the lecture, the instructor will introduce cognitive load theory and the cognitive theory of multimedia learning verbally by:
        - Defining cognitive load and explaining its types (intrinsic, extraneous, and germane).
        - Discussing how multimedia learning occurs and involves the integration of visual and auditory information and how cognitive load affects this process by using the schematic representation of the cognitive theory of multimedia learning.
- Interactive Group Activity (20 minutes):
    - After the lecture part, the instructor will want students to divide into small groups in the metaverse and give a task:
        - Task: Students will work in groups to discuss cognitive load theory and the cognitive theory of multimedia learning by:
            - Discussing the characteristics of a multimedia environment designed to optimize the students' cognitive load
    - After the group discussion, each group will share their findings with the class to foster collaborative and active learning in the metaverse learning environment.
- Q&A Session (5 minutes):
    - The instructor will allow students to ask questions about the cognitive load theory and cognitive theory of multimedia learning to ensure that students understand the main assumptions and their implications of these theories.

4. Conclusion (10 minutes):

- Wrap-up
    - The instructor will summarize the key points covered in the lesson by emphasizing the structure and main functions of the brain and the core concepts of the cognitive load theory and cognitive theory of multimedia learning.

APPENDIX J

ETHICAL APPROVAL OF THE STUDY

T.C.
BOĞAZİÇİ ÜNİVERSİTESİ REKTÖRLÜĞÜ
Sosyal ve Beşeri Bilimler İnsan Araştırmaları Etik Kurulu (Sbinarek)

Sayı : E-84391427-050.04-206452 14.11.2024
Konu : 2024-70T Kayıt Numaralı Başvurunuz
Hakkında

Sayın Dr. Öğr. Üyesi Oğuz AK

Tez danışmanlığını yürüttüğünüz öğrenciniz Emre Yıldırım'ın "Examining Higher Education Students' Cognitive Load and Flow in 2D and 3D Metaverse Learning Environments" başlıklı projesi ile Boğaziçi Üniversitesi Sosyal ve Beşeri Bilimler İnsan Araştırmaları Etik Kurulu (SBİNAREK)'e yaptığınız 2024-70T kayıt numaralı başvuru 30.10.2024 tarih ve 2024/08 sayılı kurul toplantısında incelenmiş ve projeye etik onay verilmesi uygun bulunmuştur.

Bu karar tüm üyelerin toplantıya on-line olarak katılımıyla ve oybirliği ile alınmıştır. Onay mektubu tüm üyeler adına Komisyon Başkanı tarafından e-imzalanmıştır. Bilgilerinizi rica ederiz.

Saygılarımızla,

Dr. Öğr. Üyesi Işıl ERDUYAN
Kurul Başkanı

APPENDIX K

TRANSLATED QUOTATIONS

Participant ID	Turkish Version	English Version
2D_Interview_#4	2 boyutlu ortam dengeli bir alan gibi hissettirdi. Ne Zoom kadar sade ne de bir oyun kadar eğlenceli. Çok fazla görsel dikkat dağıtıcı olmadığı için derse daha iyi odaklanabildim.	The 2D environment felt like a balanced space—neither too plain like Zoom nor too playful like a game. Because it didn't contain too many visual distractions, I could concentrate better on the lecture.
2D_Interview_#5	3 boyutluya kıyasla bence 2 boyutlu ortamın sadeliği dersi takip etmeyi ve içeriği anlamayı kolaylaştırdı.	I believe the simplicity of the 2D environment, compared to 3D, made it easier to follow the lesson and understand the content.
2D_Interview_#6	Kişisel bilgisayarımı kullandığım için zaman zaman internette gezinirken veya mesajlara bakarken buldum kendimi. Metaverse'deki denetim eksikliği odaklanmayı zorlaştırdı.	Because I was using my personal computer, I occasionally found myself browsing the internet or getting distracted by messages. The lack of supervision in metaverse made it easier to lose focus.
2D_Interview_#1	Bazen bilgisayardan uzaklaşıp arkama yaslanıyordum bu durum da beni zihinsel olarak dersten uzaklaştırıyordu. Aynı cihazı eğlence için de kullandığım için derse bağlı kalmak daha zordu.	I sometimes drifted away from the computer and leaned back, which made me mentally distant from the class. Since it's the same device I use for entertainment, staying engaged was harder.
2D_Interview_#1	Beyin simülasyonuna doğrudan erişebilmek odaklanmayı sürdürmek için harika bir yoldu.	Having direct access to the brain simulation was a great way to stay focused.
2D_Interview_#4	Görsel ve etkileşimli öğeler özellikle simülasyon ve beyaz tahta etkinlikleri dersi normal derslere kıyasla	The visual and interactive elements, especially the simulation and whiteboard activities, made the class more enjoyable and easier to

	daha keyifli ve anlaşılır hale getirdi.	understand than traditional lectures.
2D_Interview_#2	Gruplara ayrıldığımızda ve beyaz tahta üzerinde birlikte çalıştığımızda gerçekten fiziksel bir sınıftaymışım gibi hissettim.	When we divided into groups and worked together on the whiteboard, I truly felt like I was in a physical classroom.
2D_Interview_#4	Ortak kullandığımız dijital araçlar beni derse daha bağladı ve heyecanlı hissettirdi, özellikle de içeriği başkalarıyla birlikte manipüle edebilmek.	Those shared digital tools made me feel more connected and excited about the class, especially being able to manipulate content with others.
2D_Interview_#3	3 boyutlu bir ortamda karakterler ve çevre nedeniyle çok fazla dikkatim dağılabilirdi ve derse odaklanmam zorlaşabilirdi.	In a 3D environment, I might get too distracted by the characters and surroundings and lose focus on the lecture.
2D_Interview_#6	Dersi 3 boyutlu ortamda almayı tercih ederdim çünkü daha gerçekçi ve ilgi çekici hissettiriyor.	I would have preferred to take the course in a 3D setting because it feels more realistic and engaging.
2D_Interview_#1	Dersin ikinci bölümünde sadece pasif olarak dinlediğimizde, sanki bir Zoom dersine katılıyormuşum gibi hissettim ve ilgim azaldı.	During the second part of the class, when we were just listening passively, I felt like I was attending like a Zoom session and lost some interest.
2D_Interview_#3	İkinci derste herhangi bir etkileşim olmadan dersi dinlemek dikkat dağınıklığına ve kopmaya neden oldu.	Listening to the lecture without any interaction in the second class led to distraction and disengagement.
2D_Interview_#2	Gerçek hayattaki derslere kıyasla metaverse'de derse katılmak beni daha rahat hissettirdi. Nedenini tam bilmiyorum ama bilgisayar başında olmak ve bir şeyleri grupça yapmak motivasyonumu ve odağımı artırdı.	Compared to real-life classes, I felt more relaxed attending in the metaverse. I don't know exactly why, but being behind a computer and doing things together as a group helped increase my motivation and focus.

3D_Interview_#4	2 boyutlu ortama kıyasla, 3 boyutlu benim için daha iyiydi. Daha gerçekçi ve gerçek bir sınıfa daha yakın hissettirdi. 2 boyutluda öğrenmek daha zor olurdu diye düşünüyorum.	Compared to the 2D environment, 3D was better for me. It felt more real and closer to a real classroom. I think learning in 2D would have been more difficult.
3D_Interview_#2	2 boyutlu metaverse'de sadece bir ekrana bakıyormuş gibi hissederdim. 3 boyutluda sınıfın içindeymişim gibi hissettim.	In a 2D metaverse, I'd feel like I'm just watching a screen. In 3D, I felt like I was inside the classroom.
3D_Interview_#1	Neden 2 boyutlu bir dünyada öğreneyim ki, biz 3 boyutlu bir dünyada yaşıyoruz? 2 boyutlu bir ortamı ciddiye almak daha zor olurdu.	Why would I learn in a 2D world when we live in a 3D one? A 2D environment would be harder to take seriously.
3D_Interview_#2	Simülasyonu keşfederken dersi dinlemek odaklanmama yardımcı oldu. Duyduklarımı gördüklerimle birleştirebildim.	Listening to the lecture while exploring the simulation helped me focus more. I could combine what I was hearing with what I was seeing.
3D_Interview_#4	Beynin bölümlerine dokunabildiğimde ve bilgiler çıktığında öğrenmek çok daha kolay ve keyifli hale geldi.	When I could touch the parts of the brain and information would appear, it made learning much easier and more enjoyable.
3D_Interview_#1	Metaverse, karmaşık içeriği gerçekten sadeleştirmeye yardımcı olan çok güzel görselleştirme araçları sundu.	The metaverse allowed for excellent visualization tools that really helped simplify complex content.
3D_Interview_#1	Grup çalışması sırasında daha odaklı ve aktif hissettim. Pasif öğrenmeye göre çok daha verimli ve ilgi çekiciydi.	During group work, I felt more focused and active. It was much more efficient and engaging than passive learning.

3D_Interview_#4	Grup çalışması gerçekten gerçek bir sınıftaymışız gibi hissettirdi. Bir ekip olarak düşündük ve tartıştık, bu da içeriği daha iyi anlamama yardımcı oldu.	Group work really made it feel like a real classroom. We thought and discussed as a team, and that helped me understand the content better.
3D_Interview_#1	Herkesin aynı alanda beyaz tahtaya yazabilmesi harikaydı. Notlar bölümünü de çok kullandım organize olmama yardımcı oldu.	It was great that everyone could write on the whiteboard and work together in the same space. I also used the notes section a lot—it helped me stay organized.
3D_Interview_#4	Beyaz tahta ve grup tartışmalarımız çok verimliydi. Bu araçlar kesinlikle yardımcı oldu.	The whiteboard and our discussions as a group were very productive. These tools definitely helped.
3D_Interview_#1	Yurttayken ve kameramı açmam gerekmeyince odaklanmak zorlaştı. Ayrıca ekran süresi yüzünden dersten sonra daha yorgun hissediyordum.	Being in my dorm and not needing to turn on my camera made it harder to stay focused. I also felt more tired after class because of screen time.
3D_Interview_#1	Bilgisayar başında çok fazla zaman geçirmek sınıf ortamından daha yorucuydu. 60 dakikalık 2 ders yaptık ama bilgisayarda bu daha yorucuydu. Mesela gözlerim çok ağrıdı, sonrasında çok daha yorgun hissediyordum.	Spending too much time on the computer was obviously more tiring than the classroom environment. We did 2-60 minutes, but I was more tired to do 2-60 minutes on the computer than 2-60 minutes in the classroom. I mean, my eyes hurt a lot, for example, I felt much more tired afterwards.
3D_Interview_#1	Dersin ikinci bölümü daha teorikti ve takip etmesi daha zordu. Odaklanmayı daha kolay kaybettim.	The second part of the class was more theoretical and harder to follow. I lost focus more easily.
3D_Interview_#3	Teorik kısım görselden yoksundu ve bu yüzden daha az faydalıydı. Beyin görselleri olan kısım çok daha etkiliydi.	The theoretical part lacked visuals, and I think that made it less helpful. The part with the brain visuals was much more effective.

3D_Interview_#4	Sözel içerik bu ortamda daha zorlayıcı. Beyin görselleri olan oturum ikinci oturumdan çok daha iyiydi.	Verbal content is more difficult in this environment. The session with brain visuals was far better than the second session.
3D_Interview_#4	Biraz kaygım var, bu yüzden gerçek bir sınıftansa bu ortamda öğrenmek benim için daha rahat. Sorulara cevap vermek daha kolay oluyor.	I have some anxiety, so I actually feel more comfortable learning in this environment than in a real classroom. It helps me respond to questions more easily.

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