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Today's Date

Development of Immersive Cognitive Tasks for use in Human Memory Research

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An abstract of

a thesis submitted to the Faculty of Emory College of Arts and Sciences

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Abstract

Development of Immersive Cognitive Tasks for use in Human Memory Research

By Noah Okada

Virtual Reality (VR) has been identified as a promising tool for improving cognitive assessments due to its ability to increase ecological validity while maintaining high experimental control. Previous studies have demonstrated that immersive environments may lead to increased cognitive performance and the measurement of cognitive phenomena. However, it remains unclear how virtual reality compares to standard two-dimensional displays. To address this gap, this study aimed to investigate the effect of immersion on familiarity memory processes and develop a framework for creating immersive cognitive assessments. The study utilized a series of three experiments to examine the impact of immersive reality on various cognitive processes, including scene recall, scene familiarity-detection during recall failure, the subjective experience of déjà vu, memory for a spatial trajectory, and subjective feelings of prediction. The experiments successfully reproduced effects from a previous two-dimensional non-immersive task and showed larger effect sizes in a more immersive virtual reality version of the task. These findings provide support for the idea that virtual reality-based cognitive assessments can elicit stronger effects in cognitive phenomena. Additionally, the framework developed in these experiments could facilitate the development of new tools and assessments that could improve the detection of memory deficits in clinical populations. Overall, this study contributes to the growing body of literature supporting the use of VR technology for cognitive neuroscience research and demonstrates its potential for developing new tools to study cognitive processes in more naturalistic settings while maintaining experimental rigor.

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Chapter 1

Introduction

1.1 Immersive Cognitive Assessments

Researchers studying cognitive phenomena have long been challenged with the tension between ecological validity and experimental control. Traditional assessments were limited by technological constraints, and as a result, they could only evaluate cognitive processes in artificial settings (Goldstein, 1996; Rabin et al., 2016). However, recent advances in virtual reality (VR) technologies have created new opportunities to overcome this tension (Matheis et al., 2007; Parsons, 2015). VR provides a way to develop ecologically valid experiments within a controlled laboratory environment by immersing participants in photo-realistic surroundings (Parsons, 2015; Parsons et al., 2017). This allows researchers to study cognitive processes in more naturalistic settings while still maintaining a high degree of experimental rigor.

Although virtual reality (VR) technology has existed since the late 1960s, recent technological advances have led to its widespread adoption in various research and industry settings (Mazuryk, 1999). Specifically, VR has emerged as an important tool in human neuroscience research, allowing for the investigation of domains that were previously inaccessible in human experiments. For example, VR has enabled the development of navigation tasks that are comparable to those used in rodent research, providing an opportunity to study spatial cognition and navigation (Bohil et al., 2011; Lopatina et al., 2020; Rosas et al., 2013) One notable example is the virtual Morris Water Maze task, which simulates the Morris Water Maze task in a virtual environment and enables participants to navigate through it (Moffat et al., 2007). In addition, VR has allowed researchers to develop tasks that extend our understanding of human memory and cognition, including those related to social neuroscience and subjective memory phenomena (Parsons et al., 2017). With these advancements, researchers have been able to create novel tasks that simulate naturalistic environments, providing a more ecologically valid approach to studying cognitive processes. Overall, VR has opened up new avenues for research and holds great promise for advancing our understanding of the human brain and behavior.

One crucial area of interest for modern immersive cognitive assessments is the assessment of memory function in patients who have undergone temporal lobe (TL) surgery. Patients with temporal lobe epilepsy often undergo TL surgery to reduce the frequency of epileptic seizures, but recent evidence suggests that such surgical interventions can result in substantial cognitive deficits (Drane et al., 2008, 2009). These deficits, including aspects of language, visuo-perceptual processing, and semantic learning and recall, have not been routinely explored in a clinical context due to a lack of appreciation for their vulnerability in TL surgery and a scarcity of adequate assessment measures.

The ability to carry out basic functions is crucial for successful daily functioning, and even minor variations in competency can significantly impact academic, social, and work performance (Moritz-Gasser et al., 2012). However, little research has been conducted on the impact of TL surgery on novel learning, with most studies focusing on accessing pre-existing knowledge. Furthermore, few if any tasks have been developed that employ simultaneous learning in multiple modalities, such as integrating information from varying sensory modalities with linguistic and semantic information and concepts (Drane et al., 2015). Immersive cognitive assessments offer a valuable toolset for assessing these functions. By leveraging the ability to capture subtle aspects of performance variability, such as eye tracking and sub-second changes in processing speed/reaction times, and implementing these tasks in virtual environments that enable spatial navigation, VR-based immersive assessments enable researchers to model multi-modal learning experiences.

To encourage the adoption of these assessments in clinical research settings, in this thesis, we developed tools to measure the impact of immersion on cognitive processes. Specifically, three experiments were conducted with varying degrees of immersion to investigate how immersive settings impact familiarity memory. Furthermore, a framework was validated to time lock neurophysiological data with immersive stimuli, which could open the door for the development of new immersive assessments to improve our understanding of cognitive function in humans. Overall, this thesis aims to promote the adoption of immersive cognitive assessments in clinical research settings and to advance our understanding of cognitive function in patients with temporal lobe epilepsy across a range of cognitive domains.

Chapter 2

Validating Immersive Assessments Via the Study of Déjà vu

2.1 Background

To effectively leverage the benefits of immersive reality paradigms, careful consideration must be given to selecting cognitive tasks that are well-suited to virtual environments. While the technology supporting VR offers many advantages, there is little advantage to employing conventional cognitive paradigms, such as simple list-learning or face recognition, in a VR system. The key strength of VR lies in its ability to simulate real-world visuospatial environments, which greatly enhances ecological validity. Therefore, in this project we investigated the impact of immersive assessments on the measurement of familiarity memory in the context of spatial cognition. Furthermore, because this study aims to build tools that would be transferable to cognitive assessments for patients with TLE, we focused specifically on studying the phenomena of déjà vu.

Déjà vu is the phenomenon of experiencing a new situation with an overwhelming feeling of familiarity and sometimes prediction. It is an experience that has been recorded across the general population, with a modified form prominent in patients with TLE (Brown, 2004). Studies focusing on patients with TLE have established that alterations in electrical activity within the medial temporal lobe (MTL) can be correlated with the report of déjà vu (Adachi et al., 2010; Bancaud et al., 1994; Gloor et al., 1982). It has therefore been suggested that disturbances of the recollection and recognition systems within the MTL produce déjà vu (Gillinder et al., 2022). However, this association has been difficult to study due to the rarity of spontaneous déjà vu and the difficulty of eliciting the distinct experience in a laboratory setting. Cleary et al. introduced a paradigm demonstrating that déjà vu can be elicited using virtual scenes (Cleary et al., 2012; Cleary & Claxton, 2018). Their study employed an early precursor to modern immersive VR technology to test the Gestalt similarity hypothesis (Brown, 2004; Cleary & Brown, 2022), which suggests that déjà vu can occur when a current scene has a spatial layout identical to a previously encountered place that fails to be recollected. This hypothesis is commonly classified as an explanation for déjà vu that pertains to implicit memory, and is based on the idea that some aspect of the current situation has been previously encountered. This hypothesis diverges from other implicit memory explanations in proposing that familiarity is not attributable to any specific element of the scene or explicit episodic experience, but rather to the overall structure or framework of the setting itself (Brown & Marsh, 2010). Importantly, this explanation is aligned with the idea of a global familiarity signal that some have suggested resides in the cortical structures surrounding the hippocampus (O'Reilly et al., 2014). However, the difficulty of eliciting a déjà vu experience in neuroimaging and electrophysiological settings have left a gap in the evidence required to support these models. Therefore, a cognitive assessment to study déjà vu built upon VR holds the potential to provide key insights that will contribute to our understanding of the mechanisms of human memory by enabling a circuit-based approach to investigating familiarity.

In this study we sought to address this challenge by conducting a series of experiments to develop and validate a modern immersive paradigm to elicit deja vu. In three experiments, we compared the effects of spatially similar and dissimilar scenes displayed across varying levels of immersion (non-immersive 2D monitors vs. fully immersive VR). We hypothesized that stimuli displayed in fully-immersive VR would elicit greater feelings of familiarity and subjective reports of déjà vu compared to non-immersive scenes. By testing this hypothesis we hoped to validate this framework as a tool that could be deployed in clinical research settings to study familiarity memory in patients with TLE. Furthermore, by integrating key features such as eye-tracking and millisecond level temporal precision in the data management we designed this framework to be compatible with electrophysiological recordings. Overall, the development and validation of this immersive VR paradigm for studying déjà vu has the potential to advance our understanding of human memory mechanisms and provide a valuable tool for clinical research settings.

2.2 Methods

2.2.1 Participants

All participants were undergraduate students from Colorado State University who completed a given experiment in exchange for course credit.

Experiments 1-2 Using G*Power (Faul et al., 2007), a power analysis determined that a sample size of 44 would be sufficient to detect a significant effect with power set at .90, alpha set at .05, and a medium effect size (d = .50). Therefore, we aimed to collect data from at least 50 participants in each experiment. To counterbalance the experiment, participants were assigned pseudorandomly to one of four versions. In Experiment 1, which was remotely delivered, 74 participants attempted to complete the experiment. However, due to a glitch, the counterbalancing was uneven, and some participants did not complete at least 75% of the experiment. Therefore, we removed participants chronologically from versions with more participants to achieve even sample sizes within each of the counterbalanced versions. This resulted in a final sample of 56 participants. In contrast, Experiment 2 had 62 participants who completed the experiment in an in-person laboratory setting.

Experiments-3 Cleary et al. (2012) reported a substantial déjà vu effect (d = .78) in their VR study. With this effect size as a reference, we conducted a power analysis using G*Power (Faul et al., 2007) with an alpha level of .05 and power of 90%, which indicated that a sample size of 20 participants would be necessary to detect a similar effect. Therefore, 23 undergraduate students from Colorado State University participated in Experiment 3 and received course credit in return. Unfortunately, three participants experienced technical issues and were excluded from the final sample, resulting in a total of 20 participants.

2.2.2 Stimuli

The study utilized 64 pairs of similarly configured scenes as stimuli, which were created as 15-second video tours using the Unity Game Engine. A total of 128 virtual environments were developed using open-source 3D objects from public repositories, which were modified using Blender 3D modeling software and then configured into identifiable scenes using the Unity Game Engine. To ensure configurational similarity, the scenes were created on a uniform plane with objects placed in specific locations corresponding to their counterparts. A Unity camera-object was used to simulate first-person perspective navigation through each scene, with a waypoint script guiding movement along a predetermined path. To ensure consistency, the paths were designed to be identical for each scene in a pair, with a critical turn at the end of each path. The resulting images were converted into 15-second MP4 files for Experiments 1 and 2, and VR was used for Experiment 3. An audio file was created for each study scene, featuring a female voice stating the name of the scene. The Sorensen-Dice index was used to quantify the configurational similarity between scenes by measuring the overlap between two sets of binary images taken from an isometric perspective for each axis of the scene. The SDI was calculated using MATLAB functions from the Image Processing Toolbox to compare each image and quantify the configurational similarity between each of the 128 distinct scenes in the inventory.

The 64 configurationally identical study-test virtual tour pairs (whose creation is described above under Stimuli Development) were randomly divided into two study-test blocks, such that each block consisted of 16 unique study scenes and 32 unique test scenes. Within each block, the tours were randomly ordered (see Figure 2.1). In order to counterbalance whether a given test scene corresponded to a spatially similar study scene, and whether its spatially similar study scene had a leftward versus rightward critical turn, four versions of the experiment were developed to balance the particular scene stimuli across all of the conditions.

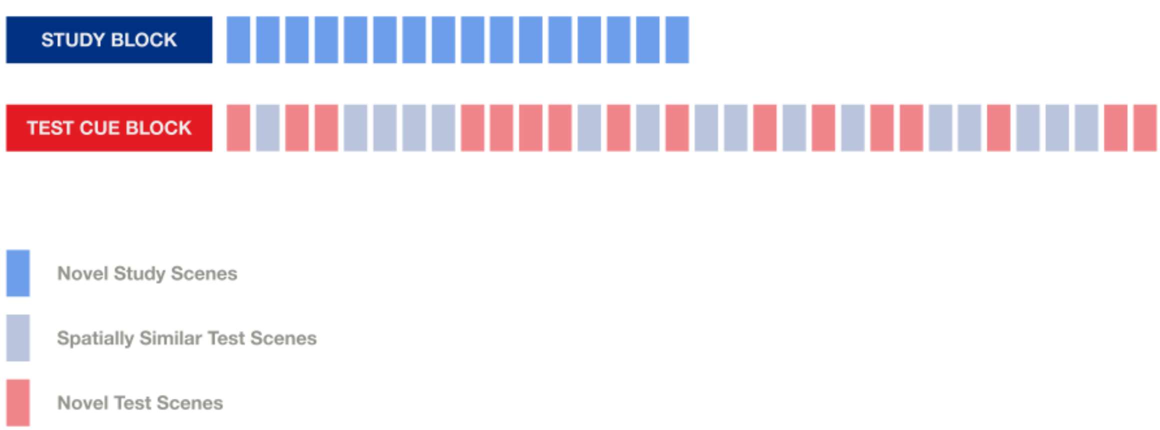

Figure 2.1: Randomization of Study Test Scenes

2.2.3 Materials

Experiment 3 The stimulus set consisted of the same virtual tours and audio files used in Experiments 1 and 2. The stimuli were loaded into a Unity3D editor (Unity Technologies, 2018) environment running Unity version 2020.3.17f1 with the VR-Rig package by OpenXR (Khronos Group, 2019) Additionally, three questionnaires were administered, including the IDEA (Sno et al., 1994), the SSQ (Kennedy et al., 1993), and a Gaming and Computer Usage Questionnaire.

The experiment was conducted using an HTC VIVE Pro head-mounted display (HMD) and an HP Z4 G4 Workstation running Microsoft Windows 10 Pro for Workstations with an Intel Xeon W-2123 CPU 3.60GHz processor, an NVIDIA GeForce GTX 1070, and 32GB RAM.

2.2.4 Procedure

Experiment 1 and 2

Experiment 1 was conducted remotely, using Qualtrics, and followed the general procedure used in prior déjà vu research (e.g., Cleary et al., 2012; Cleary et al., 2018). Experiment 2 was identical (including use of Qualtrics) except for being run in an in-person laboratory setting. After providing consent to participate in the experiment, participants were instructed to adjust their computer's sound volume to a comfortable level, as there would be sound throughout the experiment. They were then provided with the following instructions pertaining to the study phase: *"Instructions: You will see a series of brief video tours. During the first phase, while watching each video, you will hear a voice tell you what the scene is. For example, while viewing a golf course, the voice would say "This is a golf course. Golf course." Simply watch each scene and try to remember it. When the first set of video tours is over, you will be presented with a second phase. Please click the blue arrow key to begin the first study phase."*

The study phase consisted of 16 videos (whose creation is described above under Stimuli Development) presented in random order. While watching each study video, the participant heard a female voice indicating the name of the scene (e.g., "Subway car. This is a subway car."). After completing the first study phase, participants were then provided with test instructions. They were told that they would see a set of completely new virtual tours, some of which might resemble scenes encountered in the study phase. After viewing each tour, the participant was told that they would be asked a series of questions concerning it. First, they would be asked to indicate whether the test scene prompted them to feel a sense of déjà vu, which was defined as "the feeling of having experienced something before without knowing why and despite knowing that the current situation is new." Following this, participants were told that they would be asked to indicate if they had a sense of knowing which way to turn next on a scale of zero (No feeling of prediction at all) to 10 (Strong feeling of prediction). Additionally, they were told that regardless of their previous answer, they would be asked to indicate which way the scene would proceed (Left or Right), even if it was just a guess. Participants were then instructed that they would be prompted to indicate how familiar the test scene feels on a scale of zero (Not at all familiar) to 10 (Very familiar). Finally, they were told that the last prompt would ask if the current test scene reminded them of a particular earlier-presented scene encountered during the study phase, and if so, that they should type in the name of the scene.

After receiving the test instructions, participants were presented with 32 randomly ordered test scenes, half of which corresponded to a spatially similar scene presented during the study phase while the other half did not (see Figures 1 and 2). After viewing each video of the test scene, a frozen image of the scene remained on the screen while participants answered a series of questions. First, participants were asked to indicate whether the scene prompted them to feel a sense of déjà vu (Yes or No). They were then asked to indicate if they had a sense of knowing which way to turn next on a scale of 0 (No feeling of prediction at all) to 10 (Strong feeling of prediction). The next prompt had participants indicate which direction they felt the scene would turn next (Left or Right). Participants were then asked to rate how familiar the scene felt on a scale of 0 (Not at all familiar-seeming) to 10 (Extremely familiar-seeming). Finally, participants were asked if the scene reminded them of a particular scene presented from the previous phase, and if so, to type in the name of the scene. All prompts, aside from the final recall attempt prompt, were forced-choice, such that participants could not proceed to the next prompt until they had selected an option.

Upon completing the first test block consisting of the 32 randomly presented test scenes, the participants were then given interblock instructions indicating that they would now complete a new study-test block. They were told that the procedure would be exactly the same, with the only difference being that the scenes would be completely different than the scenes from the prior study-test block. After receiving these instructions, participants completed the second study-test block.

Experiment 3 Participants were pseudo-randomly assigned to one of the four counterbalanced versions of the experiment, which contained scene stimuli that were the same as those used in Experiment 1 and 2. Upon providing consent to participate in the experiment, participants were asked to complete the IDEA questionnaire, which was administered via paper and pencil. They were then seated in the middle of the room and fitted with the VR headset and paddles. Participants were free to move their head around while viewing the instructions and experimental stimuli, but were required to remain seated throughout the experiment.

The experimental instructions were the same as those used in Experiments 1 and 2, with the following exceptions that were due to a change from being asked to give ratings to being asked to give yes-no responses in the VR version of the experiment. First, instead of being told that they would be asked to provide feeling-of-prediction and familiarity ratings, participants in Experiment 3 were instructed that they would be asked to indicate whether they had experienced a sense of knowing which way to turn next (Yes or No), and also whether the scene had prompted a sense of familiarity (Yes or No). Additionally, when asked whether the current test scene reminded them of a particular scene from the previous study phase, instead of personally typing their recall response, the participants in the VR experiment were instructed to verbalize the name of the scene (or any details they could recall) so that the attending research assistant could type in the response for them.

The study phase consisted of 16 scenes displayed in HMD-VR on the HTC Vive. While immersed in each study scene, the participants heard a female voice indicating the name of the current scene. Following the presentation of the study scenes the participants were immersed in 32 test scenes. During the presentations of all of the scenes, the virtual environments were displayed as stereoscopic images with 6 degrees of freedom (6DoF; marker-based). Participants were guided along a path through each scene using a modular waypoint system along a path adjusted for the critical turn displayed during the study scenes, but stopped before this turn in the test scenes. To reduce cybersickness, the scenes were faded to darkness before rendering the next environment.

After viewing each test environment, as with Experiments 1 and 2, participants were prompted to answer a series of questions concerning the subjective experiences with the test scene (note that unlike with Experiments 1 and 2, a frozen image of the test scene did not remain visible while responding to the prompts). The prompt appeared in the center of the participant's visual field and the participant was to respond by pointing the visible beam from the hand paddle toward the desired response option (e.g., a box for Yes or a box for No) and once pointing there to pull the trigger on the hand controller to register the response. First, participants were prompted to indicate whether or not they had experienced a sense of déjà vu while viewing the virtual environment (Yes or No). They were then prompted to indicate whether the test scene had prompted them to feel a sense of knowing which way to turn next (Yes or No) and were then prompted to indicate whether they felt the next turn would be Left or Right. Next, participants were prompted to indicate whether they had felt a sense of familiarity with the test scene (Yes or No). Finally, participants were asked whether the scene reminded them of a particular scene presented in the prior study phase. If participants were able to generate the potential name of a study scene or any details about it, they verbalized this information to the research assistant, who typed the information into the computer that was controlling the VR.

Upon completing the first study-test phase of the experiment, participants were instructed to temporarily remove the headset and remain seated for a short break. Once the participant felt ready to proceed with the experiment, they then completed the second study-test phase. Post-experiment questionnaires were then administered, consisting of the SSQ and the Computer and Gaming Usage questionnaires. As with the IDEA, participants completed these questionnaires using pencil and paper to keep the amount of participation time in VR to that needed for the immersive task.

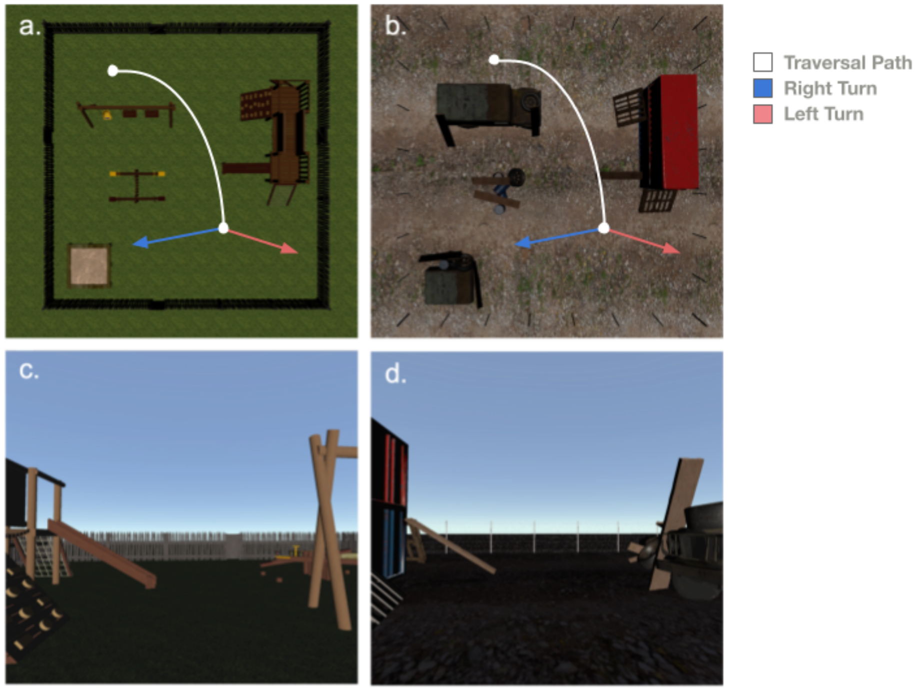

Figure 2.2: Immersive Traversal Through 3D Scenes

2.3 Results

2.3.1 Immersive VR is Associated with Better Recall

Experiments 1 and 2 aimed to reproduce the findings of Cleary & Claxton (2018) by utilizing newly developed Unity Game Engine scenes in the form of videos. This approach facilitated an assessment of whether the same general patterns observed by Cleary and Claxton could be replicated using the new scenes. Experiment 1 was conducted remotely via Qualtrics due to the COVID-19 pandemic, while Experiment 2 was carried out in-person on individual lab computers following the resumption of in-person data collection, which enabled a direct comparison of the two modes of data collection. In Experiment 3, participants were fully immersed in the scenes by wearing an HTC Vive Pro headset and were transported through the scenes as if they were on a virtual roller coaster (e.g. "It's a small world").

In the study, each trial was manually categorized based on the degree of success in recalling or identifying the study scene. The results showed that participants were able to identify the study scene in some capacity in 34.8% (SD = .24) of the test trials corresponding to spatially similar study scenes in Experiment 1, and 37.7% (SD = .16) of the test trials in Experiment 2. However, in Experiment 3, where fully immersive VR was used, the rate of scene identification success was significantly higher at 58.7% (SD = .19). This finding suggests that fully immersive VR can enhance recall compared to other presentation methods.

2.3.2 Spatially Similar Scenes Elicit Greater Familiarity when displayed in VR

We conducted a mixed-measures ANOVA on familiarity ratings to investigate the impact of spatial configuration on subjective familiarity ratings during recall failure in Experiments 1 and 2. The ANOVA had a 2x2 design, with Spatial Similarity (Similar, Dissimilar) and Experiment (1 Remote, 2 In-Person) as factors. Results revealed a significant main effect of Spatial Similarity (F(1, 116) = 24.30, MSE = .39, p <.001, np2 = .17, BF10 = 4.92 x 103), indicating higher familiarity ratings for spatially similar test scenes. Experiment 3 also showed a similar effect, with significantly higher familiarity ratings for spatially similar scenes (M = .58, SD = .19) than spatially dissimilar scenes (M = .44, SD = .17), t(19) = 3.61, SE = .04, p = .002, d = .77, BF10 = 21.36. The effect size in Experiment 3 (d = .77) was much larger than in Experiments 1 (d = .27) and 2 (d = .24), suggesting that immersive VR may have positively impacted participants' encoding and retrieval processes.

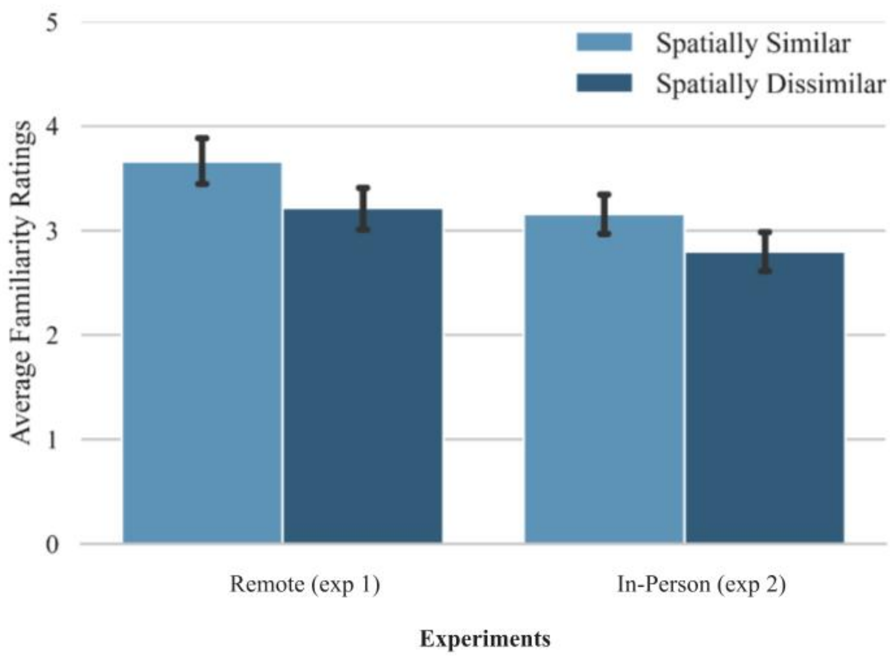

Figure 2.3: Average familiarity ratings provided during retrieval failure as a function of spatial similarity (Spatially Similar, Spatially Dissimilar) and experiment (Remote Experiment 1, In-Person Experiment 2).

2.3.3 Identification Failure in Spatially Similar Scenes Was Associated with Déjà Vu and is enhanced in VR

We next investigated how manipulating spatial similarity affected the likelihood of participants experiencing déjà vu during retrieval failure. Results revealed that participants were more likely to report déjà vu for spatially similar test scenes (M = .46, SD = .18) compared to spatially dissimilar test scenes (M = .37, SD = .15), t(19) = 2.57, SE = .04, p = .02, d = .54, BF10 = 3.05. Interestingly, the effect size observed in VR (d=.54) was larger than those found in Experiments 1 (d = .33) and 2 (d = .35).

To further explore this phenomenon, we conducted a mixed-measures ANOVA on the probability of reporting déjà vu during retrieval failure for test scenes that spatially corresponded to scenes presented during the study phase. The results showed a significant main effect of Spatial Similarity, F(1,116) = 19.08, MSE = .01, p <.001, np2 = .14, BF10 = 672.44, indicating that participants were more likely to report déjà vu when test scenes spatially mapped onto unrecalled study scenes compared to test scenes that did not map onto any study scene. This pattern emerged in all three experiments. Overall, our findings suggest that spatial similarity plays a role in the subjective experience of familiarity and déjà vu during retrieval failure. Moreover, the effect seems to be more pronounced in immersive VR environments.

2.3.4 Déjà Vu Was Associated with Intense Familiarity Across all Presentation Modalities

We conducted a mixed-measures ANOVA on participants' familiarity ratings to investigate whether the associations between déjà vu and feelings of familiarity observed in previous studies were present in our experiments. The ANOVA involved a 2 x 2 design with factors for Déjà Vu State (Déjà vu, Non-Déjà vu) and Experiment Type (1 Remote, 2 In-Person). Results showed a significant main effect of Déjà Vu State, F(1, 113) = 668.71, MSE = 1.20, p <.001, np2 = .86, BF10 = 5.32 x 1054, indicating that participants in both experiments provided higher familiarity ratings when reporting déjà vu (see Figure 4). Notably, there was no significant interaction effect, and the Bayes Factor did not support a main effect of Experiment Type. We found a similar association in Experiment 3, where participants were more likely to report a sense of familiarity during déjà vu states (M = .92, SD = .10) compared to non-déjà vu states (M = .19, SD = .22), t(19) = 12.95, SE = .06, p <.001, d = 4.33, BF10 = 1.27 x 108.

2.3.5 Déjà vu was Associated with Feelings-of-Prediction

In previous research conducted by Cleary and Claxton, it was found that reports of déjà vu were associated with significantly higher feeling-of-prediction ratings compared to reports of non-déjà vu, despite no actual association with successful prediction ability. Similar findings were observed in our current experiments. When we conducted a mixed-measures ANOVA on participants' feeling-of-prediction ratings using a 2 x 2 design with factors for Déjà Vu Report (Déjà vu, Non-Déjà vu) and Experiment Type (1 Remote, 2 In-Person), a significant main effect of Déjà Vu Report was found, F(1, 113) = 200.47, MSE = .76, p <.001,

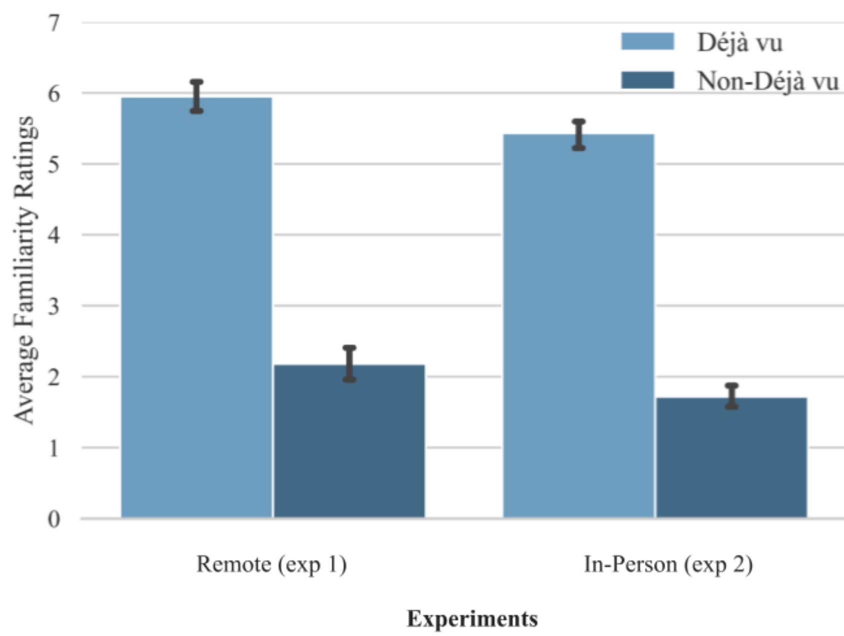

Figure 2.4: Average familiarity ratings provided during retrieval failure as a function of déjà vu reports (Déjà vu, Non-Déjà vu) and experiment (1 Remote, 2 In-Person).

np2 = .64, BF10 = 3.77 x 1023 (Figure 2.5). This indicates that, regardless of the experiment, participants reported significantly higher feeling-of-prediction ratings while experiencing déjà vu compared to non-déjà vu. This pattern was also observed in the immersive Experiment 3, where participants were significantly more likely to report a feeling-of-prediction when experiencing déjà vu (Figure 6).

2.3.6 Turn Prediction Accuracy Accompanied Recall Success

If participants were successful in recalling the scene, they could predict the direction of the next turn within test scene tours with above-chance accuracy. In Experiment 1, participants who correctly identified the spatially similar study scene showed above-chance accuracy (M = .68, SD = .22) in predicting the next turn of the test scene, t(48) = 5.98, p <.001, BF10 = 5.54 x 104 (critical value = .50). Similarly, in Experiment 2, participants demonstrated above-chance accuracy (M = .75, SD = .14) in predicting the next turn of a test scene that spatially matched an identified studied scene, t(61) = 14.03, p <.001, BF10 = 5.07 x 1017. These results were also replicated in VR Experiment 3, where participants achieved an average prediction accuracy of .62 (SD = .15), which was significantly higher than chance (.50), t(19) = 3.56, p = .002, BF10 = 23.03.

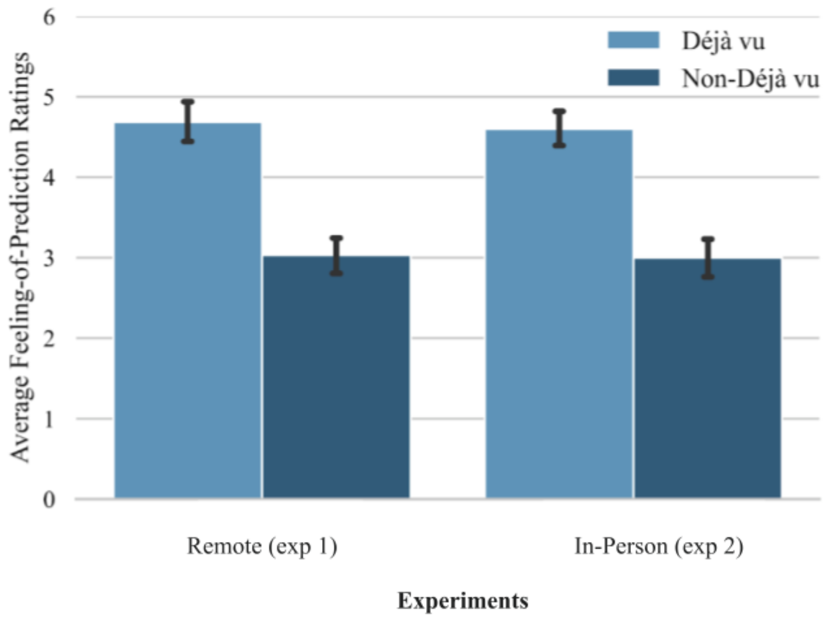

Figure 2.5: Average feeling-of-prediction ratings provided during retrieval failure as a function of déjà vu state and experiment (Experiment 1, Experiment 2).

2.3.7 When stimuli were displayed in VR Déjà vu States were Associated with Increased Correct Turn Judgments

To investigate the possible relationship between the experience of déjà vu and prediction accuracy when memory retrieval fails, we examined the likelihood of accurately predicting the direction of the next turn during déjà vu and non-déjà vu states. In Experiment 1, participants did not show a significant difference in their ability to predict the next turn direction when they reported a sense of déjà vu for a test item that corresponded to an unrecalled study scene ($M = .59$, $SD = .27$) compared to when they reported a sense of non-déjà vu ($M = .55$, $SD = .21$), $t(49) = .95$, $SE = .04$, $p = .35$, $BF01 = 4.26$. Similarly, in Experiment 2, there was no significant difference in turn prediction accuracy between trials associated with a sense of déjà vu for test items that spatially corresponded to an unidentified study scene ($M = .61$, $SD = .23$) and those associated with non-déjà vu ($M = .59$, $SD = .16$), $t(61) = .66$, $SE = .03$, $p = .51$, $BF01 = 5.82$.

In contrast to previous experiments such as Experiments 1 and 2 as well as Cleary and Claxton 6, Experiment 3 revealed a different result. The use of immersive VR led to better predictive ability during déjà vu reports compared to non-déjà vu reports. Specifically, participants who reported a sense of déjà vu for test trials that spatially corresponded to an unrecalled study scene demonstrated significantly higher predictive abilities ($M = .65$, $SD = .21$) compared to when they reported a sense of non-déjà vu ($M = .42$,

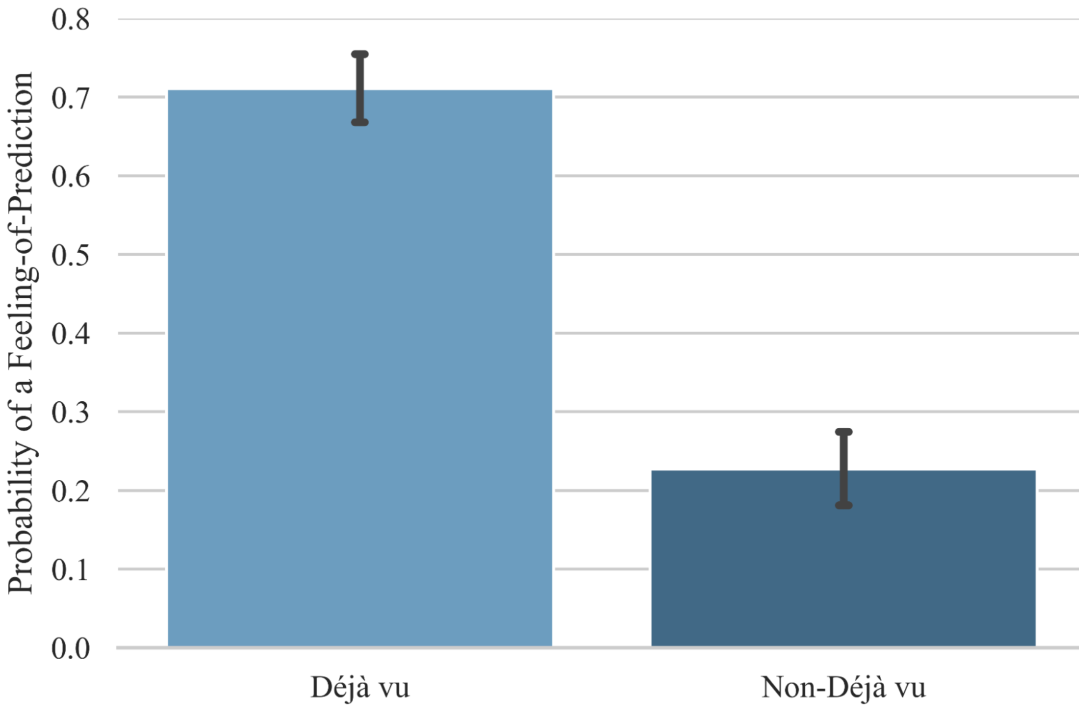

Figure 2.6: Average probability of reporting a feeling-of-prediction during retrieval failure as a function of reported déjà vu state in Experiment 3.

SD = .26), t(19) = 3.40, SE = .07, p = .003, d = .97, BF10 = 14.01. Additionally, we investigated whether the probability of accurately predicting the direction of the next turn was significantly above chance (.50) during déjà vu reports, and whether it was significantly below chance during non-déjà vu reports. The results showed that the probability of accurately predicting the proceeding turn during déjà vu reports was significantly above chance, t(19) = 3.15, p = .01, BF01 = 8.79. However, accuracy was not significantly below chance during non-déjà vu reports, t(19) = -1.38, p = .18, BF01 = 1.89.

2.4 Discussion

The current study builds upon previous research on deja vu conducted by Cleary and colleagues (2012, 2018, 2021), using a new set of configurally mapping scenes created for immersive virtual reality (VR). By demonstrating that these scenes can elicit scene recall, familiarity detection during recall failure, feelings of predication, and deja vu, this study validates this immersive reality framework as a viable tool for researchers investigating familiarity memory phenomena. Furthermore, by comparing the effects of fully immersive VR against non-immersive displays we were able to quantify the impact of immersion on familiarity memory phenomena.

Our findings provide several pieces of evidence that support the idea that immersive VR can enhance the impact of memory phenomena, which aligns with the assertion that experiencing realistic scenes from a first-person perspective is crucial to human episodic memory. For example, in Experiment 3, where participants experienced full immersion within highly realistic 3D scenes through a VR headset, scene recall rates were higher compared to Experiments 1 and 2, where the same scene tours were presented in 2D on a screen. Participants in the immersive VR experiment had significantly higher scene recall rates ($M = .59$, $SD = .19$) compared to participants in Experiment 1 (the remote, 2D experiment), who had an average recall success rate of .35 ($SD = .24$), $t(74) = 4.02$, $SE = .06$, $p < .001$, $d = 1.05$, BF10 = 162.96. Similar results were found when comparing the recall rates of participants in the immersive VR experiment to those of participants in Experiment 2 (the in-person, 2D experiment), who had an average recall rate of .38 ($SD = .16$), $t(80) = 4.86$, $SE = .04$, $p < .001$, $d = 1.25$, BF10 = 2.64 x 103. These results are consistent with previous research on the beneficial effects of immersive VR on memory encoding and retrieval (Smith, 2019).

Furthermore, the use of fully immersive VR led to a higher spatial resemblance effect on the probability of reporting déjà vu during instances of recall failure, as evidenced by the larger effect size in Experiment 3 compared to Experiments 1 and 2. Participants in the immersive VR experiment reported a higher rate of déjà vu for test scenes that spatially resembled an unidentified study scene ($M = .46$, $SD = .19$) than participants in Experiment 1, where scenes were presented on a 2D screen ($M = .35$, $SD = .23$), $t(74) = 2.00$, $SE = .06$, $p = .05$, $d = .50$, BF10 = 1.39. Similarly, rates of reporting déjà vu in Experiment 3 were significantly higher than those reported by participants in Experiment 2 ($M = .36$, $SD = .17$), $t(80) = 2.22$, $SE = .04$, $p = .03$, $d = .57$, BF10 = 2.01. These findings support the idea that human episodic memory heavily relies on memory for one's place within a scene from a first-person perspective (e.g., Rubin, 2022). Full immersion within realistic scenes from a first-person perspective not only improves episodic recall compared to viewing scenes on a 2D screen but also increases the likelihood of reporting déjà vu during recall failure for scenes with the same spatial layout. This suggests that immersion from a first-person perspective is an essential component of the déjà vu experience itself.

Overall, this study provides evidence that virtual reality (VR) technology can be a valuable tool for neuropsychological testing, especially when investigating familiarity memory phenomena. The precision and versatility offered by modern game engines, such as Unity, enable researchers to create immersive experiments with high levels of realism and experimental control. The use of VR technology in this study allowed for the creation of detailed scene stimuli with precisely managed object placement and movement trajectories. This level of control is a significant advantage compared to traditional cognitive assessments. Moreover, the versatility of the platform enabled the collection of data across a variety of VR modalities, generating a robust dataset that could be used to compare the impact of immersion on memory. Experiments built using these modern game engines also offer the opportunity to rapidly simulate naturalistic environments while seamlessly monitoring participants from a variety of peripheral devices. Overall, the findings of this study suggest that VR technology has significant potential as an important tool for neuropsychological testing and future research could further explore the possibilities of VR in memory research.

Chapter 3

Limitations and Future Directions

3.1 Limitations and Future Directions

3.1.1 Limitations in Participant Sample

Our goal with this research is to improve cognitive assessments in clinical settings by uncovering generalizable findings. However, collecting data from patients with temporal lobe epilepsy (TLE) in clinical settings can be challenging due to logistical limitations and low sample sizes. To fully capture the effect of immersion on cognitive processes, we chose to collect data from healthy controls. While our results indicate a significant effect, it is important to further study this phenomenon in clinical populations to make clear generalizations. To address this challenge, we are currently recruiting patients with TLE for a follow-up study to investigate the neural correlates of déjà vu using physiological measures. By exploring this connection, we hope to contribute to the development of improved cognitive assessments that can better serve clinical populations.

3.1.2 Lack of Direct Physiological Data

Another limitation of our study is the absence of direct physiological measures that are correlated with the cognitive phenomena under investigation. When using virtual reality (VR), one challenge is to synchronize the timing of the VR system with the physiological data collection devices such as eye-tracking, electrocardiogram (EKG), electroencephalogram (EEG), and electrodermal activity (EDA). At the time of conducting these experiments, we were in the process of developing a system to unify the timing information between the VR system and physiological monitoring tools. As a result, we were unable to utilize physiological monitoring devices in this study. However, as part of this thesis work, we have successfully developed a framework to display VR stimuli while simultaneously recording physiological data. This unified system will be employed in future experiments to collect electrophysiological data that can be correlated with the experience of déjà vu. This development will help address the limitations of the current study and provide valuable insights into the physiological mechanisms underlying the cognitive phenomenon of déjà vu.

3.1.3 Increased Noise from VR

In this thesis, we advocate for the integration of virtual reality (VR) tools as a means of enhancing the ecological validity of experiments while still maintaining a high level of experimental control. Nonetheless, some may counter that the expanded range of actions and options available in virtual environments may lead to unwanted noise in experimental results. For instance, in our own experiment, we permitted participants to move their heads freely throughout the virtual scene, which may be viewed as a diminution of experimental control due to the increased variability that this creates among participants.

In light of these concerns, we contend that allowing participants to interact with virtual environments in a more naturalistic manner can offer a more thorough comprehension of human behavior in realistic scenarios. Furthermore, since virtual environments are completely simulated, researchers can parameterize and track affordances as a variable within the experiment. This enables a more robust dataset by expanding the dimensionality of the data. Additionally, recent advancements in the field of machine learning make it possible to use this high-dimensional data to create ethograms that better model behavior, as suggested by advocates of the emerging field of computational ethology (Mobbs et al., 2021).

By incorporating these tools into our experiments, we can leverage the best of both worlds: the ability to maintain a high degree of experimental control while simultaneously gathering a rich and complex set of data points. This can lead to a deeper understanding of the nuances of human behavior in ecologically valid settings, and can open up new avenues of research for the scientific community as a whole. While it is important to acknowledge the potential for noise in VR experiments, we firmly believe that the benefits of these tools for advancing our understanding of human behavior outweigh any potential limitations.

3.1.4 Areas to Target as we Increase Ecological Validity

The findings of this study highlight the promise of VR for enhancing the ecological validity of cognitive assessments and improving the detection of memory phenomena. This leads us to consider which specific areas could benefit from these new assessment tools. Some researchers have already started developing cognitive assessments that aim to evaluate memory function during everyday activities. For instance, Parsons et al. created a virtual grocery store task to collectively measure individual components of memory correlated with standard neuropsychological batteries (Parsons & McMahan, 2017). Others, have utilized VR tools to develop spatial navigation tasks to assess cognitive decline (Wais et al., 2021). However, relatively few studies have explored the multimodal binding of information.

To address this gap, we propose the Emory Multimodal task as a tool to assess the integration of sensory modalities, linguistic information, and semantic concepts by using VR technology combined with physiological measures such as eye tracking and EEG. This assessment aims to capture subtle aspects of performance variability and provide a more accurate representation of memory function in real-world scenarios. The task can help advance our understanding of learning and memory mechanisms and provide a valuable tool for assessing memory and other cognitive functions in clinical and research settings. The proposed task involves a computer-based presentation of video-clips to assess various processes involving face and object processing, semantic and episodic learning, and memory function. The task aims to determine structure-function relationships in the temporal lobe and use this information to spare critical cognitive processes in patients undergoing neurosurgical intervention.

Assessing the multimodal integration of information is absent in the clinical assessment of patients, and a multimodal assessment would represent a first step towards bridging this gap. Technological advances, such as VR and physiological measures, make it possible to capture complex motor and sensory processing and measure response time accurately. The tool would include targeted data acquisition points that allow for assessing many of the novel areas of function that decline in patients undergoing brain surgery. Additionally, the tool would build in the capacity to measure some standard cognitive functions, ultimately minimizing the need for additional tests.

3.2 Conclusion

In conclusion, the current study has demonstrated that immersive virtual reality (VR) is a valuable tool for investigating familiarity memory phenomena. The use of fully immersive VR led to higher scene recall rates and a higher spatial resemblance effect on the probability of reporting déjà vu during instances of recall failure. These findings support the scene hypothesis of recollective experience and suggest that immersion from a first-person perspective is essential for the déjà vu experience itself. Moreover, the study highlights the potential of VR technology as a tool for neuropsychological testing and future research. However, limitations such as the lack of direct physiological data and the use of healthy controls call for further research to generalize the findings to clinical populations. Overall, this study provides valuable insights into the use of immersive VR in memory research and paves the way for future studies that aim to advance the field of neuropsychology.

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