Exploring Emotional Memory Encoding and Recall in Virtual Reality

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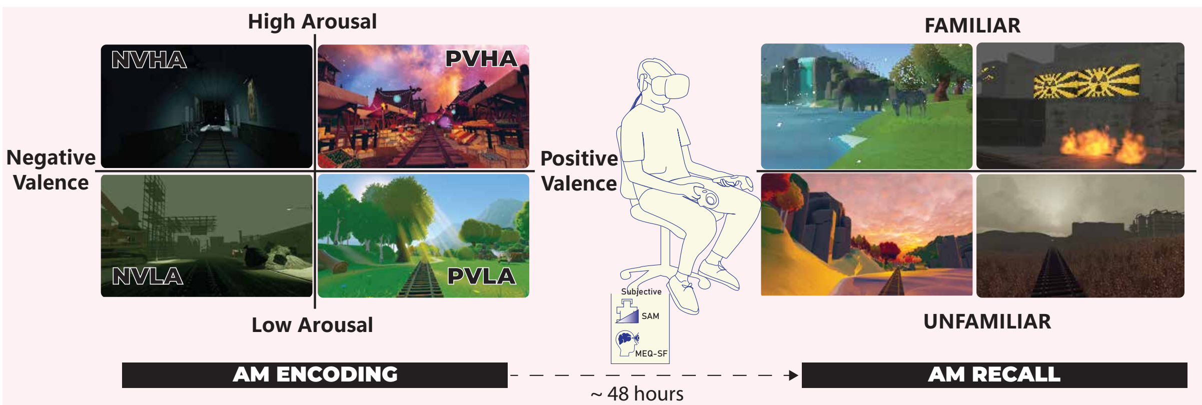

Figure 1: Study design for evaluating autobiographical memory (AM) in VR. Participants encoded memories in VR environments varying in valence (positive/negative) and arousal (low/high). Memory recall was tested after 48 hours in familiar and unfamiliar scenes, with subjective measures assessed using SAM and MEQ-SF.

Abstract

This study investigates the effects of emotional and spatial contexts on autobiographical memory recall in virtual reality (VR). In a two-session experiment (N=8), participants encoded memories in VR scenes themed for fear, excitement, relaxation, or boredom, then recalled either those scenes or unfamiliar ones after 48 hours. We collected both subjective measures (e.g., emotional intensity, vividness) and behavioral metrics (e.g., recall accuracy, response time). Results revealed that VR effectively induced target emotions, with high-arousal environments enhancing vividness and emotional engagement during recall. Familiar scenes improved memory vividness, accessibility, and emotional intensity, demonstrating the importance of spatial familiarity in memory retrieval. These findings provide insights into leveraging VR for therapeutic and educational applications, emphasizing the interplay between emotion, memory, and spatial context. Limitations and future directions, including sample size and lack of biosignals, are discussed.

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1 Introduction

Autobiographical memories (AM) refer to personally meaningful recollections of past experiences, integrating episodic details with self-referential meaning and emotional content [9, 42]. Central to AM, autonoetic consciousness is the ability to mentally project oneself into the past and vividly re-experience specific events [44]. This unique aspect of AM underpins identity formation, emotional regulation, and future-oriented behavior, making it critical to understanding human cognition [28, 45]. Emotional intensity plays

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a critical role in the encoding and recall of AM, with emotionally salient events often being remembered with more vividness, sensory detail, and a heightened sense of "reliving" compared to neutral ones [1, 40]. Positive memories often enhance peripheral and sensory, whereas negative memories prioritize central details, reflecting adaptive memory processes [29, 38]. Traditional AM research has predominantly relied on static word-cue tasks and 2D imagery, which fail to capture the complexity of real-world experiences [32, 49]. Moreover, the reliance on abstract cues necessitates extensive cognitive effort from participants to locate specific memories, potentially introducing biases in the recall process.

Virtual Reality (VR) environments have been shown to enhance memory vividness and accessibility by combining spatial familiarity with emotional resonance [21, 33]. Beyond memory recall, VR is an effective tool for inducing emotional states through controlled manipulations of valence and arousal, creating opportunities to investigate how these emotions influence AM encoding and retrieval [5, 17, 30, 47]. Despite these advantages, the use of VR for encoding AM and subsequently recalling it in the same context remains underexplored. Such an approach could offer new insights into how spatial and emotional congruence influence recall dynamics, reducing the cognitive load often associated with traditional cue-based methods. Specifically, we aim to answer: **RQ1)** How effectively do VR environments elicit target emotional states (valence and arousal) as measured through subjective self-reports? **RQ2)** How do familiarity and emotional characteristics (valence and arousal) influence memory recall dimensions such as vividness, accessibility, emotional intensity, valence, and visual perspective, and how are these relationships reflected in behavioral metrics such as recall speed and accuracy? This study employs immersive VR environments to develop standardized tools for investigating emotional memory with greater ecological validity.

2 Related Work

2.1 Autobiographical Memory, Emotional Processing, and Virtual Reality

Autobiographical memory (AM) comprises personal recollections integrating episodic details with self-referential meaning and emotional significance, forming a critical basis for identity and emotional well-being [8, 10]. Unlike episodic memory, which focuses on recalling the "what," "where," and "when" of events, AM embeds these details within a narrative framework, reflecting identity and personal relevance [10, 42]. Emotion significantly influences AM processes, shaping encoding, retrieval, and the vividness of recollections. Highly emotional events are often remembered with enhanced sensory richness and a strong sense of reliving, mainly when they are central to personal experiences [1, 6]. Positive memories are more likely to include peripheral and sensory details, while negative memories focus on emotionally charged central aspects, sometimes at the expense of contextual richness [11, 29, 38, 41].

A critical gap in AM research is understanding the interplay between memory recall, emotional context, and self-referential awareness. Autonoetic consciousness, the capacity to vividly re-experience past events with self-awareness and temporal anchoring, remains challenging to investigate using traditional methodologies like word-cue tasks and static stimuli. These approaches often fail to replicate the immersive and dynamic qualities of real-world experiences needed to study AM comprehensively [32, 49]. VR offers a promising alternative, creating lifelike, emotionally engaging environments that facilitate memory recall while addressing these methodological limitations [21, 33].

VR-based AM research has utilized diverse strategies, ranging from simple cues (e.g., words, images, and sounds) to recreations of personally significant locations [15, 16, 48]. Advanced applications include immersive scenarios, such as navigating an airport [18] or engaging in social interactions [20]. These environments enable researchers to explore how spatial and emotional contexts influence memory processes. Simpler setups, like 360-degree videos, have been used in comparative studies between VR and traditional laboratory methods [21], while more complex designs, such as Google Earth VR, have supported reminiscence therapy by recreating meaningful spaces [14]. High-immersion VR environments featuring interactive elements, detailed visuals, and auditory cues have demonstrated significant potential for enhancing memory vividness and emotional engagement [33].

2.2 Existing VR technologies in inducing emotions

Emotion induction in Virtual reality (VR) has been extensively studied via various methodologies, including external stimuli (e.g., video, images, and sound), recall-based tasks, and dynamic, scenario-driven environments [23, 26, 30]. For example, Chirico et al. used natural landscapes, such as waterfalls, mountains, and space views, to evoke awe and joy [5], while Wu et al. employed fear-inducing elements like darkness, heights, and omnious footsteps [47]. Similarly, film scenes have been utilized to reliably provoke anger and other strong emotional states[39]. In addition to simpler stimuli, more advanced VR scenarios have targeted complex emotional experiences. Hur et al. designed an interactive social environment to induce social anxiety [20], while Lipp et al. created a distressing car crash simulation incorporating vivid details, such as child-related objects and torn car parts, to elicit fear and grief [24].

However, the success of these approaches often depends on the specificity, realism, and interactivity of the VR environments. While simpler setups, like 360-degree videos, are easier to deploy, they may lack the depth needed for more nuanced emotional responses [21]. In contrast, fully immersive VR environments enable richer emotional engagement by integrating multisensory stimuli, realistic spatial dynamics, and user-driven interactions [27, 33].

Addressing this limitation, the present study employs the valence-arousal model to design immersive VR environments that systematically explore the interplay between emotional states, spatial context, and memory recall. We hypothesize the following:

H1: VR environments with specific valence and arousal traits will elicit corresponding emotional states.

H2: Negative-valence memories encoded in VR will evoke stronger emotional intensity than positive-valence ones.

H3: High-arousal memories will be recalled with more vividness and emotional engagement than low-arousal ones.

H4: Familiar VR environments will enhance memory recall's vividness, accessibility, visual perspective, emotional intensity, and valence compared to unfamiliar ones.

H5: Familiar VR environments will enable faster and more accurate memory recall due to spatial cues aiding retrieval.

3 System Design

3.1 Focus Group Insights for Emotional Environment Design

Mood boards featuring screenshots of conceptual designs were used to help the group visualize and imagine themselves within the proposed environments. These mood boards included detailed depictions of scene elements such as lighting, soundscapes, and key environmental features. Based on this visualization exercise, participants evaluated the environments' emotional potential using the Self-Assessment Manikin (SAM) to rate valence and arousal. Their feedback emphasized the importance of design elements critical to emotional realism, including warm lighting, rustling leaves, and flowing water for relaxation; dim lighting, flickering effects, and ominous sounds for fear; muted colors, fog, and a lack of interaction for boredom; and vibrant lighting, celebratory music, and dynamic activity for excitement. For instance, participants suggested a forest with flowing waterfalls, and bird calls to promote relaxation, while a post-apocalyptic industrial scene with overturned cars and radioactive materials was proposed to evoke boredom. Similarly, inspiration for the fear environment included rain, lightning, and shadowy corridors reminiscent of horror themes like Resident Evil. The excitement environment drew on other-worldly aesthetics, featuring celebratory music, space views, and bustling social activity.

3.2 Designing Interactive Emotional VR Environments

We created four distinct environments to align with the valence-arousal model: excitement (Positive Valence, High Arousal; PVHA), fear (Negative Valence, High Arousal; NVHA), relaxation (Positive Valence, Low Arousal; PVLA), and boredom (Negative Valence, Low Arousal; NVLA). The PVHA environment, set in a Viking village, incorporated awe-inducing elements such as space views, magical effects, and a vibrant soundscape with 3D audio to immerse participants in the scene [5]. In contrast, the NVHA environment, inspired by classic horror themes, featured dimly lit corridors of an abandoned hospital with eerie visuals, unsettling ambient sounds, and subtle lighting effects to create a persistent sense of dread [12, 19]. The PVLA environment, a serene forest, used flowing waterfalls, swaying trees, and calming ambient sounds to promote stress reduction [2, 36], while the NVLA environment, an abandoned industrial site, employed muted colors, repetitive visuals, and minimal interactivity to evoke monotony [13]. A neutral "dark room" was used between scenes to reset physiological baselines and minimize emotional spillover [15, 30].

Participants explored the environments via a slow-moving cart, ensuring consistent exposure to key elements while minimizing distractions and cyber-sickness. To enhance engagement, they used a virtual camera, controlled via an HTC Vive controller, to photograph meaningful details. Photography was an active memory-encoding task, encouraging participants to focus on specific environmental elements and form stronger cognitive associations [35, 37]. Real-time feedback, including visual camera flash and sound effects, maintained immersion during the task.

3.3 Recall Environment Design

The recall stage reintroduced participants to significant locations from the encoding session, enabling comparisons with unfamiliar scenes. Familiar locations were recreated using metadata logged during encoding, such as coordinates and scene details. Participants were teleported to these points in a stationary cart, allowing focused memory retrieval without the distractions of movement. Unfamiliar locations, designed for baseline comparisons, were set in the same familiar environments but with varying levels of contextual differentiation. For the relaxation and boredom environments, unfamiliar scenes shared terrain and ambiance with minor alterations, such as changes in time of day or asset placement. In contrast, the high-arousal excitement and fear environments required entirely new layouts and assets to maintain their emotional intensity while ensuring sufficient unfamiliarity. This design aimed to preserve the immersive emotional experience critical for high-arousal conditions, although it introduces a potential limitation. The differing degrees of unfamiliarity across emotional environments may influence recall performance and emotional reactivity beyond the intended variables. Future studies should aim to standardize unfamiliar scene designs or further investigate the effects of varying spatial contrasts on memory processes.

4 User Study

We conducted a pilot study with eight participants (4 female, 4 male; aged 18–35, M = 23.1, SD = 3.65). Eligibility criteria required normal or corrected-to-normal vision, no history of severe motion sickness, and no known neurological or psychological disorders. Participants completed two sessions, encoding and recall, spaced 48 hours apart, consistent with memory retrieval paradigms in prior research [37]. The study featured two independent variables: (1) emotional states induced by VR environments, structured in a 2x2 factorial design with valence (positive vs. negative) and arousal (high vs. low), and (2) location type during recall (familiar vs. unfamiliar). Emotional conditions (NVLA, NVHA, PVLA, PVHA) were represented in both encoding and recall phases, with each condition including four familiar and four unfamiliar recall scenes. Dependent measures included subjective self-reports of emotional engagement during encoding (valence, arousal; Self-Assessment Manikin [SAM] [3]) and memory recall dimensions during retrieval (vividness, emotional intensity, valence, visual perspective; Memory Experience Questionnaire - Short Form [MEQ-SF] [25]). Behavioral data, including recall accuracy and reaction times, captured memory performance.

4.1 Experimental Procedure

We designed the experiment to evaluate encoding and retrieving autobiographical memories in VR environments across two sessions, encoding and recall, spaced 48 hours apart. We conducted the study in a dedicated VR space (minimum 2m x 2m) using HTC Vive Pro Eye hardware and Unity3D. Figure 2 outlines the workflow.

In the encoding session, we briefed participants, obtained their consent, and administered a pre-experiment questionnaire. We

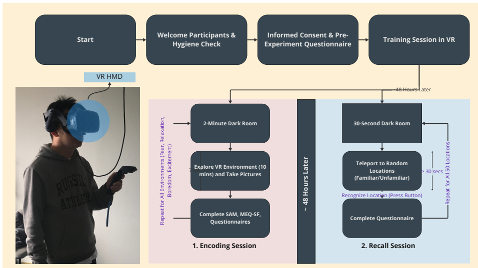

Figure 2: Experiment Procedure for Memory Encoding and Retrieval

introduced them to the VR system and provided training on navigating the virtual camera and capturing photographs. Using a Latin Square design, participants experienced four 7-minute emotional VR environments (fear, relaxation, boredom, and excitement) presented randomly. Participants traveled through the environments on a slow-moving cart and photographed scenes they found emotionally meaningful. We included two-minute neutral "dark room" intervals between environments to reset emotional states. At the session's end, participants completed SAM and MEQ-SF questionnaires. In the recall session, conducted 48 hours later, participants revisited 32 VR snapshots: 16 familiar locations from their photographs and 16 unfamiliar locations from baseline environments. We gave them up to 30 seconds to classify each snapshot as "Definitely Unknown", "Rather Unknown", "Familiar", and "Vividly Remembered" in VR. After each task, participants completed SAM and MEQ-SF questionnaires to assess emotional and memory-related ratings. We included 30-second neutral "dark room" intervals between snapshots to reset emotional states.

4.2 Data Analysis

We analyzed subjective and behavioral data to evaluate participants' emotional and memory-related experiences. Three hundred four post-trial subjective responses (4 Encoding + 16 Familiar + 16 Unfamiliar x 8 participants) were recorded and analyzed. Subjective measures included Familiarity Scores, SAM Valence and Arousal Ratings, and memory-related metrics derived from the Memory Experience Questionnaire-Short Form (MEQ-SF), such as Memory Vividness, Visual Perspective, Accessibility, Emotional Intensity, and Memory Valence.cluding Recollected Hits, Familiar Hits, and False Positives, further divided into False Recollected Positives, False Familiar Positives, and False Unfamiliar Positives. Recognition accuracy was calculated as the ratio of correctly recollected scenes to the total number of scenes presented. Discrimination sensitivity (d') was used to quantify participants' ability to distinguish between familiar and unfamiliar scenes, while response bias (C) measured tendencies toward cautious or lenient judgments. Statistical tests were conducted in IBM SPSS. Normality was assessed using the Shapiro-Wilk test [34], with parametric tests applied to normally distributed data and non-parametric tests otherwise. A two-way repeated-measures ANOVA was used for parametric data to analyze the effects of valence and arousal, while non-parametric data were assessed using the Aligned Rank Test (ART) [46]. For pairwise comparisons, paired t-tests were applied to parametric data, and Wilcoxon Signed-Rank tests [7] were used for non-parametric data.

5 Results

5.1 Self-Assessment Manikin (SAM)

SAM-Valence and SAM-Arousal ratings were analyzed across encoding, familiar recall, and unfamiliar recall conditions to assess emotional induction and memory retrieval. Positive-valence conditions consistently showed higher valence ratings compared to Negative-valence conditions ($F(1, 7) = 67.207$, $p < .001$, $\eta_p^2 = .706$), supporting the validity of the valence manipulation. Similarly, high-arousal conditions had higher arousal ratings than low-arousal conditions ($F(1, 7) = 4.740$, $p = .038$, $\eta_p^2 = .145$), reflecting effective differentiation between arousal levels during encoding. Pairwise comparisons for SAM ratings revealed notable differences across conditions as shown in figures 3.

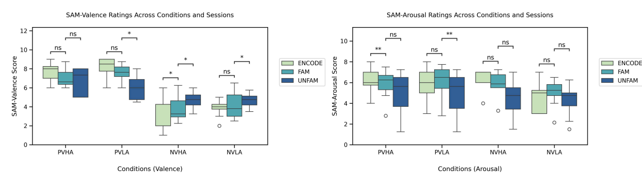

Figure 3: Boxplots of SAM Valence and Arousal Ratings Across Conditions

5.2 MEQ-SF Results

Across the five MEQ-SF dimensions: Vividness, Accessibility, Visual Perspective, Emotional Intensity, and Emotional Valence, we observed that Familiar Recall generally led to higher ratings than both Encoding and Unfamiliar Recall (Figure 4). High Arousal conditions also tended to produce stronger effects, particularly in measures such as *Emotional Intensity* and *Accessibility*. Meanwhile, the influence of Positive Valence was less consistent, surpassing Negative Valence in some measures (*e.g.,* Vividness, $t(7) = -4.793, p = .001, d = -1.69$) but showing smaller or non-significant differences in others. For example, *Vividness* significantly increased from Encoding to Familiar Recall in both Positive (e.g., PVHA: $t(7) = -4.552, p = .003$) and Negative Valence (e.g., NVLA: $t(7) = 8.173, p < .001$) conditions, then dropped near Encoding levels at Unfamiliar recall. *Accessibility* and *Visual Perspective* followed similar trends (with high arousal consistently amplifying recall). Finally, *Emotional Valence* ratings were higher overall under Positive Valence, although certain pairwise comparisons did not reach significance.

5.3 Familiarity Results

Overall, participants showed varying recognition thresholds (Table 1). For instance, Participant 3 had the highest discrimination sensitivity ($d' = 3.12$) with perfect accuracy, whereas Participant 8 showed the lowest $d' = 1.98$ and the highest response bias ($C = 0.45$). While some (P1, P2, P6) reported no false recollected positives, Participant 5 had the most (5). Notably, P6 combined a high recollected-hit count (15) with 93.7% accuracy, indicating strong

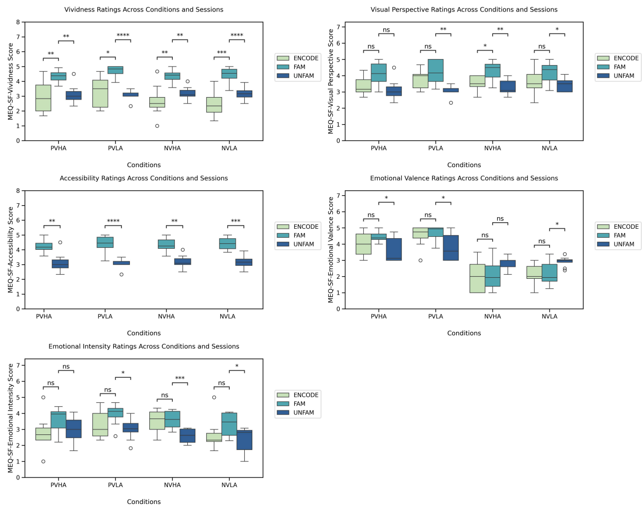

Figure 4: Boxplots of MEQ-SF: Vividness, Visual Perspective, Accessibility, Emotional Intensity and Valence

memory performance. In contrast, P8's lower d' correlated with an accuracy of 76.9%, underscoring individual recognition thresholds' effect.

Table 1: Key familiarity metrics. (RH: Recollected Hits, FH: Familiar Hits, FP: False Positives, d': Discrimination Sensitivity, C: Response Bias)

PID	RH	FH	FP	d'	C	Acc (%)
1	12	2	2	2.78	0.26	87.5
2	11	5	2	2.34	0.20	76.9
3	16	0	3	3.12	0.15	100.0
4	11	5	1	2.89	0.30	84.6
5	14	2	12	2.50	0.40	77.8
6	15	1	0	2.95	0.22	93.7
7	16	2	8	2.67	0.35	84.2
8	9	7	0	1.98	0.45	76.9

6 Discussion

The results demonstrate that VR environments effectively elicit target emotional states, confirming H1. Positive valence conditions elicited significantly higher valence ratings, while high-arousal conditions reliably induced greater arousal compared to low-arousal environments. These findings align with prior research, which highlights the efficacy of VR as a medium for controlled emotion elicitation through immersive stimuli [30, 47]. The SAM results reinforce the robustness of VR in reliably differentiating valence and arousal states, corroborating earlier findings on the utility of VR in affective computing and psychophysiological research [13, 24]. The MEQ-SF results illustrate the nuanced role of valence and arousal in memory recall. High-arousal memories, irrespective of valence, were associated with enhanced vividness, accessibility, and emotional engagement, validating H3. These findings are consistent with research indicating that arousal strengthens memory consolidation by increasing sensory and emotional engagement during encoding [1, 41]. In contrast, negative valence memories were recalled with higher emotional intensity than positive valence memories, partially supporting H2. This result aligns with studies suggesting that negative experiences are often more emotionally intense and lead to heightened recall specificity due to their adaptive significance [11, 22]. Familiar environments significantly enhanced vividness, accessibility, emotional intensity, and visual perspective, confirming H4. These results align with the theoretical framework of the self-memory system, which emphasizes the role of spatial context in autobiographical memory recall [10, 43]. Moreover, familiar environments led to faster recall times and higher accuracy, supporting H5. This aligns with studies showing that spatially anchored environments, such as those provided by VR, facilitate memory retrieval by enhancing self-referential processing [21, 31].

6.1 Practical Implications

Our findings that Familiar Recall substantially enhanced memory vividness and emotional engagement highlight multiple applications for virtual reality (VR). In **memory rehabilitation**, VR's ability to simulate spatial contexts and induce meaningful emotions could benefit patients with memory impairments such as Alzheimer's or traumatic brain injury [4, 14]. Structured VR interventions may help older adults reinforce autobiographical memories or develop coping strategies for cognitive decline [16]. In **emotional therapy**, VR can evoke targeted emotions safely and consistently, opening avenues for mood disorder interventions, anxiety exposure, and PTSD treatment [5, 26]. Patients could rehearse stressful or traumatic scenarios in a controlled VR environment, facilitating emotional processing and reducing PTSD symptoms [24]. Beyond clinical contexts, VR also provides insights into **self-identity and autobiographical memory**. Personalized or self-referential VR scenarios could support identity reconstruction for individuals with memory loss [32], potentially influencing memory vividness and emotional intensity [1]. However, the immersive nature of VR raises the risk of **memory distortions**: emotionally charged, spatially rich VR cues might inadvertently boost memory confidence or induce false recollections [38, 41]. Addressing these issues in future work could clarify how VR-based interventions balance enhanced recall with potential false memories. Investigating embodiment (e.g., self-avatars) and its relationship to AM may further elucidate how VR influences self-referential cognition and personal narrative development in both clinical and educational environments.

7 Limitations and Future Work

A main limitation of this study is the small sample size, which limits the generalizability of findings. The reliance on self-reports without integrating physiological data, such as Electroencephalograph (EEG), Electrodermal Activity, and heart rate variability, constrains the ability to cross-validate subjective experiences. Future work should employ multimodal approaches to understand emotion and memory interactions comprehensively. There are also minimal differences between familiar and unfamiliar scenes in relaxation and boredom environments, which may have led to false familiarity judgments. Future studies should create unfamiliar environments with distinct spatial layouts and features to reduce recall errors. Additionally, inconsistent levels of unfamiliarity across emotional conditions may confound results, and standardizing these differences is crucial for isolating the effects of valence and arousal on memory recall. Finally, the short interval between encoding and recall limits understanding of memory persistence. Longitudinal studies are needed to assess the evolution of VR-encoded memories over time.

8 Conclusion

This study highlights the potential of VR as a medium for investigating autobiographical memory, emphasizing the interplay between emotional valence, arousal, and spatial familiarity. These insights have significant implications for designing VR-based interventions in therapeutic and educational contexts, such as reminiscence therapy, emotional regulation training, and cognitive rehabilitation.

Acknowledgments

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