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PAPER

Investigating Emotions in Virtual Reality-Based Learning Environment: Cognitive Load, Academic Performance, and Knowledge Exploration

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ABSTRACT

The present study examined the potential of virtual reality (VR) as a tool for eliciting epistemic emotions and enhancing learning outcomes. A total of 150 undergraduate Psychology students engaged in a VR-based learning application. Following their interaction, participants reported a range of epistemic emotions, including two positive (curiosity and enjoyment), four negative (confusion, anxiety, frustration, and boredom), and one neutral emotion (surprise). They also completed a knowledge assessment based on the application's content, along with self-report measures of cognitive load and the extent of their knowledge exploration. Findings demonstrated that VR environment evoked a diverse spectrum of epistemic emotions. Path analysis revealed significant positive effects of both task performance and perceived application's cognitive load on negative emotions, particularly confusion. Surprise emerged as a pivotal emotional stimulus, positively predicting curiosity and enjoyment. These positive emotions, in turn, significantly predicted knowledge exploration. Directions for future research and educational implications are discussed.

KEYWORDS

epistemic emotions, curiosity, confusion, knowledge exploration, surprise, virtual reality (VR)

1 INTRODUCTION

Virtual reality (VR) has emerged as a promising tool for education and learning, offering new possibilities for immersive and interactive instructional experiences. In recent years, there has been growing interest in harnessing VR technologies to support and enhance educational processes [1]. The number of studies examining VR in educational contexts has increased substantially, with evidence suggesting that VR applications can positively influence learning outcomes, engagement, and conceptual understanding [2]. VR environments allow users to experience highly immersive and interactive simulations that would otherwise be inaccessible in real-world

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settings [4]. Consequently, VR has been successfully applied across diverse domains, including science education, medical training, and language learning, highlighting its adaptability and broad pedagogical potential [3]. Recent systematic reviews further confirm the growing impact of VR in education, emphasizing its effectiveness in promoting experiential learning, engagement, and skill development, while also noting variability depending on instructional design and context [6].

However, the effectiveness of VR for learning is not unequivocal. Jensen and Konradsen [5] reported that head-mounted displays show limited effectiveness in fostering cognitive, motivational, and affective outcomes when compared to less immersive technologies. At the same time, other studies highlight that VR enhances the sense of presence and immersion, which can intensify emotional responses during learning. For instance, Makransky et al. [7] found that students using immersive VR simulations reported higher levels of curiosity and interest compared to those using desktop-based environments, which contributed to deeper cognitive engagement. Conversely, Parong and Mayer [8] demonstrated that learners in VR environments may also experience increased cognitive load and confusion, suggesting that immersive environments can simultaneously support and hinder learning processes. These mixed findings indicate that the effectiveness of VR is strongly dependent on instructional design, cognitive demands, and the interaction between emotional and cognitive processes, rather than on immersion alone.

In this context, emotions have been increasingly recognized as central to learning processes [9]. Among these, epistemic emotions, such as curiosity, confusion, and surprise, are directly linked to knowledge construction and cognitive processing [12], [14]. These emotions arise in response to cognitive incongruity, uncertainty, and the evaluation of information, and they play a critical role in shaping engagement and learning outcomes. Importantly, according to Control-Value Theory, such emotions are influenced by learners' appraisals of control and task value, providing a strong theoretical framework for understanding emotional experiences in VR learning environments. More specifically, the present study is anchored in Control-Value Theory, which posits that learners' emotions emerge from their appraisals of control over learning activities and the subjective value they assign to these activities. In VR-based learning, these appraisals may be especially salient because immersive environments can simultaneously increase perceived novelty, task complexity, and personal involvement. From this perspective, cognitive load and task performance can be understood as indicators shaping learners' sense of control, whereas knowledge exploration reflects the motivational consequences of epistemic emotions. Thus, the present study does not assume that VR directly improves learning; rather, it examines whether VR constitutes a context in which specific cognitive appraisals are associated with distinct epistemic emotions and, in turn, with exploratory learning behavior.

Although VR has been widely promoted as an innovative and effective educational tool, its benefits are not universally consistent across learning contexts. Emerging evidence suggests that increased immersion does not automatically translate into improved learning outcomes. In fact, highly immersive environments may impose additional cognitive demands on learners, leading to increased cognitive load and, in some cases, confusion. For example, Parong and Mayer [8] demonstrated that learners in VR environments reported higher levels of confusion compared to those in less immersive conditions, despite experiencing greater engagement. This indicates that the richness and complexity of VR environments can overwhelm learners' cognitive resources, particularly when instructional design is not carefully aligned with learning objectives. As such, the effectiveness of VR depends not only on its immersive qualities but also on how cognitive load is managed and how information is structured within the environment. These findings highlight the importance of adopting a critical perspective on VR, recognizing that its educational value is contingent upon thoughtful design rather than immersion alone.

1.1 Epistemic emotions

In educational psychology, the term epistemic emotions refer to a distinct subset of academic emotions that are specifically elicited by the processes of knowledge acquisition, comprehension, and problem-solving [9], [11]. These emotions, such as curiosity, confusion, and surprise, are closely tied to cognitive engagement and are triggered by situations involving uncertainty, complexity, or the pursuit of understanding [9], [25]. Epistemic emotions arise from the cognitive information in a task as well as from the subsequent processing of this information [12], [13]. Their developmental mechanism involves acquiring knowledge by directing attention toward important stimuli, persisting in task completion even when it is particularly difficult, and cognitively seeking new ideas and information [13].

The basic epistemic emotions include curiosity, confusion, and surprise. These emotions are epistemic by nature, whereas others, such as frustration, boredom, anxiety, and enjoyment, can belong to various categories of emotion depending on their object focus [9]. Curiosity is one of the most significant emotions for learning, as it represents a motivational force or desire to seek knowledge, acquire new information, and bridge knowledge gaps [17]. Specifically, curiosity is a motivational state driven either by the pleasurable desire to learn new things (interest-type) or by the need to reduce uncertainty and close knowledge gaps (deprivation-type) [18]. Confusion, on the other hand, is considered a negative emotion that arises from the inability to integrate inconsistent or contradictory information [10], [20]. It is triggered when informational conflict occurs and when the individual encounters cognitive impasses [10]. Surprise is an emotional reaction to unexpected events [22] and results from a mismatch between one's cognitive schemas and new information [23], [24].

However, according to the definition, any emotion that is directed toward the knowledge aspect of a task can be classified as epistemic [12]. For example, enjoyment, boredom, and frustration have also been recognized as epistemic emotions [25]. Enjoyment is a positive, activating emotion that arises when curiosity is satisfied or when confusion is resolved [16]. This emotional state encourages engagement and fosters a desire for continued exploration or participation. Boredom is a negative, deactivating emotion triggered by the perception that a task is dull, repetitive, or insufficiently challenging. It often results in disengagement and reduced motivation to continue exploring or processing information [9]. Frustration is a negative, activating emotion that emerges when learners encounter obstacles or difficulties preventing them from progressing toward their goals. Frustration and boredom often emerge when cognitive incongruity remains unresolved [10], whereas anxiety may also arise in response to severe incongruity or when new information fundamentally challenges existing beliefs [25].

1.2 Origins and outcomes of epistemic emotions

Epistemic emotions originate primarily from cognitive processes involved in knowledge acquisition, problem-solving, and comprehension activities [16].

They arise in response to cognitive appraisals of situations involving uncertainty, novelty, incongruity, or complexity during learning and knowledge exploration [25]. Specifically, emotions such as curiosity, confusion, and surprise emerge when learners encounter new information or face challenges in understanding complex or unexpected material [10]. Surprise often arises first when learners are confronted with unexpected or schema-incongruous information [21]. Curiosity typically arises from perceived knowledge gaps or novel information, while confusion emerges when learners experience cognitive disequilibrium or contradiction between expectations and actual observations [20]. When learners face challenges that stretch their current abilities, a moderate level of cognitive load can spark curiosity and deeper cognitive processing [12]. However, if the task exceeds learners' perceived capacity, confusion may escalate into frustration or boredom, resulting in diminished motivation to continue [10]. Consequently, the degree of perceived task cognitive load and task performance play a pivotal role in shaping how epistemic emotions emerge and evolve during complex learning activities [13].

This theoretical perspective is particularly relevant for immersive learning environments. VR does not simply deliver information; it structures how learners attend to, interpret, and emotionally react to information. Accordingly, epistemic emotions in VR should be interpreted as emerging from the interaction between learner appraisals and task characteristics, rather than as automatic products of immersion itself. This distinction is important because it clarifies that the educational value of VR depends on how the environment shapes perceived control, novelty, and cognitive challenge.

Regarding outcomes, epistemic emotions play a key role in facilitating knowledge acquisition and are essential for knowledge construction, conceptual development, and knowledge exploration [9], [11], [13]. Surprise can serve as a trigger for emotional responses such as interest, curiosity, and confusion [13], [14]. Positive epistemic emotions such as curiosity and enjoyment enhance motivation, promote deeper cognitive processing, and lead to information-seeking behaviors [13], [19].

Conversely, negative epistemic emotions such as confusion can have dual outcomes. Mild or temporary confusion may stimulate deeper learning and critical thinking, prompting learners to resolve cognitive conflicts through greater effort and exploration [10]. However, prolonged or intense confusion, boredom, or frustration may reduce motivation, hinder learning, and result in disengagement or avoidance behaviors [25]. To illustrate, D'Mello and Graesser [10] argued that although confusion can briefly foster deeper engagement, prolonged uncertainty may lead to frustration if learners feel increasingly blocked from making progress. Over time, repeated difficulties and a perceived lack of progress can transform this confusion into boredom, characterized by low arousal and reduced motivation to continue. Consequently, confusion acts as a pivotal emotion that, if unresolved, can escalate into frustration or boredom, ultimately hindering learning and achievement.

In conclusion, limited studies have simultaneously examined multiple epistemic emotions to investigate their shared antecedents and outcomes [10], [11], [13]. Moreover, research systematically comparing the origins and outcomes of epistemic emotions within a virtual learning environment remains limited. For example, while studies often separately explore curiosity or confusion, very few investigate how these emotions interact or jointly influence learners' performance or exploratory behaviors in immersive virtual contexts.

1.3 Present study

Present study aimed to examine the antecedents, interrelations, and effects of basic epistemic emotions (surprise, curiosity, confusion, boredom, anxiety, enjoyment and frustration) within a VR learning task. Specifically:

Hypothesis 1: Cognitive load and performance will be associated with epistemic emotions in different ways. Specifically, cognitive load will be negatively associated with positive epistemic emotions (e.g., enjoyment, curiosity) and positively associated with negative epistemic emotions (e.g., confusion, frustration, boredom, anxiety). In contrast, performance will be positively associated with positive epistemic emotions and negatively associated with negative epistemic emotions. Furthermore, positive epistemic emotions are expected to be positively interrelated, while negative epistemic emotions are also expected to be positively interrelated.

Hypothesis 2: Cognitive load and performance will significantly predict confusion (H2a), as confusion typically arises when learners experience cognitive disequilibrium during knowledge acquisition [11]. In turn, confusion will positively predict frustration and boredom (H2b), as unresolved cognitive incongruity may lead to disengagement and negative affective responses.

Hypothesis 3: Cognitive load will negatively predict surprise, as excessive cognitive demands may reduce the likelihood of experiencing initial epistemic reactions, such as surprise, to learning stimuli [13], [14]. Surprise will positively predict curiosity and enjoyment (H3a), reflecting its role as an activating epistemic emotion [15]. Finally, curiosity and enjoyment will positively predict knowledge exploration (H3b), with curiosity expected to be the strongest predictor due to its central role in motivating information-seeking behavior.

2 METHODS

2.1 Participants

The study sample comprised 150 Psychology students from the authors' university. Of these, 63.3% were women, with an average age of 21.91 years (SD = 5.97). Participation was voluntary and anonymous.

2.2 Materials

Virtual reality learning environment. The primary tool utilized in this study was the "Anne Frank VR House" application, which allows users to explore the Secret Annex where Anne Frank, a Jewish girl, hid during World War II in Amsterdam. The "Anne Frank VR House" is a freely available application for the Oculus Meta Quest 2, developed by Force Field VR in collaboration with the Anne Frank Foundation. This immersive experience provides users worldwide with a unique opportunity to engage with history interactively, serving as an innovative educational tool for learning about the Holocaust and the experiences of the Frank family. By allowing users to virtually navigate through the rooms of the Secret Annex, the VR application fosters a deeper emotional connection to historical events.

This interactive approach to education may be more effective than traditional learning methods, as it enables users to experience the challenges and fears faced by individuals during that time. The virtual recreation of the Frank family's hiding place is an authentic representation of the original house. Although the application does not depict any of the individuals who lived there, it effectively conveys the daily reality of life in hiding. The VR environment incorporates two key technologies: a Head-Mounted Display (HMD) and two connected controllers. Upon entering virtual space, participants are introduced to a narration about Anne Frank's life, offering essential historical and social context. They are then placed in front of a bookcase, which conceals the entrance to the hiding place. Using their right hand, they slide the bookcase open, revealing a hallway with multiple doors. Participants explore all eight rooms of the house, beginning in Anne's room and concluding in the attic. They navigate the space by moving their heads, allowing them to discover different areas within the hiding place. The controllers enable interaction with objects and narrations found in each room. Users have the freedom to move throughout the environment while immersing themselves in Anne's thoughts, as excerpts from her diary are narrated during their journey. The experience is further enriched by narrations and audio stimuli, including passages from Anne Frank's diary read aloud to add emotional depth. Additionally, sound effects, such as the rumbling of tanks and air raid sirens, enhance the sense of historical realism, making the experience more immersive and impactful.

Prior knowledge of historical events was assessed using a pre-test developed by the authors for the purposes of the present study. The scale consisted of 10 items related to the historical content of the VR application and demonstrated a unidimensional structure with satisfactory internal consistency (Cronbach's $\alpha = 0.82$).

Performance questionnaire. To measure knowledge acquisition (i.e., performance), participants were asked to answer ten questions directly related to the content of the application. The maximum score for the questionnaire is 10 points (1 point for each correct answer). Students completed the questionnaire after using the VR application. A sample item is: "In which room did Anne Frank spend most of her time writing her diary?" (multiple-choice format). The total score ranges from 0 to 10, with higher scores indicating greater knowledge acquisition. As the instrument consists of objective knowledge items (correct/incorrect responses), internal consistency reliability (Cronbach's α) is not applicable.

Epistemic emotions questionnaire. The Epistemically- Related Emotion Scales is a tool used to measure emotions associated with cognitive processes such as knowledge acquisition. It was developed by Pekrun and colleagues [9]. The scale consists of 21 items measuring the emotions of surprise, curiosity, confusion, boredom, enjoyment, anxiety, and frustration. It includes two positive emotions (curiosity, enjoyment), four negative emotions (boredom, confusion, anxiety, frustration), and one neutral emotion (surprise). Participants are asked to indicate the extent to which they experienced each emotion using a 5-point Likert scale (1 = not at all to 5 = very much). Factor analysis revealed seven distinct factors, one for each emotion, demonstrating satisfactory internal consistency, with Cronbach's alpha ranging from $\alpha = 0.76$ to 0.88.

Knowledge exploration questionnaire. The scale measures participants' knowledge exploration after the VR applications. It consists of six statements rated on a 5-point Likert scale (1 = not at all to 5 = very much). A sample item is: "I would like to learn more about the app". A sample item is: "I would like to learn more about the app". The scale range is from 1 to 5, with higher scores indicating greater willingness to explore further knowledge. The scale was adapted for the purposes of this study. Internal consistency in the present study was satisfactory (Cronbach's $\alpha = 0.79$).

2.3 Procedure

The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the authors' university. Data collection took place in person in a specially designated room at the university. Individual appointments were scheduled with each participant to ensure a structured and personalized approach. Before participation, all individuals were thoroughly informed about the study's objectives and provided written consent. They were also made aware of their right to withdraw from study at any point without obligation to complete the research. Given that participants had no prior experience with binocular VR headsets, they first received verbal instructions on navigating the virtual environment, putting them on the headset, and using the controllers. They were also briefed on the boundaries of the "application area", a system designed to alert users when they approach the limits of the permitted space to prevent accidents.

After receiving these initial instructions, participants donned the headset and adjusted the interpupillary distance and straps to optimize image quality. They were then allowed approximately five to ten minutes to familiarize themselves with the virtual environment. Additional guidance was provided as needed, particularly for those experiencing significant challenges with navigation or interaction. This preparatory process was essential to ensure participants felt at ease using the VR application.

3 RESULTS

All analyses were conducted using the statistical software SPSS (version 29). No missing data was identified. Multivariate normality was assessed by examining item skewness and kurtosis, with all values falling within acceptable thresholds (skewness $< |2|$ and kurtosis < 7). Preliminary analyses included the computation of means, standard deviations, and intercorrelations among the study variables (Matsunaga, 2010). Descriptive statistics are presented in Table 1.

Table 1. Descriptive statistics of study's variables

	Min	Max	M	SD
curiosity	1.00	5.00	3.64	0.79
surprise	1.00	5.00	3.34	0.95
confusion	1.00	5.00	2.02	0.63
anxiety	1.00	5.00	1.89	0.85
enjoyment	1.00	5.00	3.33	1.06
frustration	1.00	5.00	1.58	0.92
boredom	1.00	4.00	1.29	0.48

(Continued)

Table 1. Descriptive statistics of study's variables *(Continued)*

	Min	Max	M	SD
cognitive load	1.00	4.00	2.17	0.45
performance	0.00	9.00	4.52	1.68
knowledge exploration	1.00	5.00	3.96	0.84

Furthermore, Pearson correlations were calculated to explore the relations between the study variables. The correlations between epistemic emotions ranged from $r = -0.190$, $p = 0.03$, to $r = 0.576$, $p < .001$ (refer to Table 2).

Table 2. Pearson correlations between variables

Variable	1	2	3	4	5	6	7	8	9
1. curiosity	–								
2. surprise	0.535**	–							
3. confusion	–	–	–						
4. anxiety	–0.195*	–	0.439**	–					
5. enjoyment	0.390**	0.659**	–0.244**	0.447**	–				
6. frustration	–0.184*	–0.186*	0.402**	0.404**	–0.576**	–			
7. boredom	–0.184**	–0.291**	0.183*	0.534**	–0.406**	0.424**	–		
8. cognitive load	–0.193**	–0.259*	0.405**	0.621**	–0.259**	0.235**	0.248**	–	
9. performance	0.196**	–	–	–0.292**	0.190*	–	–0.191**	–0.276**	–
10. knowledge exploration	0.526**	0.539**	–	–0.345**	0.458**	–	–0.242**	–0.406**	–

Note: **$p < 0.01$, *$p < 0.05$.

To further investigate the potential role of epistemic emotions in VR task, path analysis was applied to the data. Direct paths were drawn from: (a) cognitive load to confusion, (b) from task performance to confusion, and (c) from confusion to both boredom and frustration. Indirect paths were also tested. Path analysis indicated that the hypothesized model had a good fit to the data. Model modifications were guided by modification indices and theoretical plausibility, allowing for minor adjustments that improved model fit without altering the conceptual structure. To assess whether the data aligned with the proposed model, we calculated several fit indices. To evaluate the strength of the relationships between two variables, we computed the standardized path coefficients (β), along with the standard error (SE) and two-tailed p-values, considering significance at $p < 0.05$.

For model fit assessment, the following indices were estimated: (i) the comparative fit index (CFI), with values ≥ 0.95 indicating excellent fit, (ii) the Tucker-Lewis index (TLI), with values ≥ 0.90 indicating acceptable fit, (iii) the root mean square error of approximation (RMSEA), with values ≤ 0.08 indicating acceptable fit, (iv) the standardized root mean square residual (SRMR), with values ≤ 0.08 indicating good fit, (v) PClose, with values > 0.05 indicating close fit, and (vi) the chi-square to degrees of freedom ratio (χ^2/df), with values ≤ 3 indicating acceptable fit (Hu and Bentler, 1999). The model demonstrated an acceptable but not optimal fit to the data, $\chi^2 = 34.9$, p = 0.01, CFI = 0.96, TLI = 0.90, RMSEA = 0.08, SRMR = 0.06. Therefore, the model should be interpreted with some caution. The R-squared (R^2) values were examined to assess the proportion of variance explained by the model for each variable (see Figure 1).

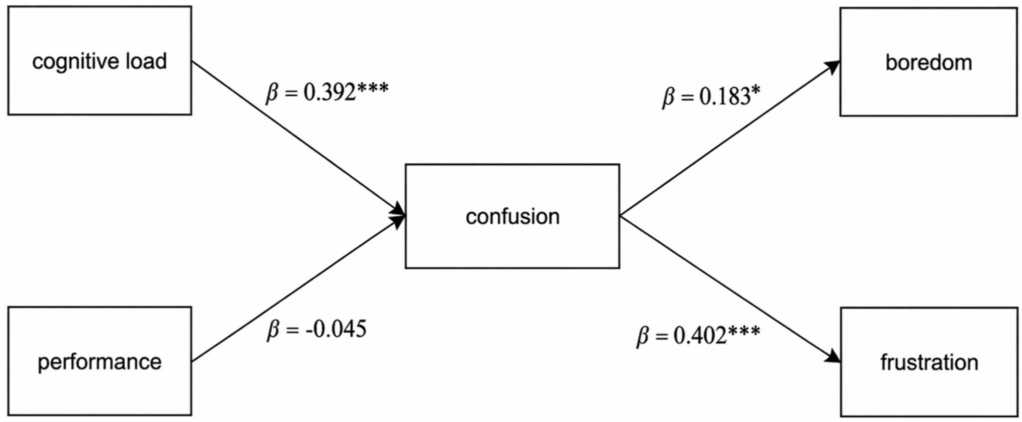

Fig. 1. The path model of negative emotions

Note: ***$p < 0.001$, *$p < 0.05$.

The path analysis revealed significant relationships among cognitive load, task performance, confusion, boredom, and frustration. Specifically, cognitive load was found to positively predict confusion with a strong significant path coefficient, indicating that higher cognitive load is associated with greater confusion. Task performance had a small, non-significant negative effect on confusion. Furthermore, confusion significantly influenced both boredom and frustration. It had a significant positive relationship with boredom, as well as a stronger positive relationship with frustration. This indicates that participants experiencing higher levels of confusion also tended to report increased boredom and particularly elevated frustration levels.

For the second model, the following fit indices were estimated: the CFI, with values ≥ 0.95 indicating excellent fit; the TLI, with values ≥ 0.90 indicating acceptable fit; the root mean square error of approximation (RMSEA), with values ≤ 0.08 indicating acceptable fit; the standardized root mean square residual (SRMR), with values ≤ 0.08 indicating good fit; PClose, with values > 0.05 indicating close fit; and the chi-square to degrees of freedom ratio (χ^2/df), with values ≤ 3 indicating acceptable fit (Hu & Bentler, 1999). The model demonstrated a good overall fit to the data, $\chi^2(5) = 23.27$, $p < 0.01$, CFI = 0.98, TLI = 0.92, RMSEA = 0.05, SRMR = 0.05, PClose = 0.06. Although the chi-square test was significant, the remaining fit indices indicated a good model fit. The R-squared (R^2) values were examined to assess the proportion of variance explained by the model for each variable (see Figure 2).

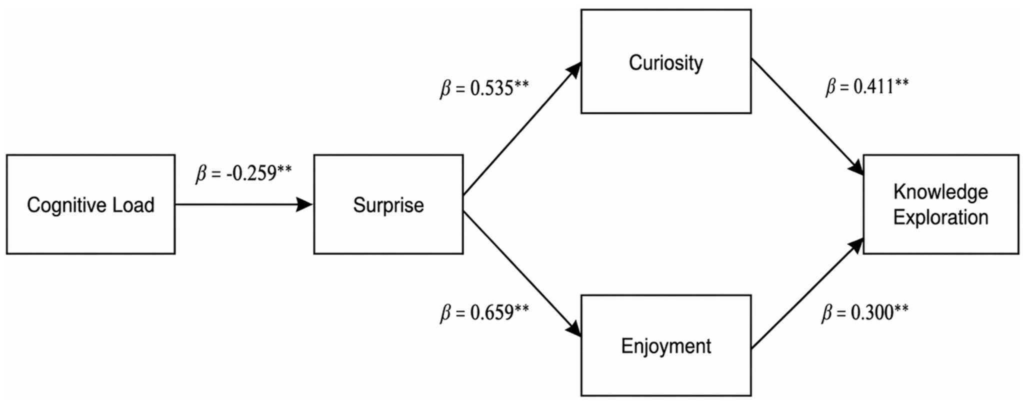

Fig. 2. The path model of positive epistemic emotions

Note: **$p < 0.01$.

4 DISCUSSION

The current study aimed to investigate how VR influences the activation of basic epistemic emotions and their interaction with key cognitive factors, including cognitive load, performance, and knowledge exploration. Although the role of emotions in learning has gained growing attention in recent years, empirical research on the emotional impact of immersive VR remains limited. Even fewer studies have explored the underlying psychological mechanisms through which immersion in VR environments shapes emotional responses that may, in turn, promote knowledge exploration [25]. The findings of this study offer practical implications for educational interventions by highlighting ways to enhance positive epistemic emotions, such as curiosity, while also addressing and managing negative emotions such as frustration and confusion that may arise in VR-based learning contexts.

Overall, the findings provided partial support for the proposed hypotheses. More specifically, the correlational results were broadly consistent with Hypothesis 1, showing that positive epistemic emotions were positively interrelated and linked to knowledge exploration, whereas negative emotions were positively associated with one another and with cognitive load. However, the path analyses offered a more differentiated pattern than originally hypothesized. Rather than showing uniformly beneficial effects of performance on positive emotions and uniformly negative effects on negative emotions, the results indicated that performance had a limited and selective role, whereas cognitive load emerged as the more robust antecedent of epistemic emotional experiences in the VR task. Thus, the findings suggest that learners' emotional responses in immersive environments may be shaped more strongly by perceived cognitive demands than by success on the knowledge test alone.

In line with Hypothesis 1, the findings reveal a complex network among epistemic emotions, cognitive factors, and learning outcomes within a VR context. Positive epistemic emotions were significantly and positively interrelated, aligning with previous research [13]. Curiosity, enjoyment, and surprise demonstrated strong correlations with knowledge exploration, further supporting their role in promoting active and meaningful engagement with learning content [13], [19]. Conversely, negative emotions showed positive correlations with one another, as well as with cognitive load, indicating that challenging tasks can intensify negative emotional experiences [10]. Specifically, confusion was positively associated with frustration and boredom [10]. D'Mello and colleagues argued that affective states such as confusion, and perhaps frustration, are likely to occur during cognitive disequilibrium, while affective states such as boredom and flow typically occur during cognitive equilibrium.

With regard to Hypothesis 2, the findings supported the central role of confusion as a transitional epistemic emotion. As expected, cognitive load and performance were linked to confusion, and confusion, in turn, predicted boredom and frustration. However, the effect pattern was not fully symmetrical. Cognitive load was the stronger predictor, whereas performance showed a weaker contribution. Therefore, Hypothesis 2 was supported in directional terms, but the results underscore that confusion in VR learning may be driven primarily by the subjective experience of processing demands rather than by performance outcomes per se.

Furthermore, the path analysis revealed that cognitive load significantly and positively predicted confusion, suggesting that higher cognitive load intensified learners' feelings of confusion. By contrast, task performance showed a small, non-significant association with confusion. Thus, confusion was predicted primarily by cognitive load and only weakly by performance. According to Muis et al. [11], confusion is triggered by the perception that one lacks understanding of the content. In VR, this perception can be amplified due to the sensory-rich and often novel interface, which can increase the cognitive complexity of the task. Moreover, confusion significantly predicted boredom and frustration, with stronger effects on frustration. These findings support the notion that unresolved cognitive incongruity often escalates negative epistemic emotions [10]. Specifically, prolonged confusion without effective resolution may lead to frustration, which in turn impairs learners' motivation and cognitive engagement [13].

Hypothesis 3 also received partial support. Consistent with expectations, surprise predicted curiosity and enjoyment, and both positive emotions predicted knowledge exploration. These findings align well with theoretical models describing surprise as an activating epistemic emotion that can initiate further cognitive and motivational engagement. At the same time, the results refine the original hypothesis by showing that the pathway from cognitive load to exploration was largely indirect, operating through surprise, curiosity, and enjoyment rather than through a simple direct effect. The data supports a mediated emotional process in which positive epistemic emotions function as proximal drivers of exploratory behavior in VR learning. According to emotion theories, surprise is typically elicited by unexpected events, not necessarily challenging ones [21]. In a VR setting, high cognitive load may reduce surprise because the immersive environment sets expectations for complexity, making cognitive load anticipated rather than novel. In turn, surprise strongly predicted both curiosity and enjoyment, highlighting its key role in activating positive epistemic emotions. The data demonstrate that both enjoyment and, especially, curiosity were positively related to subsequent motivation to explore. These findings are consistent with previous literature emphasizing the beneficial effects of surprise in stimulating curiosity and enjoyment, thereby promoting effective knowledge-seeking behaviors [13]. Educators and instructional designers could therefore consider integrating elements of novelty or unexpectedness into VR learning tasks to foster positive emotional engagement and optimize learning outcomes.

Taken together, the present findings suggest that epistemic emotions in VR-based learning are not uniformly positive or negative but are dynamically organized around learners' appraisals of cognitive challenge and novelty. In this sense, the study extends prior work by showing that confusion may function as a key pathway through which demanding VR experiences lead to adverse emotional outcomes, whereas surprise may serve as an entry point to curiosity, enjoyment, and knowledge exploration. The results therefore only partially confirm the initial hypotheses, but they offer a more theoretically precise account of how cognitive and emotional processes may interact in immersive learning environments.

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Conflicts of interest: The authors declare no conflicts of interest.

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