



# Learning, motivation, gender, and epistemic emotions: how are they connected in the context of immersive virtual reality?

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## Abstract

Emotions shape cognitive processes, motivation, and academic outcomes. Among these, epistemic emotions have significant impacts on intellectual engagement. The increasing utilization of immersive virtual reality (ImVR) in education enhances the potential for emotion-driven learning experiences due to its capacity to create absorbing and emotionally evocative environments. Despite ImVR's transformative potential, limited research has examined the dynamic interplay of epistemic emotions and their influence on learning motivation and academic performance. For that matter, the study developed and tested a model to analyze how positive and negative epistemic emotions interact, shape learning outcomes and motivation, and vary by gender in ImVR contexts. An application able to evoke emotions was selected and 124 university students participated in the study. Findings revealed that positive epistemic emotions, particularly enjoyment, curiosity, and surprise enhanced both motivation and learning. Enjoyment emerged as the most impactful factor, suppressing negative emotions such as anxiety and boredom, while fostering motivation and learning. Negative emotions like frustration and anxiety hindered learning, with anxiety reducing motivation and frustration demonstrating a paradoxical positive effect. Gender differences were evident, with males showing elevated enjoyment and surprise and reduced anxiety and confusion. Overall, ImVR amplified emotional engagement, highlighting its promise for advancing research and practice in emotion-driven educational design.

**Keywords** Epistemic emotions · Gender · Immersive virtual reality · Motivation · Learning

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## 1 Introduction

Emotions play a central role in learning and education, influencing cognitive processes, motivation, and overall academic outcomes (Pekrun, 2006). Among the spectrum of emotions tied to learning, academic emotions, defined as those directly linked to academic activities such as attending classes, completing assignments, or taking examinations, have gathered significant attention for their impact on student engagement, achievement, and well-being (Pekrun, 2006, 2024). These emotions span a broad spectrum, including positive emotions like pride and enjoyment as well as negative ones such as anxiety and boredom. Of particular interest are epistemic emotions, which relate to cognitive activities such as problem-solving and knowledge acquisition (Pekrun, 2006; Vilhunen et al., 2022). These emotions impact motivation, intellectual engagement, and learning, through complex mechanisms. Consequently, the systematic study of emotions is fundamental to advancing theories in educational psychology and improving pedagogical practices aimed at fostering supportive and effective learning environments (Eliot & Hirumi, 2019; Pekrun & Linnenbrink-Garcia, 2012).

Emotions are not only present in traditional educational contexts but also in technologically enhanced learning environments. Among these, immersive virtual reality (ImVR) represents a sophisticated subset of virtual technology, designed to provide users with the sense of presence, interaction, and engagement in simulated environments. Defined as a digitally-created 3D space that users experience through specialized hardware such as head-mounted displays (HMDs), sensory gloves, and motion tracking systems, ImVR serves as a novel tool for education, healthcare, entertainment, and beyond (Atsikpasi & Fokides, 2022). Its capacity to transport users into compelling, fully immersive environments, where physical reality is replaced by an artificial one, sets it apart from other media technologies, marking it as a breakthrough for contemporary digital innovation.

As ImVR is characterized by its capacity to create highly engaging environments, it offers significant opportunities to shape emotions and enhance educational outcomes. Indeed, ImVR as well as VR in general, has demonstrated the potential to evoke epistemic emotions such as enjoyment, curiosity, surprise, and awe by simulating complex, knowledge-rich scenarios (Chirico et al., 2016; Makransky & Lilleholt, 2018). In this respect, the examination of epistemic emotions in ImVR environments is a critical domain of inquiry in educational research.

Although research has primarily focused on methods for eliciting epistemic emotions and measuring their intensity, relatively little attention has been given to examining the pedagogical implications of these emotions in ImVR environments, as well as their contributions to learning processes. This study seeks to address this gap. By deliberately selecting emotionally evocative learning materials and presenting them in a highly immersive virtual environment capable, in itself, of eliciting emotional responses, the research developed and tested a model to analyze session-level associations among various epistemic emotions and their impact on learning motivation and outcomes. Through this approach, the study offers valuable insights and a novel perspective on how emotions influence, shape, and enhance educational experiences. The subsequent sections provide a detailed account of the study's rationale, methodology, findings, and discussion of its potential contribution to advancing both research and practice in this domain.

## 2 Academic emotions

Academic emotions, defined as emotions directly tied to academic activities, learning, and academic performance (e.g., studying, attending classes, or taking exams), play a crucial role in student engagement, motivation, success, and well-being (Pekrun, 2006, 2024). They range from enjoyment and curiosity to anxiety, boredom, and shame. Understanding their nature and impact on learning outcomes is crucial for educators seeking to create supportive and effective learning environments. Therefore, their study is quite important in educational psychology (Eliot & Hirumi, 2019; Pekrun & Linnenbrink-Garcia, 2012).

Several theories attempted to explain the origins and consequences of academic emotions. Among them, Pekrun's (2006, 2024) Control-Value Theory (CVT) is a well-received framework. It emphasized the interplay between cognitive appraisals and emotional responses, while it highlighted the importance of fostering self-efficacy and perceived value in students. In short, it posited that academic emotions arise from students' appraisals of control (perceived ability to succeed) and value (perceived importance of the outcome). For instance, student who believe they are capable of mastering a subject (high control) and value achieving a good grade in the course (high value) are more likely to experience positive emotions like enjoyment. Conversely, students struggling with the material (low control) and fearing failure (high negative value) might experience anxiety and frustration.

The Broaden-and-Build Theory (Fredrickson, 2004) suggested that positive emotions, such as enjoyment and interest, can broaden students' cognitive resources. These positive emotions can facilitate exploration, creativity, and the development of coping strategies. Negative emotions, like anxiety and frustration, can narrow attention and hinder learning. Research also investigated the interplay between academic emotions and other factors, such as engagement (Linnenbrink-Garcia et al., 2011), suggesting that academic emotions are closely linked to motivation, with positive emotions often fueling engagement and effort, while negative emotions can lead to avoidance and disengagement. Muis et al. (2015) noted that emotions such as curiosity, surprise, and confusion influence how students pursue knowledge and regulate their learning strategies. These emotions can have cascading effects on academic performance by shaping critical thinking and problem-solving behavior.

Academic emotions can be broadly categorized into three domains: activity-related emotions, outcome-related/achievement emotions, and epistemic emotions. Activity-related emotions refer to emotions experienced during the learning process itself, for example, enjoyment in working on a challenging math problem or frustration when encountering obstacles. Achievement emotions, by contrast, are tied to academic outcomes. These include pride and satisfaction after achieving a high grade or shame and disappointment following poor performance (Pekrun, 2006, 2024). Lastly, epistemic emotions arise in relation to cognitive tasks and knowledge acquisition, for instance, curiosity about an intriguing topic or confusion stemming from a lack of understanding. Each of these emotional types illustrates how academic experiences are intertwined with affective responses. Of particular interest to this study are the epistemic emotions, presented in the following section.

### 3 The role of epistemic emotions

Epistemic emotions are affective states that arise during knowledge-generating activities, such as learning, problem-solving, or evaluating information. These emotions are intrinsically linked to cognitive processes and play critical roles in shaping cognitive engagement, motivation, decision-making, and in regulating learning and knowledge construction. Unlike academic emotions, which are broader, epistemic emotions are specifically tied to the content of learning and the process of understanding it. As mentioned in the preceding section, CVT posited that emotions are shaped by appraisals of control (perceived ability to influence outcomes) and value (perceived importance of activities/outcomes). Learners evaluate the novelty, complexity, and coherence of information, which triggers specific emotional responses. For example, encountering a surprising fact might lead to curiosity and a desire to learn more. Originally focused on achievement emotions, CVT has expanded to explain epistemic emotions by linking them to cognitive inconsistency (e.g., discrepancies between new information and prior knowledge) (Pekrun, 2024). Recent studies also emphasized the interplay between epistemic emotions and metacognitive processes (an individual's awareness and regulation of their own cognitive processes), where emotions like curiosity, confusion, and frustration, which often arise during metacognitive monitoring, guide self-regulated learning (Vogl et al., 2021).

Key epistemic emotions are:

- **Enjoyment.** It is a positive emotion arising from successful engagement with learning tasks. It is associated with the feeling of mastery, understanding, and progress in learning. Enjoyment enhances intrinsic motivation and persistence. For example, in L2 learning, enjoyment correlates with higher effort, increased use of metacognitive strategies, and vocabulary retention (Nikitina et al., 2025).
- **Surprise/Awe.** This emotion is triggered by unexpected or disconfirmed expectancies, or when encountering unexpected or novel information that contradicts existing knowledge. It facilitates attention shifts and exploratory behavior. It can also trigger curiosity and a desire to resolve the incongruity, leading to deeper learning (Silvia, 2009). It has to be noted that a recent study distinguished surprise from awe, noting that surprise was linked to higher arousal and approach tendencies in epistemic activities, promoting adaptive information-seeking (Noordewier & Gołowska, 2024).
- **Curiosity.** This emotion is related to the intrinsic desire to seek new information, to resolve knowledge gaps, to explore, investigate, and understand something new. It mediates between motivation and learning outcomes, while it is positively correlated with effort and goal-oriented motivation (Nikitina et al., 2025). Researchers also noted that curiosity is associated with high coping potential and exploration (Noordewier & Gołowska, 2024). All in all, this emotion is particularly critical in educational contexts, as it motivates learners to deepen their understanding.

- **Anxiety.** Anxiety is probably the most well-studied epistemic emotion. It is tied to perceived threats to epistemic goals. In the context of epistemic emotions, anxiety can arise when learners feel overwhelmed by the complexity of information or uncertain about their ability to understand it. It impairs cognitive processing unless regulated. CVT links anxiety to low control appraisals (Pekrun, 2024). Anxiety during conflicting-text tasks predicted avoidance behaviors, though its effects were mitigated by high task value (Pekrun et al., 2017). On the other hand, anxiety can motivate individuals to direct their attention toward resolving the uncertainty (Luo et al., 2020). In this sense, anxiety can push individuals toward greater effort and resource investment. It is thus crucial to manage the balance of this emotion to leverage its motivational benefits while minimizing its potential to hinder cognitive functions.
- **Frustration.** A negative emotion resulting from blocked goals, unresolved incongruity, and during moments of difficulty or perceived failure in achieving cognitive goals. It can either motivate persistence or lead to disengagement. Frustration is correlated with lower task value but higher cognitive effort in problem-solving tasks (Pekrun et al., 2017). However, frustration forces individuals to persist by signaling that current cognitive approaches may require modification. When combined with resilience, frustration can lead to innovative thinking and mastery of challenging material.
- **Confusion.** Confusion arises from cognitive incongruity, information overload, complexity, ambiguity, or when learners perceive inconsistencies or gaps in their understanding. Paradoxically, despite its association with discomfort, it is a productive epistemic emotion as it is beneficial for deep learning (when resolved) and can enhance learning outcomes when appropriately managed (D’Mello et al., 2014). For example, confusion during complex tasks predicted increased use of cognitive strategies, such as elaboration (Vogl et al., 2021). Another study, classified confusion as a negative emotion with low coping potential yet linked to exploration in problem-solving (Noordewier & Gołowska, 2024).
- **Boredom.** This emotion is the result of under-stimulation, lack of engagement and interest in the learning material, or because of repetitive tasks. As it can signal that the information is irrelevant or too easy, it reduces effort and metacognitive engagement and it is negatively correlated with motivation and curiosity (Nikitina et al., 2025). Boredom was also associated with low arousal and avoidance tendencies, particularly in over-challenging tasks (Nikitina et al., 2025; Noordewier & Gołowska, 2024).

While the above findings are promising, existing studies on the relationship between emotions and learning underscored the need for further investigation. Several fundamental research questions remain unaddressed, particularly concerning how emotions can be effectively induced in learners and the impact of these emotions on learning outcomes in digital environments (Um et al., 2012). Furthermore, much of the research exploring the interplay between emotions and cognition has relied on mood-induction tasks to evoke emotional states rather than leveraging features of the learning environment itself (Um et al., 2012).

## 4 The impact of gender on emotions and learning

The relationship between emotions and gender is a complex area of research; the findings that are not always consistent. While gender differences might impact educational trajectories, it has to be acknowledged that gender is a complex social construct, and observed differences may be influenced by a variety of factors, including cultural norms, socialization practices, and individual experiences. In any case, such differences are evident (Fidalgo et al., 2018), probably due to variations in perceived control and value appraisals (Pekrun, 2006).

Differences are evident in both emotional experience and emotional expressivity. Research suggested that men tend to have more intense emotional experiences when exposed to emotionally evocative stimuli, such as videos, while women display greater emotional expressivity, particularly in relation to negative emotions. Moreover, these gender differences are influenced by the specific type of emotion rather than its valence (Deng et al., 2016). There might also be gender differences in the strategies used to manage emotions. For example, males may be more likely to suppress sadness but less likely to suppress anger than females. Females may be more likely to use emotion-focused coping strategies, such as seeking social support, while males may be more likely to use problem-focused coping strategies, such as focusing on the task at hand (Gross & John, 2003). A meta-analysis by Chaplin and Aldao (2013) examining gender differences in emotion expression among children found that girls demonstrated greater positive or internalizing emotions, such as anxiety, sadness, and sympathy, but exhibited fewer externalizing emotions, such as anger, than boys.

In terms of specific learning contexts, while there are studies suggesting few or no gender differences in the overall experience of emotions, others indicated potential variations in the expression, regulation, or antecedents of these emotions, which might or might not impact learning outcomes. For example, research indicated that while most academic emotions are experienced similarly by genders, exceptions exist, particularly in test anxiety, which is higher among females, which, in turn, can hinder performance and engagement (Simić et al., 2024). Yet, another study found that although gender differences exist in emotional intelligence, these did not significantly impact learning outcomes or motivation (Hiluf & Alemu, 2024).

There might also be differences in the trajectory of emotions. For instance, it was found that women exhibited a higher average of affective responses before engaging in educational activities indicating that women may start with a more emotionally charged state in educational settings. Yet, after participating in activities, men showed an increase in their average emotional responses, while women's responses remained stable (Rosser & Soler, 2023).

In the context of learning from conflicting texts, Pekrun et al. (2017), found that there are no gender differences in epistemic emotions except for enjoyment in which male students experienced slightly higher levels of this emotion. On the other hand, it was suggested that females may be more prone to experiencing higher levels of hopelessness, and shame related to learning maths (Else-Quest et al., 2010; Frenzel et al., 2007) and lower levels of enjoyment and pride (Frenzel et al., 2007). Yet, in another study it was found that females demonstrated more positive activating emo-

tions, enjoyment, hope, pride, and less anger, anxiety, shame, hopelessness, and boredom than males. Moreover, females seemed to have more positive emotions and less negative ones that foster favorable math-class related emotions (Zamir et al., 2023). In physical education, boys reported more positive emotions such as pride and enjoyment, which were linked to their intention to be physically active. Girls, on the other hand, experienced more negative emotions like hopelessness, affecting their engagement and performance (Fierro-Suero et al., 2022). In the context of EFL, gender differences were observed in various emotions, impacting motivation and engagement; females experienced higher levels of enjoyment (Dewaele et al., 2018; Wang et al., 2024) and lower levels of boredom than boys, while there were no differences in hope, pride, and anxiety (Wang et al., 2024).

## 5 Immersive virtual reality

As discussed in the “Introduction,” ImVR is a cutting-edge technology that generates a digitally simulated environment, enabling users to experience it as though they are physically present. This immersive effect is achieved through the use of HMDs that deliver stereoscopic visuals and integrate advanced features such as spatial audio, haptic feedback, and motion tracking. Unlike traditional VR systems, ImVR is designed to deeply immerse users by engaging multiple senses, creating the sense of presence, the perception of “being there” in the virtual world (Fokides, 2023). This heightened sense of presence stands out as a defining feature of ImVR, that contributes to its potential impact on learning and other learning related factors.

In educational contexts, ImVR has demonstrated the ability to enhance learning experiences by making them more engaging and interactive. For example, it allows students to immerse themselves in historical events, conduct virtual experiments, or practice complex skills in a safe, controlled virtual environment, all of which have been shown to produce positive learning outcomes (Antonopoulos et al., 2024). Beyond facilitating skill acquisition and knowledge retention, ImVR has been shown to significantly enhance learner motivation. Its novelty, paired with its highly engaging features, boosts intrinsic motivation by encouraging learners to devote greater time and effort to educational activities (Atsikpasi & Fokides, 2022).

ImVR provides a unique platform for examining the complex interplay between technology and emotions. Emotions, as previously discussed, are intrinsically linked to the process of knowledge acquisition and understanding. ImVR scenarios were found to induce high-arousal emotions, both pleasant (e.g., excitement, joy, and enthusiasm) and unpleasant ones (e.g., anger, fear, and anxiety). This is supported by both subjective evaluations and neurophysiological data, indicating ImVR’s potential as a tool for emotional research (Li et al., 2022). In fact, the emotional value of ImVR is significantly greater than that of desktop VR, probably because of its ability to deliver highly immersive and interactive experiences, which, in turn, significantly influence the generation and regulation of several emotions. Indeed, it was suggested that individuals can experience intense, multidimensional emotions in ImVR (Meuleman & Rudrauf, 2018). This complexity of emotional responses underscores the need to account for multiple emotional components within educational settings (Soma-

rathna & Mohammadi, 2024). Moreover, behavioral and psychophysiological results suggested that identical exogenous and endogenous cognitive and emotional mechanisms are deployed to process real-life and virtual experiences, implying that ImVR is capable of mimicking reality and can be used for the investigation of real-world cognitive and emotional processes (Schöne et al., 2023).

In the context of education, there is research suggesting that ImVR environments are capable not only to improve academic performance and motivation but also to encourage students to emotionally invest in their learning tasks (Akgün & Atıcı, 2022). That is because students reported experiencing heightened feelings of enjoyment, satisfaction, curiosity, and excitement during their virtual interactions. Similar were the results in the review of Somarathna et al. (2022); besides the abovementioned positive emotions, the authors noted that there is research in which VR applications were used for the elicitation of negative ones such as fear, anger, boredom, and sadness. For example, in a study exploring how ImVR experiences influenced climate change-related cognitions, emotions, and behaviors, it was found that participants experienced higher spatial presence, which lead to stronger negative emotional responses (Meijers et al., 2023). A study conducted by Ślósarz et al. (2022) observed significant shifts in learners' emotional intensities following ImVR interventions. Specifically, positive emotions such as joy and enthusiasm increased, while negative emotions diminished.

All the above findings underline ImVR's potential to influence students' emotional states. Yet, it can be supported that the existing VR content is more suitable for eliciting positive emotions rather than negative ones (Somarathna et al., 2022). In addition, it seems that the research is more focused in exploring the quantity and quality of emotions in ImVR environments rather than the exploration of the impact they have on learning.

## 6 Statement of the problem, research rationale, and research questions

Despite the substantial progress in understanding the role of epistemic emotions in educational contexts, there are still underexplored areas. For instance, prior investigations have relied predominantly on external mood-induction tasks (Um et al., 2012), rather than leveraging intrinsic aspects of the learning design, such as emotionally charged content or immersive settings that naturally evoke emotional responses. Another research gap is related to the interplay between emotions and digital learning environments, particularly ImVR. Studies have consistently highlighted the capacity of ImVR to generate intense emotional experiences, similar to the ones in reality, due to its immersive and interactive nature (e.g., Makransky & Lilleholt, 2018; Meuleman & Rudrauf, 2018; Schöne et al., 2023). However, insufficient attention has been paid to assessing how these emotions directly influence cognitive processes, engagement, and learning outcomes. For instance, Somarathna et al. (2022) noted that current VR content primarily targets the elicitation of positive emotions, yet there is little insight into how specific emotions, whether positive, negative, or mixed, moderate the effectiveness of learning or the retention of complex subject matter in such environments.

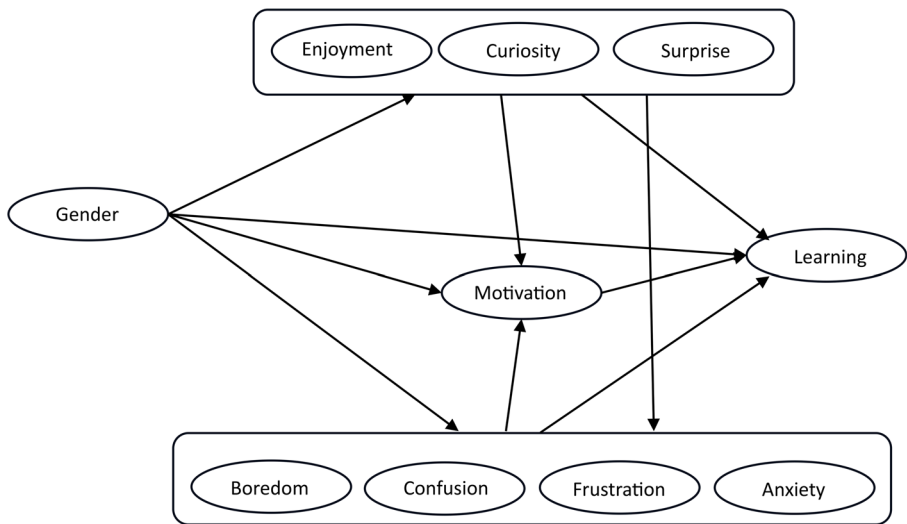
Moreover, while studies have examined the effects of discrete emotions such as confusion, anxiety, and boredom (e.g., Pekrun, 2024; Vogl et al., 2021; Nikitina et al., 2025), there remains limited understanding of how concurrent or conflicting emotions experienced in immersive settings interact to shape learning. For example, confusion, a paradoxical but productive epistemic emotion, can lead to deeper knowledge acquisition when resolved effectively (D’Mello et al., 2014), but its co-occurrence with frustration may produce disengagement. Investigating such dynamic emotional interactions in the immersive learning context would provide valuable insights into designing environments that balance emotional complexity while maintaining learner engagement.

While studies emphasized gender differences in academic emotions (e.g., Fidalgo et al., 2018; Simić et al., 2024), there seems to be a lack of research systematically exploring whether such differences persist in immersive settings. Moreover, research implied a link between emotional intensity and cognitive engagement (e.g., Akgün & Atıcı, 2022; Somarathna et al., 2022), but further investigation is required to determine whether genders respond differently to these immersive, emotionally charged environments. Finally, while ImVR systems have demonstrated their ability to elicit multi-dimensional emotional and cognitive responses comparable to real-world experiences (Schöne et al., 2023), deeper exploration into their pedagogical utility is needed. Existing research has predominantly focused on quantifying emotional intensities rather than evaluating the specific pedagogical effects of these emotions on learning (Somarathna & Mohammadi, 2024).

Addressing these gaps will help refine theoretical frameworks such as Pekrun’s CVT, enabling a more profound understanding of the critical role that emotions play and advance the practical applications of ImVR and other innovative digital technologies in education. For that matter, a project was designed and carried out. Its objective was to develop a model to clarify the interplay between various epistemic emotions and gender and how they impact motivation to learn and learning outcomes in the context of ImVR, as presented in Fig. 1.

The following research questions (RQs) were formed:

- RQ1a-b. To what extent does anxiety influence: (a) motivation and (b) learning, when engaging with an ImVR educational application?
- RQ2a-b. To what extent does boredom influence: (a) motivation and (b) learning, when engaging with an ImVR educational application?
- RQ3a-b. To what extent does confusion influence: (a) motivation and (b) learning, when engaging with an ImVR educational application?
- RQ4a-b. To what extent does frustration influence: (a) motivation and (b) learning, when engaging with an ImVR educational application?
- RQ5a-f. To what extent does curiosity influence: (a) anxiety, (b) boredom, (c) confusion, (d) frustration, (e) motivation, and (f) learning, when engaging with an ImVR educational application?
- RQ6a-f. To what extent does enjoyment influence: (a) anxiety, (b) boredom, (c) confusion, (d) frustration, (e) motivation, and (f) learning, when engaging with an ImVR educational application?



**Fig. 1** The suggested model. Note: For the reduction of the number of arrows, the emotions were grouped as positive and negative.

- RQ7a-f. To what extent does surprise influence: (a) anxiety, (b) boredom, (c) confusion, (d) frustration, (e) motivation, and (f) learning, when engaging with an ImVR educational application?
- RQ8. To what extent does motivation influence learning when engaging with an ImVR educational application?
- RQ9a-i. To what extent does gender influence: (a) anxiety, (b) boredom, (c) confusion, (d) frustration, (e) curiosity, (f) enjoyment, (g) surprise, (h) motivation, and (i) learning, when engaging with an ImVR educational application?

## 7 Method

### 7.1 Participants

During the initial phase of the study, a critical question emerged regarding the selection of the target population, particularly its demographics and size. It was evident from prior observations that many imVR educational applications are predominantly designed for adolescents or young adults. Furthermore, recent systematic reviews (e.g., Alfaisal et al., 2022; Atsikpasi & Fokides, 2022; Tlili et al., 2022) highlighted a trend in which the majority of studies have concentrated on university or college students. Guided by this evidence, the decision was made to focus on university students as the target demographic for this study.

Determining the appropriate sample size required careful consideration of various factors. Key considerations included the number of items in the data collection instruments, the research context, the statistical estimation method, and the complexity of the model employed (Brown, 2015). Additional logistical constraints, such as the availabil-

ity of HMDs, further influenced the decision-making process. Nevertheless, as Partial Least Squares Structural Equation Modeling (PLS-SEM) was the statistical method of choice for analyzing the data, as it will be elaborated in a coming section, a commonly referenced guideline for sample size is the “10 times rule,” which suggests that the minimum sample size should be ten times the maximum number of arrowheads pointing at a latent variable anywhere in the PLS path model (Barclay et al., 1995). On the basis of the RQs the maximum number of arrowheads pointing to a latent variable is nine, meaning that at least 90 participants were needed. To achieve a more accurate sample size estimation, a power analysis was conducted using G\*Power (Faul et al., 2007). For an effect size ( $f_{Cohen}$ ) of 0.15, a power of 0.80, a significance level of 0.05, and having nine predictors, the desired sample size was estimated to be 114 individuals.

Taking the above considerations into account, a convenience sample comprising 124 students was selected. These students were enrolled in a course focusing on the educational applications of ImVR in the Department of Primary Education at the University of the (name omitted for anonymity purposes). No prior experience with HMDs or ImVR was necessary; the sole eligibility requirement for participation was proficiency in English, for reasons detailed in the subsequent section. The sample composed entirely of white Caucasians. Among them, 81 identified as females (65.3%), while the remainder identified as males; no participant selected a non-binary or other gender identity. Participants’ mean age was 21 years ( $M=20.95$ ,  $SD=4.07$ ). It has to be noted that because of the convenience sampling in a single European university, the imbalance in gender distribution, and the exclusively white Caucasian composition of the sample, the study sample was not intended to be representative of broader student populations.

This study is part of an ongoing research initiative, which has undergone review and received formal ethical approval from the Research and Ethical Committee of the Department of Primary Education at the University (name omitted for anonymity purposes). In addition to the above approval, all participants were briefed on their rights and provided informed consent prior to participation.

## 7.2 Materials and apparatus

The selection of a suitable educational application for this study was a critical consideration. Although a broad array of applications is available, many are characterized by complexity, specialized focus on specific subject matter, or substantial time requirements for completion. Additionally, applications offered in the Greek language are scarce, narrowing the available options. As a result, the decision to utilize an application in the English language emerged as the most practical and viable solution. This is why proficiency in English was a prerequisite for participants, as outlined in the preceding section.

Probably the most important consideration arose from the necessity to select learning material able to evoke emotions. The heterogeneity of ImVR applications suggests that emotion-learning associations are likely genre- and task-dependent. Narrative historical simulations foreground affective engagement and presence, whereas pedagogically focused applications (e.g., virtual labs, procedural training, and language practice) embed goal-directed tasks, graded challenge, and feedback that not always

elicit strong of emotions. Therefore, in the present study, a high-arousal historical simulation was selected, to maximize variance in session-level emotions. Then again, this design choice likely biased the emotional profile toward enjoyment of exploration and surprise at narrative revelations, while potentially suppressed other emotions that typically arise in problem-solving contexts with targeted scaffolding. Among the freely accessible imVR experiences, the “Anne Frank House VR” (<https://www.annefrank.org/en/about-us/what-we-do/publications/anne-frank-house-virtual-reality/>) was selected for its educational and historical significance. This virtual experience recounts the story of Anne Frank, a Jewish girl aged 13, who, along with her sister, parents, and four others, went into hiding in a secret annex in Amsterdam from 1942 to 1944. Developed collaboratively by Force Field VR and the Anne Frank Foundation, the application provides a detailed reconstruction of the hiding place. It allows users to explore and immerse themselves in the daily lives of its inhabitants while offering insights into the conditions of life in hiding, the individual biographies of the occupants, and the broader context of the Holocaust (Mulders, 2023).

Among the various HMDs available on the market, the Meta Quest 2 and Meta Quest 3 were selected for this study due to their relatively low cost and suitable technical specifications. A notable feature of the Meta Quest 2 and 3 is their untethered design, enabling standalone operation without reliance on an external computer. This cordless functionality eliminates cable management challenges and enhances user mobility. However, this advantage comes at the expense of reduced graphical performance, a limitation arising from the devices’ internal image processing capabilities. To facilitate the experiment, a spacious office was used. The room was cleared of all furniture, yielding an open space of approximately 40 square meters. This setup served two critical purposes: first, it minimized injury risks by preventing participants from accidentally colliding with physical objects; second, it provided participants with the freedom to navigate the virtual environment naturally, without reliance on the HMD’s controllers for simulated movement. This approach was deliberately chosen to amplify the immersive quality of the VR experience, fostering a more authentic interaction within the virtual setting.

### 7.3 Instruments

To measure knowledge acquisition, an evaluation test was employed. This test was based on the translated version of the one used in Mulders’ (2023) study, which can be accessed at <https://uni-duisburg-essen.sciebo.de/apps/onlyoffice/s/fIAIkk1lKTCutO?fileId=1323754669>. The test comprised ten multiple-choice questions directly tied to the application’s content. Each question allows for a maximum score of two points based on the completeness of the response.

To gather data regarding the factors included in the model, a questionnaire was administered. Its items were derived from various validated scales and questionnaires. Specifically, for measuring motivation, six items were sourced from the Multiverse Learning Experience Scale (Fokides, 2023), which, as its name implies, examines various dimensions of one’s learning experience and overall satisfaction when using Multiverse educational applications, including imVR. Epistemic emotions were measured using the Epistemically-Related Emotion Scale developed by Pekrun et al. (2017). This scale consists of 21 items assessing three positive (surprise,

curiosity, and enjoyment) and four negative emotions (confusion, anxiety, frustration, and boredom). Each emotion is examined using three items. All items were presented on a five-point Likert scale. Furthermore, an additional item was included to capture participants' gender. This item was presented as: "I identify my gender as: male; female; self-described as;; and prefer not to say. Both the evaluation test and the questionnaire were made accessible online through Google Forms.

#### **7.4 Procedure**

The experiments were designed as an extracurricular activity, devoid of formal teaching. This decision ensured an unambiguous assessment of the media's inherent effects. Including any instructional activities would have complicated the process of unravelling the influence of the media from that of pedagogical interventions. Therefore, the exclusion of teaching was intentional and essential, allowing the observed outcomes to be attributed solely to the media under investigation.

An appointment schedule was established to streamline the process. Each participant was greeted and provided with verbal instructions detailing what to expect and how to interact with the application. Following this, participants were equipped with HMDs. Adjustments were made to the straps and interpupillary distance to optimize image clarity. After these adjustments, participants were given 15 to 20 min to familiarize themselves with the virtual environment, including the welcome space and navigation menus. They were also instructed on managing encounters with the "play" area boundaries, where the HMD operating system would notify them of potential physical space limits to prevent accidents. This preparatory phase was crucial, given that none of the participants had prior experience with imVR or HMDs.

Subsequently, participants launched the application and engaged with it for a duration of 35 to 45 min, deemed sufficient for thorough exploration. Additional support was provided to those encountering significant challenges with navigation or interaction. Once this phase was completed, participants were asked to fill out the questionnaire and take the evaluation test. A 20-minute period was provided to ensure sufficient time. In total, the procedure required approximately one and a half hours per participant.

It is important to note that as the emotion questionnaire was administered immediately after the ImVR session, the emotion scores reflect participants' retrospective, session-level appraisals rather than moment-to-moment fluctuations. This approach reduced disruption to immersion but it may have introduced retrospective biases (e.g., peak-end and recency effects) and may have emphasized integrated summaries of the experience over discrete emotional episodes in specific learning moments.

To address potential cases of simulator sickness, participants were instructed to discontinue use of the application and remove their headsets if symptoms became severe, allowing them time to rest. Participants experiencing mild or moderate symptoms had the autonomy to decide whether to continue or terminate their participation in the experiment. Regardless of their choice, all participants completed both the test and questionnaire, as the potential impact of simulator sickness on emotions and learning outcomes was theorized to be considerable and would be reflected in participants' responses.

## 8 Results

### 8.1 Initial data processing

Taking into account that the study's primary research objective was to explain the variance of the endogenous constructs together with its exploratory nature that might lead to the development of new theory, the recommended statistical method for analyzing the data was PLS-SEM (Hair et al., 2019). In accordance with the guidelines provided by Hair et al. (2019), the following were assessed prior to advancing with PLS-SEM:

- The dataset was examined for any missing data and for unengaged responses (i.e., participants showing no variance in their responses ( $SD=0.00$ )). No participants met these criteria for exclusion.
- Item reliability was assessed by examining the indicator loadings. All loadings were above the 0.70 threshold, thus providing acceptable item reliability (see Appendix, Table 4).
- Internal consistency and reliability were assessed using rho\_A and Cronbach's  $\alpha$ . No issues were noted (see Appendix, Table 5).
- Convergent validity was examined using the average variance extracted (AVE) for all items on each construct. As the AVE was higher than 0.50 in all cases (see Appendix, Table 6), it was concluded that there were no convergent validity concerns.
- Discriminant validity was assessed using the heterotrait-monotrait (HTMT) ratio of the correlations. The discriminant validity was confirmed given that all the HTMT values were below the strict threshold of 0.85 (see Appendix, Table 7).
- Finally, as the Variable Inflation Factor (VIF) of all items was below the threshold of 0.50 (see Appendix, Table 8), it was concluded that there were no multicollinearity concerns.

### 8.2 PLS-SEM results

Since the measurement model assessment demonstrated satisfactory outcomes, the subsequent step involved evaluating the structural model by analyzing the PLS-SEM results. Please note that a Bias-Corrected and Accelerated (BCa) bootstrap procedure, utilizing 10,000 subsamples, was employed to determine the significance of the path coefficients and to assess their values. The results are presented in Tables 1, 2 and 3, while Fig. 2 presents the final model.

The final stage of the analysis was the evaluation of the model's out-of-sample predictive power, utilizing the PLSpredict procedure. While PLSpredict provides various metrics to assess predictive performance on out-of-sample data, Hair et al. (2019) recommend researchers prioritize the comparison of root mean squared error (RMSE) values obtained from two distinct analyses: predictions generated by the PLS-SEM model and those based on a naïve linear regression model (LM). In this study, the PLS-SEM predictions demonstrated consistently lower RMSE values compared to the naïve LM benchmark for the vast majority of indicators (in three cases

**Table 1** The results of PLS-SEM, direct effects

Path	t	p	$\beta$	f <sup>2</sup>	Interpretation
Anxiety -> Motivation	5.42	<0.001	-0.38	0.22	Moderate path, medium effect
Anxiety -> Learning	0.23	0.817	0.02	0.00	-
Boredom -> Motivation	4.18	<0.001	-0.28	0.12	Modest path, small effect
Boredom -> Learning	2.62	0.009	-0.20	0.07	Modest path, small effect
Confusion -> Motivation	1.08	0.279	-0.06	0.01	-
Confusion -> Learning	0.75	0.451	-0.03	0.01	-
Frustration -> Motivation	2.39	0.017	0.18	0.07	Modest path, small effect
Frustration -> Learning	3.34	0.001	-0.18	0.08	Modest path, small effect
Curiosity -> Anxiety	3.09	0.002	-0.22	0.08	Modest path, small effect
Curiosity -> Boredom	4.27	<0.001	-0.33	0.17	Moderate path, medium effect
Curiosity -> Confusion	1.28	0.201	-0.14	0.02	-
Curiosity -> Frustration	0.56	0.574	-0.06	0.00	-
Curiosity -> Motivation	2.29	0.022	0.16	0.06	Modest path, small effect
Curiosity -> Learning	0.28	0.783	0.01	0.00	-
Enjoyment -> Anxiety	9.20	<0.001	-0.66	0.68	Strong path, very large effect
Enjoyment -> Boredom	5.31	<0.001	-0.54	0.42	Strong path, large effect
Enjoyment -> Confusion	5.00	<0.001	-0.52	0.22	Strong path, medium effect
Enjoyment -> Frustration	5.55	<0.001	-0.64	0.43	Strong path, large effect
Enjoyment -> Motivation	2.32	0.020	0.21	0.06	Modest path, small effect
Enjoyment -> Learning	2.00	0.046	0.13	0.03	Modest path, small effect
Surprise -> Anxiety	0.64	0.523	0.05	0.00	-
Surprise -> Boredom	0.08	0.939	0.01	0.00	-
Surprise -> Confusion	1.73	0.084	0.20	0.03	-
Surprise -> Frustration	0.25	0.804	0.03	0.00	-
Surprise -> Motivation	1.87	0.061	0.14	0.04	-
Surprise -> Learning	7.15	<0.001	0.37	0.40	Moderate path, large effect
Gender -> Anxiety	2.53	0.011	-0.14	0.05	Modest path, small effect
Gender -> Boredom	1.35	0.179	-0.08	0.02	-
Gender -> Confusion	2.51	0.012	-0.19	0.05	Modest path, small effect
Gender -> Frustration	1.73	0.084	-0.11	0.02	-
Gender -> Curiosity	1.19	0.236	0.11	0.01	-
Gender -> Enjoyment	3.72	<0.001	0.29	0.09	Moderate path, small effect
Gender -> Surprise	2.11	0.035	0.18	0.03	Modest path, small effect
Gender -> Motivation	1.55	0.120	-0.07	0.02	-
Gender -> Learning	0.22	0.827	0.01	0.00	-
Motivation -> Learning	2.36	0.018	0.21	0.05	Modest path, small effect

- = not statistically significant. Path coefficients ( $\beta$ ) indicate relationship strength while  $f^2$  indicates the predictor's contribution to  $R^2$ . For the interpretation of  $\beta$ , the following cutoff values apply:  $\beta$  0 to 0.10=weak path,  $\beta$  0.11 to 0.30=modest path,  $\beta$  0.31 to 0.50=moderate path, and  $\beta > 0.50$ =strong (Hair & Alamer, 2022). For the interpretation of the effect sizes, the following cutoff values apply:  $f^2 \geq 0.35$ =large effect,  $f^2 \geq 0.15$ =medium effect,  $f^2 \geq 0.02$ =small effect,  $f^2 < 0.02$ =negligible effect (Cohen, 2013). For the interpretation of gender effects, it is important to note that as no participant selected the "non-binary/other and prefer not to say" options, the gender variable is a binary coded as female=1 and male=2. Consequently, a positive coefficient indicates that males experienced higher levels of a given emotion compared to females, while a negative coefficient suggests that males experienced lower levels of that emotion relative to their female counterparts

**Table 2** The results of PLS-SEM, total indirect effects

Path	t	p	$\beta$	Interpretation
Anxiety -> Learning	2.17	0.030	-0.08	Weak path
Boredom -> Learning	2.28	0.023	-0.06	Weak path
Confusion -> Learning	0.87	0.387	-0.01	-
Frustration -> Learning	1.72	0.086	0.04	-
Curiosity -> Motivation	3.42	0.001	0.17	Modest path
Curiosity -> Learning	3.72	<0.001	0.14	Modest path
Enjoyment -> Motivation	4.18	<0.001	0.32	Moderate path
Enjoyment -> Learning	5.09	<0.001	0.33	Moderate path
Surprise -> Motivation	0.52	0.602	-0.03	-
Surprise -> Learning	0.23	0.816	0.01	-
Gender -> Anxiety	3.47	0.001	-0.21	Modest path
Gender -> Boredom	3.10	0.002	-0.19	Modest path
Gender -> Confusion	2.83	0.005	-0.13	Modest path
Gender -> Frustration	3.47	0.001	-0.19	Modest path
Gender -> Motivation	3.76	<0.001	0.28	Modest path
Gender -> Learning	3.66	<0.001	0.26	Modest path

. - = not statistically significant. Effect sizes cannot be calculated for indirect effects

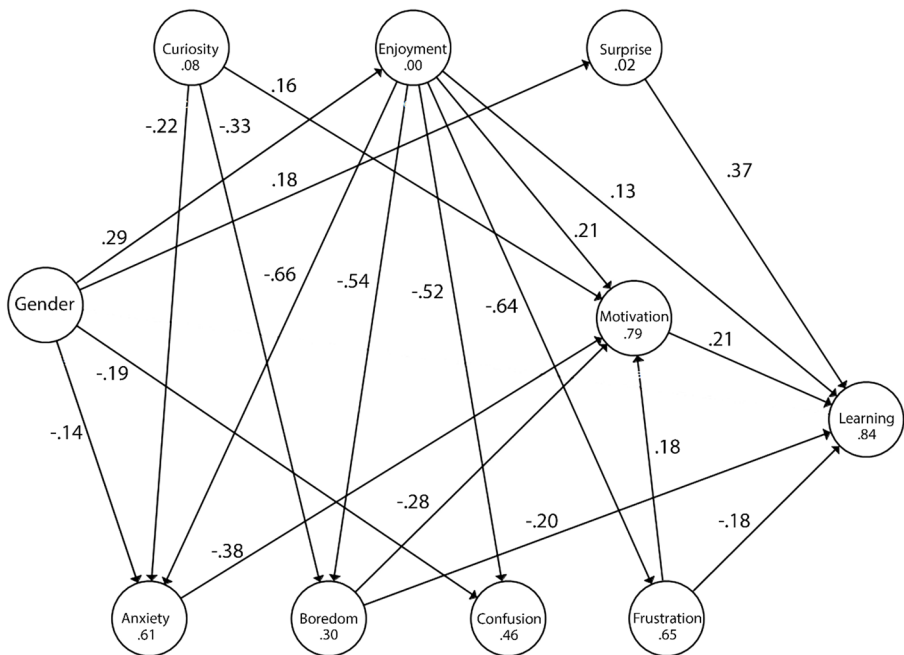
**Table 3** The model's explanatory power/in-sample predictive power

Factor	Adj. $R^2$	Interpretation
Anxiety	0.65	Strong explanation
Boredom	0.61	Strong explanation
Confusion	0.30	Modest explanation
Frustration	0.46	Moderate explanation
Curiosity	0.00	Weak explanation
Enjoyment	0.08	Weak explanation
Surprise	0.02	Weak explanation
Motivation	0.79	Very strong explanation
Learning	0.84	Very strong explanation

For the interpretation of  $R^2$  values, the following cutoff values apply: between 0 to 0.10=weak, 0.11 to 0.30=modest, 0.31 to 0.50=moderate, and  $\geq 0.50$  strong (Hair & Alamer, 2022)

out of the 28 it was higher, see Appendix, Table 8). These results provide evidence that the model exhibits moderate to strong out-of-sample predictive power.

In addition to the aforementioned findings, it is important to highlight that the epistemic emotions examined in this study, together with gender, demonstrated a noteworthy ability to predict/explain a significant proportion of the study's central variables, namely motivation and learning, accounting for  $R^2$  values of 0.79 and 0.84, respectively. Furthermore, gender and positive epistemic emotions were able to predict a large proportion of anxiety's and boredom's variance, a moderate proportion of frustration's variance, and a modest one of confusion's variance ( $R^2$  values of 0.65, 0.61, 0.46, and 0.30 respectively). Contrary to the above, the  $R^2$  values of the positive emotions were rather low; yet, this is not a source of concern, given that their only predictor was gender.



**Fig. 2** The study's final model. For clearance of presentation, only the statistically significant direct paths are presented. The numbers in the arrows are the path coefficients, while the numbers in the circles are the factors'  $R^2$  values

## 9 Discussion

The data revealed the ability of epistemic emotions, when considered alongside gender, to explain/predict significant proportions of the variance in motivation and learning. Furthermore, these results align with prior theories in educational psychology and digital learning research, serving to expand and refine existing frameworks. In the sections below, the results of each RQ are discussed in detail.

### 9.1 The role of anxiety (RQ1a-b)

While anxiety has the potential to prompt resource investment under certain conditions (Luo et al., 2020), in the context of ImVR environments, its effects appear largely detrimental. It exerted a moderate negative direct effect on motivation ( $\beta = -0.38$ ,  $p < .001$ ,  $f^2 = 0.22$ ), diminishing learners' drive and engagement in ImVR. Although it had no significant direct effect on learning, it had a weak negative indirect impact ( $\beta = -0.08$ ,  $p = .030$ ), indicating that it has the potential to impair cognitive outcomes through motivational pathways. These results align with CVT (Pekrun, 2006, 2024), which links anxiety to low control appraisals that inhibit intrinsic engagement and impede academic achievement. However, the weak indirect effect implies that motivation acts as a protective buffer, mitigating some negative consequences of anxiety on learning.

Features of ImVR, such as heightened sensory input and high task complexity, may have amplified learners' perceptions of cognitive overload, strengthening the negative influence of anxiety. Its capability in evoking multidimensional and intense emotional responses (Meuleman & Rudrauf, 2018; Schöne et al., 2023) also call for consideration. The sense of presence may have inadvertently intensified anxiety, particularly in settings designed to elicit emotional engagement, as in the case of this study which used Holocaust narratives.

Nevertheless, it can be supported that fostering positive epistemic emotions could serve as a powerful strategy to neutralize anxiety's adverse impacts. The observed strong positive effects of enjoyment ( $\beta = -0.66, p < .001$ ) and curiosity ( $\beta = -0.22, p = .002$ ) on reducing anxiety offer evidence for the efficacy of ImVR applications in cultivating learner emotional resilience. This aligns with Fredrickson's Broaden-and-Build Theory (2004), which argues that positive emotions like curiosity and enjoyment can expand cognitive resources and counteract narrowing effects induced by negative emotions.

## 9.2 The role of boredom (RQ2a-b)

On the basis of the findings, it seems that boredom plays a negative role in shaping both learning and motivation. It exhibited modest negative direct effects on both motivation ( $\beta = -0.28, p < .001$ ) and learning ( $\beta = -0.20, p = .009$ ), each with small effect sizes ( $f^2 = 0.12$  and  $f^2 = 0.07$ , respectively). It also exerted a weak negative indirect effect on learning ( $\beta = -0.06, p = .023$ ), further amplifying its influence on students' academic engagement and outcomes.

Boredom, as earlier discussed, is triggered by under-stimulation and lack of engagement with the learning material (Nikitina et al., 2025). Its presence may stem from repetitive content, low interactivity, or insufficient novelty, which reduce task value and cognitive engagement and subsequently impact motivation and may lead to avoidance reactions (Nikitina et al., 2025; Noordewier & Gocłowska, 2024; Pekrun, 2006). The results reinforce the idea that boredom not only undermines intrinsic motivation but also diminishes students' ability to sustain effort and derive meaningful understanding from the educational material. These outcomes are particularly relevant to ImVR environments, which, while often praised for their immersive and engaging nature (Antonopoulos et al., 2024; Fokides, 2023), appear susceptible to evoking boredom. The mere presence of immersive features, interactivity, and presence is insufficient to eliminate boredom if the content and structure of the virtual experience fail to engage learners deeply, or if they perceive it as being too demanding, thus losing their interest.

The weak negative indirect effect of boredom on learning through motivation indicates that its effects are multifaceted: not only does it harm attention and engagement during the task, but it also sets off a motivational decline that compromises deeper cognitive processing. This aligns with Fredrickson's (2004) Broaden-and-Build Theory, which emphasizes positive emotions as broadening cognitive resources, in contrast to negative ones (such as boredom) narrowing effects.

As with anxiety, enjoyment's and curiosity's negative effects on boredom ( $\beta = -0.54, p < .001, f^2 = 0.42$  and  $\beta = -0.33, p < .001, f^2 = 0.17$  respectively) can be viewed as factors that mitigate its negative impact on motivation and learning.

### 9.3 The role of confusion (RQ3a-b)

No direct or indirect effects of confusion on motivation or learning were observed. At first glance, this null result appears counterintuitive given confusion's dual status as both a negative and a potentially productive epistemic emotion (D'Mello et al., 2014; Noordewier & Gocłowska, 2024). In contrast, the findings suggest that confusion may operate differently in ImVR, where heightened presence and affective intensity can dampen its impact or even suppress its emergence. The application used in this study was a historical simulation designed to elicit emotional engagement and reflection rather than to challenge learners' cognitive structures through tasks requiring resolution or problem-solving. Without system-guided tools, personalized feedback, or other mechanisms for resolving discrepancies, participants may have experienced cognitive incongruities that did not activate confusion's productive dimensions (Vogl et al., 2021), diminishing its potential to motivate learners.

While this account helps explain the absence of positive effects, it does not clarify why confusion also failed to exert negative effects. A plausible explanation lies in the affective profile of ImVR. Immersive technologies frequently elicit high-arousal positive emotions, such as enjoyment and surprise (Li et al., 2022; Makransky & Lilleholt, 2018; Ślószarz et al., 2022), which can overshadow less intense or more ambiguous states like confusion. ImVR's sensory richness may also draw attention toward embodied exploration and narrative immersion rather than analytic resolution, guiding learners past the disruptive phases typically associated with confusion. This interpretation is consistent with evidence that ImVR can simulate lifelike emotional and cognitive processes that absorb learners' attention (Schöne et al., 2023).

In addition, enjoyment exerted a strong negative effect on confusion ( $\beta = -0.52$ ,  $p < .001$ ,  $f^2 = 0.22$ ), suggesting that positive emotions may suppress the emergence or impact of confusion; surprise also showed a positive trend for learning. These dynamics align with Fredrickson's (2004) Broaden-and-Build Theory, which posits that positive emotions broaden cognitive resources and can override disruptive negative states. In this context, ImVR may prioritize positive activating states (e.g., enjoyment and surprise) over confusion, constraining its direct influence on motivational and learning outcomes.

To summarize, confusion's null effects are subject to three complementary explanations. First, measurement timing and instrumentation may have obscured episodic confusion. The post-session measure likely prioritized salient high-arousal states and down-weighted brief or ambiguous confusion episodes. Because productive confusion is tightly coupled with resolution, it often requires time-sensitive assessment; without in-VR experience sampling or psychophysiological proxies, momentary confusion can go undetected at the session level. Second, "Anne Frank House VR" presented few explicit discrepancies to resolve. In Control-Value terms, cognitive incongruity may have lacked tractable resolution pathways, weakening appraisals of coping potential and impeding the transformation of confusion into elaboration or metacognitive strategy change (Pekrun, 2024). Third, ImVR's medium affordances may have altered confusion's role by shifting attentional priorities from analytic resolution to embodied exploration and narrative assimilation. In such contexts, learners may appraise incongruity as affectively interesting rather than as a problem to solve, converting potential confusion into curiosity or surprise without the hallmarks of productive resolution.

#### 9.4 The role of frustration (RQ4a-b)

Frustration exhibited a modest positive direct effect on motivation ( $\beta=0.18, p = .017, f^2 = 0.07$ ) and a modest negative direct effect on learning ( $\beta = -0.18, p = .001, f^2 = 0.08$ ). No indirect pathways were observed, underscoring the distinct influences of frustration on these constructs. This pattern is consistent with two concurrent mechanisms: a motivational energization pathway and a cognitive-interference pathway. In Control-Value terms (Pekrun, 2006, 2024; Pekrun et al., 2017), frustration arises when learners value task goals but encounter blocked progress. When perceived control is moderate to high, frustration can signal “work to be done,” increasing action readiness and effort. When perceived control is low or obstacles appear intractable, frustration narrows attention, increases intrusive thoughts, impairing comprehension and consolidation.

There are several conditions under which frustration enhances motivation but impairs learning. For example, mild-to-moderate or brief/episodic frustration that is quickly resolved can heighten motivational intensity and focus by signaling that additional effort is needed, especially when coupled with high task value and clear paths to resolution. On the other hand, high-intensity or prolonged/unresolved frustration, when unaccompanied by timely feedback, is likely to induce cognitive interference, elevate extraneous load, degrade learning, and can lead to boredom (D’Mello & Graesser, 2012; Pekrun et al., 2017).

ImVR’s specific mechanisms may have amplified both sides of this duality. In ImVR applications, their level of “desirable difficulty” may catalyze positive emotions, exploration, and strategy change, that suppress frustration (Li et al., 2022; Makransky & Lilleholt, 2018; Ślósarz et al., 2022). Indeed, enjoyment showed a strong negative effect on frustration ( $\beta = -0.64, p < .001, f^2 = 0.43$ ), indicating that positive activating states can buffer frustration’s intensity and duration, increasing the likelihood that it remains motivational rather than cognitively disruptive (D’Mello & Graesser, 2012; Pekrun et al., 2017). Moreover, if learners perceive rich affordances for corrective action (e.g., interactive artifacts, clear progress cues), frustration may spur exploration and effort.

Then again, despite ImVR’s ability to elicit epistemic emotions, frustration may arise due to cognitive challenges, technical obstacles, or heightened self-perception of inadequacy. For instance, high immersion and presence can heighten the salience of obstacles (e.g., navigation friction, interface incongruities, emotionally charged narrative elements), increasing frustration’s arousal. In short, if the experience affords limited agency or opaque feedback, frustration can persist and impair encoding and integration, especially when difficulties are not calibrated as desirable.

The positive path to motivation without a corresponding positive indirect path to learning also suggests that, in the absence of resolution opportunities, frustration may energize effort that does not translate into immediate performance gains. The “Anne Frank House VR” foregrounds historically complex, emotionally charged content with limited system-guided scaffolds for resolving cognitive impasses, a design profile likely to increase motivational striving while allowing frustration to impair concurrent information processing.

Taking together the above, a process hypothesis can be suggested. In ImVR, brief, low-to-moderate frustration episodes that are followed by timely resolution supports will increase motivation and, when resolution is achieved, will also support learning; sustained or high-intensity frustration in the absence of resolution supports will continue to energize behavior in the short term but will impair learning via increased extraneous load and cognitive interference.

### 9.5 The role of curiosity (RQ5a-f)

Curiosity exhibited a modest positive direct effect on motivation ( $\beta=0.16$ ,  $p = .022$ ,  $f^2 = 0.06$ ) and an indirect one through other factors ( $\beta=0.17$ ,  $p = .001$ ). These findings echo earlier research emphasizing curiosity's capacity to mediate intrinsic motivation and goal-directed effort in educational contexts (Noordewier & Goçłowska, 2024; Nikitina et al., 2025). As curiosity sparks a desire to resolve knowledge gaps and explore, the learners in ImVR likely perceive their tasks as meaningful and rewarding, enhancing their motivational states. However, curiosity demonstrated no direct effect on learning, although it contributed indirectly ( $\beta=0.14$ ,  $p < .001$ ) through its influence on other factors. This indirect pathway suggests that curiosity is a precursor for deeper engagement and effort, which drives learning outcomes (Muis et al., 2015). In this respect, curiosity might not translate immediately into measurable academic performance but rather set the stage for cognitive gains.

Curiosity demonstrated a modest but meaningful negative direct effect on anxiety ( $\beta = -0.22$ ,  $p = .002$ ) and boredom ( $\beta = -0.33$ ,  $p < .001$ ), with small and medium effect sizes ( $f^2 = 0.08$  and  $f^2 = 0.17$  respectively). High coping potential, often associated with curiosity (Noordewier & Goçłowska, 2024), could have mitigated learners' perceived uncertainty or cognitive overload in ImVR scenarios, easing anxiety. Learners experiencing curiosity were likely to approach ambiguity or novelty in ImVR environments as opportunities for exploration rather than as epistemic threats. As boredom often emerges from under-stimulation or triviality (Nikitina et al., 2025; Noordewier & Goçłowska, 2024), the desire to seek knowledge, characteristic of curiosity, directly counters disengagement. ImVR environments further amplify curiosity, providing learners with varied informational resources to sustain engagement, a connection also highlighted by Antonopoulos et al. (2024). In contrast, curiosity did not significantly affect confusion or frustration. The absence of a direct connection may reflect the role of curiosity as primarily an exploratory emotion rather than one designed to resolve cognitive dissonance or difficulties.

All in all, it can be supported that curiosity likely capitalizes on ImVR technology's features that spark curiosity, allow them to sustain their attention and cognitive effort, and enrich their desire to pursue educational tasks, while evoking multidimensional emotions (e.g., Akgün & Atıcı, 2022; Antonopoulos et al., 2024; Chirico et al., 2016; Fokides, 2023; Meuleman & Rudrauf, 2018). These may explain why curiosity effectively decreases negative emotions like anxiety and boredom while boosting motivation and, indirectly, learning outcomes.

## 9.6 The role of enjoyment (RQ6a-f)

The findings of the study demonstrate the significant role of enjoyment. It exhibited widespread effects on all examined factors, both directly and indirectly, underscoring its critical function in shaping learning experiences and outcomes. Enjoyment had strong negative effects on anxiety ( $\beta = -0.66, p < .001, f^2 = 0.68$ ), boredom ( $\beta = -0.54, p < .001, f^2 = 0.42$ ), confusion ( $\beta = -0.52, p < .001, f^2 = 0.22$ ), and frustration ( $\beta = -0.64, p < .001, f^2 = 0.43$ ). These findings align with theories such as the CVT and Broaden-and-Build Theory (Fredrickson, 2004; Pekrun, 2024), which posited that positive emotions, including enjoyment, broaden the scope of attention and cognition, indirectly countering the narrowing effects of anxiety, confusion, and

frustration, while, at the same time, countering the disengagement typically associated with boredom (Nikitina et al., 2025).

Enjoyment exhibited a modest direct positive effect on motivation ( $\beta = 0.21, p = .020, f^2 = 0.06$ ). Additionally, the total indirect effect of enjoyment on motivation was moderate ( $\beta = 0.32, p < .001$ ), driven by its impact on reducing negative emotions which are often antithetical to motivation. These findings are consistent with research asserting that enjoyment fosters intrinsic motivation by reinforcing a learner's interest and engagement with the task at hand (e.g., Atsikpasi & Fokides, 2022; Linnenbrink-Garcia et al., 2011). In ImVR settings, the immersive and emotionally engaging nature of the medium likely amplifies this effect, making enjoyment a critical determinant of students' willingness to persist in learning tasks (Antonopoulos et al., 2024).

The direct impact of enjoyment on learning, though modest, was statistically significant ( $\beta = 0.13, p = .046, f^2 = 0.03$ ). Notably, enjoyment also exerted a moderate indirect effect on learning ( $\beta = 0.33, p < .001$ ). These results demonstrate how positive emotions, such as enjoyment, promote a positive emotional climate that facilitates expanded cognitive resources, supporting critical learning processes such as problem-solving, decision-making, and knowledge retention (Fredrickson, 2004; Muis et al., 2015). In the ImVR context, this relationship between enjoyment and learning is particularly pronounced due to the technology's ability to create immersive, high-arousal experiences that foster deep engagement and active participation (Antonopoulos et al., 2024; Li et al., 2022; Makransky & Lilleholt, 2018; Ślósarz et al., 2022).

## 9.7 The role of surprise (RQ7a-f)

Surprise is often triggered by the perception of novelty or unexpectedness, stimulating attention shifts and exploration through its inherently arousing properties (Silvia, 2009; Noordewier & Gołowska, 2024). In the context of this study, surprise significantly influenced learning outcomes, demonstrating a moderate positive direct effect with a large effect size ( $\beta = 0.37, p < .001, f^2 = 0.40$ ). This aligns with previous literature recognizing surprise as a catalyst for deep learning due to its facilitation of adaptive information-seeking behaviors (Silvia, 2009). ImVR environments are particularly well-suited to evoke surprise through novel stimuli, such as the historically rich and emotionally charged narrative of the "Anne Frank House VR" application.

This likely magnified surprise's learning-enhancing potential, fostering richer cognitive processing and retention of material, rendering it instrumental in driving deeper knowledge acquisition.

Unlike enjoyment or curiosity, surprise demonstrated no direct effect on motivation ( $\beta=0.14$ ,  $p = .061$ ). While engaging and stimulating, surprise's impact may be more circumscribed to its ability to prompt immediate cognitive engagement in learning rather than fostering motivational states. This finding underlines distinctions between the roles of various epistemic emotions in learning: enjoyment cultivates persistence and resilience (Nikitina et al., 2025), while curiosity drives intrinsic goal orientation (Noordewier & Gocłowska, 2024); surprise, on the other hand, appears to focus learners' attention on specific incongruities, pulling them into cognitive action for deeper processing rather than pushing them toward broader motivational effects.

Surprise had no direct effect on any of the negative emotions included in this study. This suggests that in ImVR environments, unexpected or disconfirmed expectancies that might evoke surprise (Silvia, 2009) are perceived not as threats (which might increase anxiety) or as cognitively taxing dilemmas (which could contribute to frustration or confusion), but rather as opportunities for exploration and goal-oriented learning behaviors. It can also be supported that surprise operates somewhat independently from the emotional regulation pathways, without necessarily interfering with other emotional states, or that it has a more "transient" nature with effects that do not cascade across other affective domains, at least compared to other emotions; thus, surprise may dissipate quickly once the incongruity is resolved, limiting its broader emotional influence. The study's findings regarding surprise's lack of indirect effects on learning or motivation provide further support to the above assertions.

## 9.8 The role of motivation (RQ8)

Motivation had a statistically significant positive direct effect on learning, albeit modest ( $\beta=0.21$ ,  $p = .018$ ), with a small effect size ( $f^2 = 0.05$ ). Motivation has often been posited as a critical determinant of learning success, particularly through frameworks like Pekrun's CVT (Pekrun, 2006, 2024). The ImVR-based educational application in this study likely fostered motivation. This aligns with findings from others, who reported that ImVR environments enhance intrinsic motivation by offering rich, interactive, and engaging learning settings (e.g., Akgün & Atıcı, 2022; Antonopoulos et al., 2024; Fokides, 2023).

The modest size of the direct effect suggests that while motivation is essential for driving learning outcomes, it is not the sole determinant in ImVR environments. Though the interplay between motivation and other epistemic emotions was discussed in previous sections, it is worth reminding readers some key points. For example, enjoyment and curiosity, exerted direct positive effects on motivation (curiosity:  $\beta=0.16$ ,  $p = .022$ ; enjoyment:  $\beta=0.21$ ,  $p = .020$ ) and further influenced learning indirectly through their impact on motivation. Yet, surprise did not influence motivation, raising intriguing questions about its mechanisms of action in immersive environments, as previously discussed.

On the other hand, negative epistemic emotions, particularly boredom and anxiety, undermined motivation. Anxiety exhibited a direct negative effect on motivation

( $\beta = -0.38, p < .001$ ) and an indirect negative effect on learning ( $\beta = -0.08, p = .030$ ). Similarly, boredom demonstrated direct negative effects on both motivation ( $\beta = -0.28, p < .001$ ) and learning ( $\beta = -0.20, p = .009$ ), along with indirect effects on learning ( $\beta = -0.06, p = .023$ ). These findings are congruent with prior studies (e.g., Pekrun et al., 2017), which suggested that negative emotions narrow cognitive focus and impede knowledge acquisition. However, it is also worth noting that frustration, a traditionally negative emotion, showed a paradoxical modest positive effect on motivation ( $\beta = 0.18, p = .017$ ), perhaps because of its capacity to signal challenges requiring persistence and innovative approaches, as theorized by Pekrun et al. (2017).

### 9.9 The role of gender (RQ9a-i)

Interpretations of observed gender differences in ImVR should be grounded in socio-cultural theory, rather than treated as intrinsic sex-based effects. Given that, the observed differences are interpreted as potentially mediated by gender role socialization, emotion display rules, and learned regulation strategies (Gross & John, 2003), which shape control-value appraisals (Pekrun, 2006, 2024). Moreover, because the sample included only participants identifying as male or female, the findings cannot be generalized to other gender identities. Additionally, it is important to note that although a BCa bootstrapping with 10,000 subsamples was employed, unequal group sizes (81 females; 43 males) can yield less stable estimates in the smaller subgroup. Accordingly, the discussion of gender effects that follows should be considered exploratory.

Gender, a construct influenced by biological, social, and cultural factors, significantly impacts emotional expression and experience in ImVR contexts. It demonstrated modest direct negative effects on anxiety, with males experiencing lower levels of this emotion than females ( $\beta = -0.14, p = .011, f^2 = 0.05$ ). This observation complements the findings of others (e.g., Chaplin & Aldao, 2013) who noted that females are more likely to exhibit internalizing emotions such as anxiety and sadness, which can hinder performance if inadequately managed (Simić et al., 2024). The negative indirect effect of gender on anxiety ( $\beta = -0.21, p = .001$ ) suggests that males might derive greater benefits from other positive emotional factors, such as enjoyment, which mitigate anxiety. Contrary to the findings of past research suggesting that females experience lower levels of boredom (Wang et al., 2024), in the context of ImVR gender did not exert direct effects on this emotion. As with anxiety, gender's indirect negative contribution to boredom ( $\beta = -0.19, p = .002$ ) highlights gender's role in influencing other -positive- affective factors in ImVR applications. As for confusion, gender demonstrated a modest direct negative effect on this emotion ( $\beta = -0.19, p = .012, f^2 = 0.05$ ). Once again, males experienced lower levels of this emotion during ImVR educational activities. Rosser and Soler (2023) observed that women may start educational tasks with more emotionally charged states but remain stable during or after activities. On the other hand, men showed an increase in their emotional responses. In this respect, males' reduced levels of confusion may have allowed them to transition more readily to cognitive processing and task-focused behaviors in ImVR. Gender showed no direct effects on frustration, but indirect negative effects were observed ( $\beta = -0.19, p = .001$ ), indicating that males may better

regulate frustration in ImVR contexts supported by positive activating emotions such as enjoyment and surprise, promoting persistence and task mastery.

Coming to positive emotions, gender exhibited no direct or indirect effects on curiosity, suggesting that this motivational epistemic emotion operates independently of gender in ImVR environments. This neutrality also suggests that curiosity may represent a universal emotional mechanism that drives exploration and intellectual engagement across genders in immersive settings. Gender had moderate direct positive effects on enjoyment, with males reporting higher levels of this emotion than females ( $\beta=0.29, p < .001, f^2 = 0.09$ ). This finding corroborates observations made by others (e.g., Frenzel et al., 2007; Pekrun et al., 2017) that male students, particularly in interactive or hands-on educational contexts, exhibit higher enjoyment levels. In addition, gender exhibited modest direct positive effects on surprise, with males more likely to experience this emotion ( $\beta=0.18, p = .035, f^2 = 0.03$ ). As surprise was linked to higher arousal and approach tendencies in epistemic activities, promoting adaptive information-seeking (Noordewier & Gocłowska, 2024), this might have enabled males to exhibit stronger attentional shifts and adaptive explorations, enhancing their learning outcomes in immersive contexts. Taking together the findings related to the impact of gender on emotions, imply that the gender differences in the strategies used to manage emotions (Gross & John, 2003), might also be applicable in ImVR.

Gender did not exhibit direct effects on motivation, but indirect positive effects were evident ( $\beta=0.28, p < .001$ ). Males probably displayed stronger motivation levels because of elevated positive activating emotions and reduced negative ones. Moreover, gender although it had had no direct effects on learning, indirect effects were observed, with males showing better performance ( $\beta=0.26, p < .001$ ), attributed to the combined influence of positive emotions, reduced negative emotions, and motivation. As ImVR has the ability to engage learners, amplify intrinsic motivation, resulting in better learning outcomes (Akgün & Atıcı, 2022; Antonopoulos et al., 2024; Atsikpasi & Fokides, 2022, Fokides, 2023), this seems to be more relevant to males.

## 9.10 Measurement timing and validity considerations

In line with theorizing that epistemic emotions are dynamic, state-based responses tied to specific knowledge-generating activities, the post-session measurement provides retrospective, combined evaluations of the ImVR experience rather than fine-tuned emotional trajectories. Consequently, the findings should be interpreted as between-person associations among session-level emotions, motivation, and learning. Claims about the temporal ordering of emotions or their evolution during discrete learning moments are beyond the evidential scope of these data. Retrospective reporting is also susceptible to memory reconstruction processes, which can emphasize the most intense or most recent episodes at the expense of earlier transient states. While the internal consistency and discriminant validity of the measures were satisfactory, temporal validity is constrained by the post-hoc timing.

Pedagogically focused ImVR applications typically incorporate goal-directed activities, immediate feedback, and graded challenge. Such designs are known to elicit cycles of curiosity, confusion, and frustration followed by resolution, which can

strengthen learning and motivation. Under these conditions, one would expect stronger positive links from confusion (when resolved) and adaptive frustration to learning and motivation, and weaker effects of surprise. Conversely, narrative historical simulations may amplify awe/surprise and enjoyment of exploration, and may elicit moral-affective states that interact with epistemic emotions. The emotionally charged, Holocaust-centered narrative of “Anne Frank House VR” falls in the second category. Moreover, it likely evoked emotions that were not captured by the Epistemically-Related Emotion Scale (e.g., empathy, sadness, or moral elevation). These unmeasured emotions may have interacted with epistemic emotions, contributing to suppression or amplification effects. Indeed, the significant influence of enjoyment on negative emotions and the strong effect of surprise on learning are consistent with such an assertion. In addition, the pleasure of immersive exploration and the salience of novel historical details probably downregulated anxiety, boredom, and frustration and directed attention toward salient information, facilitating retention. The null effects for confusion align with the absence of problem-solving tasks and system-guided resolution opportunities that typically convert confusion into productive elaboration. The modest positive effect of frustration on motivation may reflect navigational challenges or morally charged engagement rather than adaptive task struggle. Accordingly, the present findings should be interpreted as preliminary and bounded by application characteristics; cross-application validation is required to establish generalizable patterns.”

An additional validity consideration concerns the application’s language. The requirement for English proficiency may have introduced selection bias and potentially influenced both cognitive processing and emotional appraisals. Learning in a second language can increase cognitive load and affect the salience and regulation of emotions compared to native-language conditions.

### 9.11 Implications for research and practice

The study establishes ImVR as a powerful medium for fostering epistemic emotions and advancing educational goals, defining its transformative potential in education. Therefore, its findings call for research, design, and policy efforts that capitalize on the potential of ImVR, ensuring equitable, emotionally engaging, and cognitively enriching learning experiences.

The results underline the necessity of moving beyond prior research that focused on isolated emotions. It highlights the dynamic interplay of emotions and learner characteristics, such as gender, in influencing educational experiences. The refinement of theoretical frameworks, such as CVT and Broaden-and-Build Theory, is essential to understanding the interaction of positive and negative emotions (e.g., curiosity and frustration) in immersive learning contexts. Gendered differences in emotional responses also emerged as a critical finding. This underexplored area calls for systematic research accounting for gender diversity and intersectionality. Researchers should also examine cultural, societal, and content-specific factors in emotional expression and regulation, which could inform the development of inclusive ImVR systems that cater to the emotional needs of diverse learners.

ImVR developers and educators can leverage the medium’s capacity to evoke epistemic emotions, particularly enjoyment and curiosity, to design emotionally engaging

learning experiences. For example, to minimize anxiety while maximizing curiosity, developers can provide clear, choice-rich onboarding that increases perceived control. To reduce boredom while maintaining challenge and sustaining enjoyment, they can introduce micro-challenges, new viewpoints, or interactive artifacts. To harness enjoyment to suppress negative emotions and support learning, they can prioritize interaction quality. To convert frustration into productive struggle while protecting learning, it is suggested to design tasks with clear goals. To manage confusion in ImVR, channeling it toward curiosity, developers can embed just-in-time clarifications, highlight key affordances, and provide miniature concept maps or timelines when ambiguity is high. Recognizing gender influences on emotional experiences, developers must prioritize inclusivity through iterative design processes that reflect the needs of diverse user groups. Finally, to ensure applicability to multicultural and multilingual educational contexts, designers should prioritize localization and cultural inclusivity in ImVR content. This includes developing multilingual versions, adapting narratives for cultural relevance, and engaging stakeholders from diverse communities in participatory design.”

Educators, in turn, should integrate ImVR into curricula to unlock its potential for emotionally rich, experiential learning. Content that fosters enjoyment, curiosity, and surprise, while mitigating anxiety and boredom through tailored interventions, can significantly enhance learning outcomes. Educators must also receive professional development on effective ImVR implementation, equipping them to scaffold students’ emotional experiences, address heightened frustration, and adapt to gendered emotional differences. Finally, partnerships between developers, researchers, and educators are essential to co-create meaningful, standards-aligned ImVR content that supports both academic achievement and emotional engagement.

## **9.12 Limitations and future work**

Although the study provides insights into the dynamics of epistemic emotions, gender, motivation, and learning in ImVR educational contexts several limitations must be addressed to refine future research. First, the relatively homogeneous sample, predominantly university students and skewed towards females (65.3%), constrains the generalizability of findings across diverse age groups, ethnicities, and cultural backgrounds. The English proficiency requirement further introduces selection bias by favoring students with particular language backgrounds; it may also affect emotion and cognition via additional processing demands in a second language. The study’s reliance on the “Anne Frank House VR” application, selected for its historical and emotional content, may have amplified specific emotions while underrepresenting others. The findings should therefore be treated as preliminary and content-bounded, requiring replication across diverse ImVR applications, including ones that are more focused on learning. Additionally, the design captured emotional and cognitive states via a single, post-session self-report. Although this approach avoids interrupting immersion, it does not capture the temporal dynamics of epistemic emotions during specific learning moments and may be subject to retrospective biases. Furthermore, the technical limitations of the Meta Quest headsets, such as graphical quality, may have moderated the intensity of emotional engagement. The lack of hands-on tasks

also reduced opportunities for cognitive-affective states like adaptive frustration. The data collection method (i.e., online questionnaire) could be susceptible to self-report bias. The findings related to gender differences remain exploratory and call for further investigation of the underlying mechanisms like learned emotional regulation or sociocultural norms.

Future research must address these limitations by diversifying participant demographics to include a broader range of age groups, cultural backgrounds, and digital literacy levels. Longitudinal studies are essential for exploring the durability and transformation of emotions over time, as well as their impact on motivation and learning outcomes. Given the apparent content- and task-dependence of emotional profiles in ImVR, researchers should undertake multi-application comparative studies that cross emotional charge (high vs. low) with task interactivity (passive exploration vs. active, goal-directed tasks). Such designs will help establish whether the emotion–learning associations observed here generalize to pedagogically focused applications or are specific to narrative historical simulations. Advancing theoretical models, such as CVT, to account for emotional blends can enhance the understanding of how emotions interact to influence learning. From a technological standpoint, future research should investigate the potential of adaptive ImVR applications that leverage real-time emotion detection and physiological measures to personalize learning experiences. More advanced hardware could amplify immersion and emotional engagement, while custom-designed ImVR environments could systematically evoke and resolve specific emotions, to optimize learning pathways. Incorporating features like problem-solving, collaboration, and adaptive scaffolding will further enrich the emotional and cognitive landscape for future investigations. Finally, future research should incorporate multimethod, time-sensitive designs, such as in-VR experience sampling and unobtrusive psychophysiological signals to elucidate the evolution and coupling of emotions, motivation, and learning over the course of immersive tasks.

## 10 Conclusion

This study illuminates the dynamic interplay between positive and negative emotions, emphasizing their distinct roles in educational contexts. Moreover, gender differences emerged as a meaningful factor in emotional expression and regulation, with males consistently exhibiting lower levels of negative emotions and higher levels of positive emotions. Enjoyment emerged as the most influential epistemic emotion, exerting positive effects on both motivation and learning. Its ability to suppress negative emotions further solidifies its role in immersive educational settings. Curiosity similarly contributed to motivation and indirectly fostered learning by countering disengagement and promoting intellectual exploration. Surprise played a unique role by directly enhancing learning outcomes, albeit independently from other emotions, highlighting its capacity to drive deeper cognitive engagement. In contrast, negative epistemic emotions like anxiety and boredom proved detrimental to both motivation and learning. Anxiety directly reduced motivation and indirectly hindered learning, while boredom negatively impacted both constructs and fostered disengagement. Frustration exhibited a dual nature, a paradoxical enhancement of motivation paired with a

detrimental effect on learning outcomes, emphasizing its complex role in immersive educational environments. Interestingly, confusion did not directly affect either motivation nor learning. Gender differences further refined the understanding of emotional responses in ImVR settings. Male participants demonstrated higher levels of enjoyment and surprise along with lower levels of anxiety and confusion, positioning them as more emotionally resilient in immersive learning environments. The explanatory power of the study's model is notable, accounting for significant proportions of variance in motivation and learning, as well as providing insights into the interconnections between emotions, gender, motivation, and academic outcomes. In conclusion, the findings underline the central role of epistemic emotions in shaping learning experiences, particularly within cutting-edge technologies like ImVR, where immersion and emotional engagement converge to create impactful educational experiences.

## Appendix

**Table 4** Items' loadings

Items	Factors							
	Anxiety	Boredom	Confusion	Curiosity	Enjoyment	Frustration	Surprise	Motivation
Amazed							0.92	
Astonished							0.89	
Surprised							0.91	
Excited					0.94			
Happy					0.92			
Joyful					0.88			
Inquisitive				0.78				
Interested				0.93				
Curious				0.88				
Bored		0.92						
Dull		0.89						
Monotonous		0.90						
Confused			0.89					
Muddled			0.88					
Puzzled			0.77					
Dissatisfied						0.90		
Frustrated						0.94		
Irritated						0.88		
Nervous	0.89							
Worried	0.89							
Anxious	0.92							
Motivation1								0.87
Motivation2								0.85
Motivation3								0.87
Motivation4								0.87
Motivation5								0.86
Motivation6								0.82

**Table 5** Internal consistency, reliability, and convergent validity

Factor	Cronbach's $\alpha$	Composite reliability ( $\rho_A$ )	AVE
Anxiety	0.89	0.89	0.81
Boredom	0.89	0.89	0.81
Confusion	0.81	0.84	0.72
Curiosity	0.84	0.90	0.75
Enjoyment	0.90	0.90	0.83
Frustration	0.89	0.89	0.82
Surprise	0.89	0.89	0.82
Motivation	0.93	0.93	0.73

**Table 6** Discriminant validity (HTMT analysis)

Anxiety	Anxiety	Boredom	Conf.	Curiosity	Enjoyment	Frustr- tra- tion	Sur- prise	Gen- der	Learn- ing	Mot.
Boredom	0.85									
Confusion	0.61	0.54								
Curiosity	0.60	0.69	0.34							
Enjoyment	0.87	0.82	0.60	0.57						
Frustration	0.72	0.73	0.60	0.43	0.76					
Surprise	0.60	0.63	0.28	0.71	0.71	0.49				
Gender	0.37	0.29	0.36	0.11	0.31	0.31	0.19			
Learning	0.78	0.84	0.51	0.68	0.85	0.72	0.83	0.27		
Motivation	0.89	0.87	0.53	0.74	0.84	0.57	0.72	0.22	0.84	

**Table 7** Multicollinearity analysis

Item	VIF	Item	VIF
Amazed	2.89	Joyful	2.34
Anxious	2.81	Monotonous	2.43
Astonished	2.44	Muddled	2.02
Bored	2.88	Nervous	2.36
Confused	1.94	Puzzled	1.53
Curious	2.19	Surprised	2.60
Dissatisfied	2.84	Worried	2.49
Dull	2.39	Motivation1	3.16
Excited	3.50	Motivation2	3.06
Frustrated	3.68	Motivation3	3.19
Happy	3.16	Motivation4	3.27
Inquisitive	1.66	Motivation5	3.10
Interested	2.50	Motivation6	2.45
Irritated	2.26		

**Table 8** The PLSpredict results

Item	RMSE (PLS-SEM model)	RMSE (LM model)	Difference
Nervous	1.031	1.032	-0.001
Worried	1.072	1.077	-0.005
Anxious	1.072	1.074	-0.002
Dull	1.375	1.376	-0.001
Monotonous	1.222	1.224	-0.002
Bored	1.309	1.31	-0.001
Confused	1.045	1.047	-0.002
Muddled	0.922	0.923	-0.001
Puzzled	0.844	0.849	-0.005
Interested	0.906	0.907	-0.001
Curious	0.919	0.922	-0.003
Inquisitive	0.88	0.886	-0.006
Excited	1.129	1.13	-0.001
Happy	1.155	1.155	0
Joyful	1.082	1.071	0.011
Irritated	1.196	1.198	-0.002
Dissatisfied	1.292	1.293	-0.001
Frustrated	1.323	1.325	-0.002
Astonished	1.119	1.123	-0.004
Amazed	1.094	1.095	-0.001
surprised	1.062	1.063	-0.001
Performance	3.419	3.419	0
Motivation4	1.134	1.136	-0.002
Motivation2	1.195	1.199	-0.004
Motivation6	1.07	1.071	-0.001
Motivation3	1.035	1.037	-0.002
Motivation1	1.027	1.011	0.016
Motivation5	1.217	1.214	0.003

PLS-SEM model and those based on a naïve linear regression model (LM)

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**Data availability** Data will be made available on reasonable request from the author.

## Declarations

**Informed consent statement.** The study's participants volunteered, understood that they could withdraw from the experiment at any time, and provided their informed consent. They were protected by hiding their personal information; no personal data were collected and/or processed.

**Ethical statement** The author declares that this manuscript is the result of his independent creation under the reviewers' comments. This manuscript does not contain any research achievements that have been published or written by other individuals or groups, or by AI tools.

**Institutional review board statement** The research was conducted in compliance with all relevant legislative frameworks and institutional protocols. This study is an integral component of an ongoing research project, for which the Research and Ethics Committee of the Department of Primary Education at the

University of the Aegean evaluated and formally approved its methodologies and practices. During the preparation of this work the author used Ghostwriter in order to improve language and readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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