Kognitiv Minnestestning i 2D och 3D Virtual Reality

Cognitive Memory Assessment in 2D and 3D Virtual Reality

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The ultimate goal of memory research is to deconstruct how humans form representations of real-life experiences accessible in the future. However, this can be challenging to investigate thoroughly while maintaining both naturalistic exposure and experimental control. To tackle this issue, a platform for cognitive memory assessment in virtual reality (VR) has been constructed. The platform portrays photorealistic environments in which everyday objects are encoded in terms of appearance and spatial positioning. Tests for object recognition and spatial memory are integrated into the behavioral VR task. How we perceive the world differs significantly depending on how immersed we are in the experience and moreover, our memory depends on the familiarity of the form the content to be remembered is presented in. As a second aspiration, I sought to find out whether 3D through stereoscopic rendering effects specifically aids memory. Results showed quicker identification although no difference in accuracy for object recognition in 3D compared to 2D. Furthermore, spatial memory measured by precise distances was improved in stereoscopic VR perception. In conclusion, a robust, versatile, and unique VR platform has been built, ready to be applied to neuroimaging research on memory, and is perhaps of special interest for researchers focusing on cognitive memory decline such as Alzheimer's disease.

1 Introduction

“Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line.” **— Benoît Mandelbrot**

Understanding the mechanics of memory has been a pursuit in scientific psychology since its initiation and in philosophy since way before the old greeks. While tremendous progress has been made one might take a moment to ponder on how accurately we really capture memory in today’s mainstream research. Generally, the participants have to look at a 2D monitor and memorize a continuous presentation of faces, objects, or scenes. These can all constitute very concrete and isolated stimuli, but it should be a scientific duty in questioning to what degree they capture the real-world version of what they represent or more importantly how we perceive them. Field studies of memory with high ecological validity, apart from their restraints in replicability and reliability suffer from the inability to manipulate stimuli quickly enough. Researchers often struggle to incorporate both adequate degrees of ecological validity and experimental control to evaluate cognitive constructs through psychophysical metrics (Kvavilashvili & Ellis, 2004). New technological advancements in virtual reality (VR) using head-mounted displays (HMD) have entered the memory research landscape to bridge this gap. de Gelder et al, (2018, p. 1) even claim “…one can view VR as a continuation of a long psychophysical tradition that attempts to interfere with our perception in order to clarify its underlying mechanisms.” Utilizing VR allows researchers to exceedingly capture verisimilitude and veridicality at scale. It is possible to time- and cost-effectively create an unlimited number of environments as opposed to in the real world. Moreover, the environments can be crafted specifically to alter perceptual and physical aspects from one instance to another eg., night to day or Earth-gravity to Mars-gravity. In VR, a participant can also have superhuman capabilities such as selecting objects at distance with a ray interactor which might come remarkably handy for ubiquitous time and locomotion restricted experimental setups. Excitingly, VR can also conduce neuroimaging techniques in naturalistic settings. In addition, progressing towards data collection with VR, HMDs obsoletes the need for special isolated experiment rooms, since every visual information embedded in the experiment can be fit within and fully cover the participants' field of view (Smith, 2019). Despite these potential benefits, one important question to consider which there is still a lack of empirical data on is the transfer effect of VR learning to the real world. While several studies are indicating that real-world learning is superior to VR, these are relatively old studies if we take seriously the exponential rate VR as a technological medium develops (Flannery & Walles, 2003; Hoffman et al., 2001; Waller et al., 1998). In comparison of graphical capabilities from an inferiority perspective, today’s VR HMDs and graphic software renderers are closer to indistinguishable from the real world than what 2010’s state-of-the-art equivalent was to the first generation of Sims. Mania et al, (2003) investigated what happened as a consequence of restricting the real-world field of view (FOV) for participants with special goggles and contrasted it to viewing equivalent virtual images and indeed no difference in memory recollection was found, indicating that VR might soon if not already offer the same outcome as real-world memory encoding.

Monoscopic 2D & stereoscopic 3D perception

Humans have natural stereopsis, our binocular design with an average of 60 mm interpupillary distance (IPD) allows us to perceive two different images of the world. The distinct images prompt a visual parallax effect interpreted by the brain as one three-dimensional image. In VR the two-lense design represents the human eyes. When two images with a short disparity and overlap are captured by virtual cameras and rendered separately to each eye it gives depth perception, this is what is called stereoscopic VR. In monoscopic VR one and the same image are simply rendered to each eye (Hendrix & Barfield, 1995). While it seems obvious that 3D should be the preferable option when studying the memory of real-life experiences, there is currently a lack of studies investigating what effect the perception of depth given in stereoscopic VR with HMD has on memory. In a summary of results in over 180 experimental tasks on the judgment of position and distance, identifying object, spatial manipulation of real or virtual world objects, spatial understanding, memory recall and learning, etc. stereoscopic 3D viewing improved performance compared to monoscopic 2D in over 60% of the studies. The performance increased the most in tasks on manipulation and identification of objects (McIntire et al., 2014). Some doubts over the object recognition during distance perception and estimation in stereoscopic VR compared to the external world have been raised, although, the effects seem small and inhomogeneous. A typical study on distance estimation involves perceiving, analyzing and reporting. Whereas reporting on how far the object is placed from the reference is done verbally or by walking to the position of the target object (Lin & Woldegiorgis, 2015). It is further reasonable to question the resemblance of brain activation between 2D and 3D memory encoding and retrieval. Along these lines, a recent EEG study comparing learning and long-term retrieval proved experimentally that stereoscopic 3D content promotes both more cortical regions and neuronal networks than 2D content (Amin et al., 2021). In a still as of today rare fMRI experiment within the subject of question Forlim et al, (2019) spotted distinct, and in the case of the bilateral superior frontal cortex – temporal lobe pathway among others, strengthened functional connectivity during stereoscopic VR in participants concurrently gaming. Yet, the graphics were rather crude in comparison to the high-end games available today. Their results, however, witness relatively weaker neural couplings in memory-associated pathways during monoscopic VR. Complementary data on neural stereo-mono distinction can be found in the EEG results from a navigation task by Slobounov et al, (2015) who registered higher FM-theta power in conjunction with greater postural instability and modulation of overall EEG patterns in 3D VR. Phenomenologically participants experienced a higher sense of presence in the stereoscopic condition.

Age differences and applications to Alzheimer's research

One of the most imperative reasons to conduct memory research is to identify the mechanisms underlying detrimental diseases. Alzheimer's is arguably among the top pernicious elements of life that we will be able to eradicate in the near future. We now know that the parts of the brain that neurodegenerate earliest in Alzheimer's such as the entorhinal cortex are heavily linked in spatial memory. Spatial memory is commonly studied in some form of navigation task whereas patients either follow a predetermined route during encoding and has to tell certain objects location during retrieval or have to find their way out of a maze (Commins et al., 2020). Virtual reality offers a tremendous opportunity when it comes to but not limited to navigation tasks (Corriveau Lecavalier et al., 2020). Howett et al, (2019) developed a VR navigation task that could effectively classify and predict patients with mild cognitive impairment (MCI) into low and high risk of developing dementia better than the standard cognitive tests. However, navigation tasks have some serious drawbacks when considering studying underlying neural mechanisms on top of functioning as a tool for cognitive assessment. Moving around in space greatly reduces the perceptual constancy which directly determines how we encode 3D shapes. Hence, one could question whether navigation tasks are even appropriate at all for n > 1 experiment designs if the result would be that the geometric information cues given by the topological structures defined in eg. occlusion contours and edge curvature is divergent among participants due to differences in viewing angles. Even though our phenomenological experience of 3D shapes seems to be largely in concurrence there is a systematic distortion to judgments of 3D shape (Todd, 2004). Certain setups of navigation tasks also suffer from a lack of control over gaze patterns. A problem that could potentially be ciphered by incorporating eye-tracking technology (Chiquet et al., 2021). Apart from memory deficits from Alzheimer's, there exist general age differences in memory performance in VR documented. A pretest-posttest study design found that cognitive training in VR had a positive effect on older adults but not on mild dementia patients (Zając-Lamparska et al., 2019). Another recent study found that memory training in VR in contrast to on iPad improved long-term memory in healthy older adults (Wais et al., 2021). Cautioning has been raised concerning VR as inappropriate for older adults due to nebulous arguments regarding technological novelty factors. But as of yet and to my knowledge no signs have proven these concerns disruptive to current or future advances within VR memory research on older populations (Jonson et al., 2021). In one study that compared VR HMD and desktop presentation of the same memory task in both younger and older adults, no difference in user experience between the two platforms was reported (Plechatá et al., 2019).

Hypotheses and research focus

H1: Stereoscopic VR perception will improve recognition memory for objects in naturalistic scenes.
H2: Stereoscopic VR perception will improve spatial memory for objects in naturalistic scenes.

In concise, the focus of this master's thesis is twofold: 1) I attempted to build a platform for rigorous cognitive memory assessment in VR with photorealistic natural scenes, and 2) answer the question if 3D aids or inhibits memory in such conditions.

2 Designing a VR platform for memory research

Contrary to popular belief, virtual reality is not restricted to HMD, the term has a much larger scope encompassing any computer-hosted perceivable environment. A review of studies comparing different levels of immersion in VR such as

HMD vs. computer, active vs. passive navigation and stereoscopy vs monoscopy found that generally, more immersive setups increased the sense of presence (Diemer et al., 2015). Furthermore, several studies report that more immersive systems increase episodic memory performance (Dehn et al., 2018; Harman et al., 2017; LaFortune & Macuga, 2018). One aspect of immersion is visual fidelity. However, the evidence in favor of whether visual fidelity improves memory is ambiguous. I find it reasonable to attribute a performance effect on memory dependent on whether the quality difference regards distractive or task-positive stimuli. Along these lines one study observed an interaction effect wherein high visual detail promoted memory for objects inconsistent with the environment meanwhile consistent objects were unaffected by visual detail (Mourkoussis et al., 2010). Thus, the quality effect seems to have a congruency factor. For me, the main interest of the current study was not to analyze any particular effect of visual detail apart from what is added by stereoscopic viewing. Hence, I tried to keep the quality factors of the scenes and all its containing stimuli at a constant- and high as feasible level. In my literature search, I found only one study looking at the difference between stereoscopic and monoscopic HMD VR on memory. In which the same congruency interaction was reported as in the last summarized study but this time from stereoscopic over monoscopic, as opposed to high visual detail over low visual detail. Apart from the interaction effect, no main effect of depth perception on object recognition and spatial awareness proved significant (Bennett et al., 2010). Field of view (FoV) is another factor since it determines how much visual information is available to the user. There is far more visual information present in an HMD setup compared to a computer monitor where the room one is in will be present in the periphery. In a VR CAVE setup where participants are surrounded by a large screen, researchers found that high FoV improved both memory accuracy and response time (Ragan, 2010). We know that memory is generally enhanced by multimodal stimulation and so is the sense of immersion. Several studies are indicating that multimodal feedback can improve memory in VR environments (Smith, 2019). Although the long-term goal is to simulate real-world situations as veridically and holistically as possible when conducting memory research, the focus of this thesis has been on the visual modality. While mentioned influences were important considerations to keep the sensory inputs constant e.g., letting participants sit in silence without any odor from food or anything else that could dampen or even break the immersion. On that account, I also refrained from including any haptic, tactile or auditory feedback from the VR environment except a negative beep sound to indicate when participants were too slow. What I also had to refrain from albeit, more reluctantly was the full range of active interaction that some would argue is what constitutes the allure of VR. In fact, I completely disallowed any movement inside or outside the VR scene during the experiment. Keeping the participants motionless had two main purposes 1) reduce the differences between 2D and 3D conditions to only the perception of depth and 2) prototyping the paradigm for future implementation in research that aims to collect brain activity with motion-sensitive devices such as EEG and fMRI. It would have been possible to use hand-controlled navigation, nevertheless, a possibility I dismissed due to drawbacks in motion sickness along with demands on a less sequential, but more of a continuous experiment design, wherein the former is most frequently preferable in neuroimaging studies. Restrictions did not amount to all movements and interaction, indeed, interaction was yet an integral part of the experiment whereas, objects were selected and moved around in 3D space with movements of the arm, wrist and fingers in accord with the direction buttons and joystick of the hand-controller. Allowing interaction was essential to capture certain at least rudimentary aspects of the enactment effect which holds that active engagement with the surroundings aids memory as opposed to passive registering, by now a well-documented effect even in VR (Tuena et al., 2019). Convincing support for the enactment effect in VR was eloquently demonstrated in an educational setting for medical students (Jang et al., 2017). Half of the participants had to actively explore the anatomy of the ear in stereoscopic Sim-VR using a joystick to rotate and zoom in on the substructures of the inner ear. Next in order, the other half had to passively watch videos, that blindly to the passive watchers was the recordings from the other participants' active exploration. At a subsequent drawing test, the active exploration proved better spatial memory of the substructures by producing more accurate depictions of angle, shape, size and placement. Additional argument opting for a fixed position task was brought by incomplete evidence in favor of spatial memory gains with interaction in navigation tasks (Smith, 2019). Participants would possibly be overwhelmed on where to look when freely exploring the environment especially considering the high-quality texture details in conjunction with novelty impact from VR inexperience. Scenarios like these would not only constrain encoding but also induce unequal prerequisites to the monoscopic vs. stereoscopic conditions. Backing up my design choice even further, experiments on VR proved that navigation benefited spatial memory only for the spatial layout of rooms but not for the specific position of individual objects in the room (Attree et al., 1996; Brooks et al., 1999). The enactment effect was even inverted when actively navigating participants had worse recognition during image sorting of images taken along the navigated route (Wallet et al., 2011).

Not to be utterly disrespectful to the history of the field I give in to offer a word on presence. Presence in the context of VR is likely the most referenced psychometric construct. Described as "... the phenomenon of behaving and feeling as if we are in the virtual world created by computer displays" (Sanchez-Vives & Slater, 2005). Cummings & Bailenson (2016) give a slightly different interpretation of the same concept and describe presence as a concept about "being there". As the name implies, it is a concept to evaluate how the user experiences presence in the virtual environment. In other words, presence can be used to investigate how realistic the environment created in VR is, and how good the user experience is. On the other hand, critique has been posed stating presence as a construct is misleading in its unstandardized format due to the inevitable relativity of experiences generated by our predictive brain (Smith, 2019).

I used presence as a guiding principle in developing the paradigm, but it was not a central concept neither a surveyed construct since I find the measurement rather arbitrary in nature.

Although the current design was not aimed to be perfectly suitable for a specific age or patient group, there are plenty of reasons not to completely separate encoding from retrieval. Gordon et al, (2015, p. 1778) articulated it most clearly and to the purpose "Finally, studies in the field should consider combining encoding tasks with very little memory demand with memory retrieval tasks to examine the sensitivity of attention and/or memory to AD pathology.".

Software & Hardware

The choice of 3D engine software to build the platform fell on Unity 3D version 2021.1.16f1. Principally a game engine and since its free for students to use, have a robust design, large documentation database and great reputation Unity was considered appropriate for my mission. For data export, event triggering system and position & rotation tracking, Unity Experiment Framework (UXF) version 2.2.0 came handy (Brookes et al., 2020). Beyond that, all scripts controlling the actions and flow of the task paradigm were written by me in C#.

The platform was built on an RTX2070 equipped Acer gaming computer using an Oculus Quest 2 VR HMD connected with USB-C Oculus Link. The VR controllers are tracked in space through external cameras on the HMD and allowed for moving objects freely in three spatial dimensions. The tracked hand controller was essential to the memory task in that it in contrast to a classic computer mouse and keyboard enabled movement in the x, y and z-axis simultaneously and intuitively using one hand. However, one disadvantage in using the VR controller is that it cannot be used for the computer only, hence inhibiting me from naturally comparing a PC version of the task to the current setup. Not to say that this is not possible with additional hardware, nonetheless, this was outside the scope of the main research questions.

Stimuli design

Since one ambition of the study was to enhance ecological validity for cognitive memory research, a high level of realism was paramount when considering the stimuli. Two scenes were purchased through Unity Asset Store. The first henceforth referred to as Scene A was an architect visualization of a house in Scandinavian interior style (see screenshot in Figure 2). Scene A has HD 4K textures with baked lighting. The second scene henceforth referred to as Scene B was a group of American suburban neighborhood-style houses with 256 to 2K textures. Both scenes utilized Unity's native high-definition render pipeline (HDRP) to render high-fidelity graphical realism even though the net result was substantially higher quality in Scene A. The scenes had to have different project- and postprocessing settings for the shaders to be displayed in optimal quality and lighting conditions. Therefore, they had to be accessed through separate Unity projects.

For the stimuli to be remembered, henceforth referred to as *Target object*, objects within the room were thoroughly analyzed. Objects identified as eligible as targets matched the criterion of being fairly similar in size or not occupying a too unproportionate part of the FOV. Optimally, target objects were also to have an angle and position that was not requiring rotation or was too revealing by uniqueness. The stimuli & task design were largely inspired by previous neuroscience research I have been involved with, most of which is still pre-publication on the effect of Alzheimer's pathology on memory networks in the brain (Maass et al., 2019). After selection, the target object was duplicated and manipulated. For the object manipulation, henceforth referred to as *Lure* I deformed, added or subtracted a detail, or used a different but similar-looking object to the original. I was meticulous in that the lure should fit in naturally in the room and at the Target objects position. Trying to minimize any risk of choosing an object based on logical inference. While I appreciate the efforts of scientists trying to standardize VR research by providing a free database of 3D objects encouraged to be used across studies, these did not satisfy my criteria for graphical quality nor feeling native to the room (Peeters, 2018).

How the platform works

After a room was identified as appropriate to represent a trial room, the position and angle of the in-game camera's start position were decided. The height and angle were set naturally but not constant to capture different modes of viewing a scene like at chair height if in front of a kitchen table or standing height gazed slightly downwards in the backyard in front of a pool. Mixing these factors escaped benefitting participants within a certain height range through familiarity to the encoding angle. E.g. a basketball player would likely more quickly recognize and encode a mailbox's, position from above, compared to someone in a wheelchair If angling in the z-axis was not equal to zero it was adjusted minimally not to make the perceptual depth cues from stereoscopic viewing noticeably incoherent among trials. For every trial room, a choice room with unlit grey boundary walls was placed inside. This is where the two trial objects appeared during object recognition. The trial objects were centered at eye level for fast identification. Upon object selection, the choice room was deactivated, and the trial room became again visible except now empty from the deactivation of room objects. Occasionally some room objects remained visible during object positioning if it was either incidental to the trial object e.g., a table when the target object was a vase standing on the table, or leaving a too revealing shadow. As proposed by Lopez Maïté et al, (2016) a standardized familiarization phase with the technology and the behavioral task is crucial to minimize novelty effects. A comprehensive tutorial (screenshot excerpt in Figure 1) was constructed in which participants were initially given a few minutes to explore an example environment and pilot the controllers before being instructed step by step through a pop-up interface on how the task including interaction works. The tutorial included rooms reserved for practice trials. An overview of the final task setup can be seen in Figure 3.


Welcome to Virtual Reality!

Start by taking a look around to familiarize yourself with the environment. Move your hand around and notice the red line pointing in your hands direction.

Now lock your head position so that blue dot is in the center of your view. You can move your gaze around as much as you want but try to keep your head as still as possible during the whole experiment.

Direct your hand towards the button underneath that says "Continue" so that the red line becomes green and press your middle finger to start the tutorial.

Figure 1. Tutorial

Figure 2. Example of a trial room in scene A

Configurations

Even though the experiment was built and ran on top-class hardware, the photorealistic 3D environments required meticulous manual configurations and testing for optimal performance and quality. Refresh rate (how often the screen refreshes with an image) was set to 72 Hz and render resolution to the HMDs maximum at 5408 x 2736. It is possible to play up to 120 Hz but that would result in significantly heavier CPU and GPU load, an option I avoided since the only thing that is moving within the experiment is the object that is grabbed for the spatial memory task. It is also pertinent to mention that even though the render resolution was set relatively high, it is partly limited by the hardware display resolution at 1832 x 1920. To crank up the image quality even further, Sidequest was used to enter developers' settings and set the default texture size at 3072. Maximizing texture quality was an important factor especially since it can improve distance estimations in perceptual matching tasks in virtual environments (Sinai et al., 1999). Another factor to consider enabling optimal consolidation of accurate depth perception in the VR rooms is lighting. Naceri et al, (2011) found that depth was more accurately estimated in bright rooms (lit textures) compared to wireframe and dark rooms. These results are consistent with corresponding experiments in the real world (Philbeck & Loomis, 1997). To set the perceptual manipulation, a script was set to render the image from a center camera to each eye lens if monoscopic was enabled. In contrast, in executing the 3D effect, single-pass stereo rendering was enabled which combines the relevant half of two images for each eye into a single double-width render texture as opposed to the more traditional multi-pass that renders two distinct images to each eye separated in the x-axis but greatly overlapping. Using single-pass stereo mainly contributes to performance boost in heavy geometry processing where frame time dropped 20% - 30%. A common problem when dealing with high-quality textures in moving frames is jagged edges, this is generally dealt with through anti-aliasing (Yang et al., 2020). Testing different techniques with varying results I eventually ended with satisfying results applying temporal anti-aliasing (TAA) after fine-tuning with sharpening strength, anti-flicker and speed rejection. Oculus Quest 2 has three settings for interpupillary distance (IPD), 58mm, 63mm and 68mm. By script, the IPD setting was tracked and adjusted the distance between the two cameras in stereoscopic mode accordingly. OpenXR was used to enable VR interaction capabilities to solve the important issue of selecting and moving objects in 3D space. By attaching interactable scripts to the trial objects they could be moved around with an interactor ray line directed and controlled by a hand controller. The trial object had rigidbodies and freeze rotation but unfreeze for position transform in all three axes. Velocity tracking was deployed to hinder hand-controlled objects from moving through walls and other objects in the scene that had attached colliders. Force grab was set to off so that the object was controlled from the position it was selected to avoid additional delay in response time during the spatial recognition segment. The ray interactor was scripted to only be visible during the time for selecting and positioning objects so that it couldn't be used as mnemonic aid or confuse the participant about when action was required. When hoovering mid-air the ray interactor was set to a red color and clear green when hovering over one of the two trial objects regardless of correct or lure to indicate selection was possible. Translate speed at 5 was considered appropriate to move the object quickly to prevent second thought on placement but slow enough for smooth and accurate positioning before drop. The target object and both trials had a position rotation tracker script that continuously measured and saved coordinates into CSV files, permitting the spatial recognition tests with Euclidean distances between trial object position at drop and the target object. More on metrics in the methods section. More details of the configuration will eventually be documented and available on GitHub.

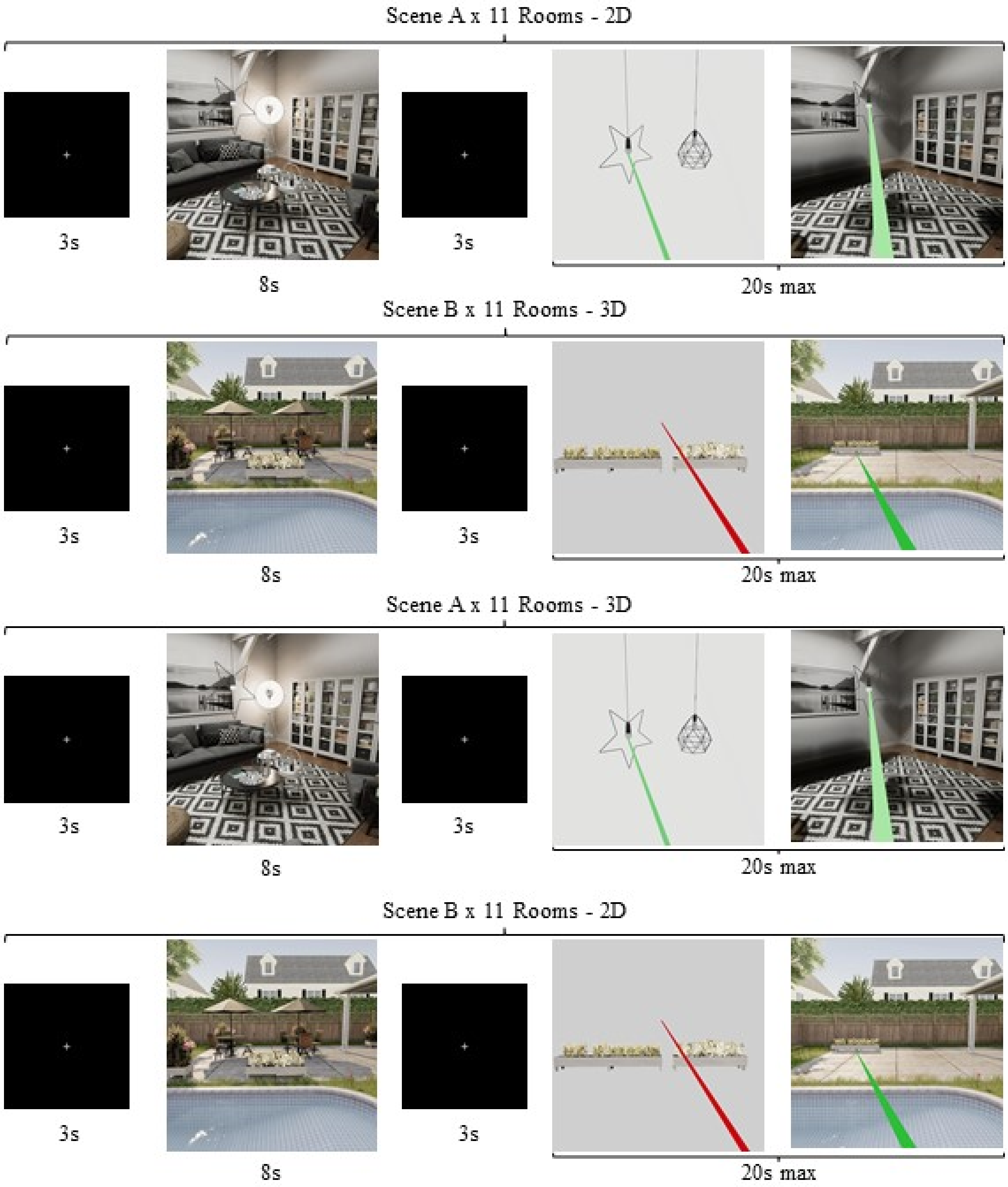

Figure 3. Task design.

3 Method

The purpose of the behavioral task was to explore if we have better recognition memory for objects in a 3D environment as compared to 2D. Therefore, a forced decision task was implemented to gather data on recognition accuracy including response times. Moreover, a free placement subtask was constructed to retrieve data on spatial memory performance

Design

A within-subject design was deployed consisting of 44 trials in total. The experiment was split into four blocks containing 11 trials defined by 2D or 3D and two stimuli sets: Scene A and Scene B. Trials was randomized within blocks and to further reduce order effects of stimuli sets each participant was assigned to one out of eight conditions, Conditions was counterbalanced so that neither 2D or 3D nor Scene A or B conditioned appeared twice as in the second round of trials per stimuli set to minimize learning effects. An illustration of the setup including one of the eight order conditions can be found in Figure 3. The total experiment time differed depending on how quickly participants completed trials but was homogeneously averaged at 30 minutes.

Participants

16 healthy participants (4 female, 10 male) were recruited at Lund University and through word of mouth, wherein around half students (mean age = 25.6 years, *SD* = 3.2) took part in the experiment. All participants had tried virtual reality before without anyone having more than intermediate experience.

Participants were compensated in the form of Fika and a lottery ticket for completing the experiment task.

Procedure

Data collection was performed in Malmö and Lund in a silent room with no external distractions. Asked to take a seat on a chair placed in the middle of the room and informed about the upcoming procedure including that a detailed tutorial was waiting inside the HMD but also that in short, they were going to see different rooms filled with objects and that the objective is to memorize the appearance and position of all the objects in the room. Participants were then told to put on the HMD, adjust it properly for maximum comfort and image sharpness within a sample scene and told to keep their heads as still as possible throughout the experiment for reasons explained previously. Participants then completed an in-VR tutorial while being encouraged to ask questions about any uncertainties to the experiment leader. As the ending segment of the tutorial participants did two rounds of five practice trials and declared that they understood the task and were ready to begin the experiment. After completing 11 trials in a Scene and perception block participants remained seated with the HMD on for around one minute before the next block started. After finishing the task and taking off the HMD every participant was asked if they recognized any perceptual differences between each session.

Behavioral task

For each trial (see illustration in Figure 3) a centered white cross against a black background (distractor) was displayed for 3 seconds before a room with filled objects was displayed in 8 s, during which participants memorized the appearance and positions of the objects in the room. After the 8 s encoding phase and an interim 3 s distractor two “Trial objects” one identical to the target object (Correct) and one similar but different (Lure) appeared against a grey background. This constituted the object recognition phase where participants selected the object they believed to be in the previous displayed room. Direct upon selection the spatial memory recognition phase began in which the previous room appeared empty of objects. At this point, participants were using the hand controller to position the selected object at the position they believed it previously occupied. When feeling determined, they released a button indicating the end of the spatial memory recognition phase and the start of a new trial.

Variables and Data analysis

The first dependent variable was *accuracy of object recognition*. This was simply a binary score determined by the selection of the correct or lure object. In addition, *response time (RT)* was calculated to capture potential differences in the speed of object recognition between conditions. RT was only analyzed for object recognition and not spatial memory recognition because the latter phase had too much temporal variation due to factors such as distance from selection position to target position, skill in using hand controller and walls or objects blockading, etc. It was simply not a reliant measurement of memory, since one could spot the recognized accurate positioning of the object sometimes a few seconds before it was moved there. Next, the three-dimensional Euclidean distance was measured between the drop position of the trial object and the initial target object position to represent spatial object recognition. A Vector3 distance function in C# performed the calculation with the following formula:

$$3D\ distance = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (1)$$

A secondary spatial object recognition metric was initially not planned. But after compilation and the first round of data analysis, it occurred to me if the x and y-axis distance differ between 2D and 3D it might demonstrate that stereoscopic perception transfers additional cues to the preexisting two-dimensional information. Only distance to target among the z-axis should be reduced as a direct consequence of the depth cue added in stereoscopic perception. To control for the likelihood that better spatial memory occurred in stereoscopic perception and that the effect was not just driven by improved distance estimation in 3D I took advantage of the position rotation trackers and could through conditional functions extract the raw data necessary to calculate the two-dimensional distances. Before I could execute formula (2) two control operations had to be performed. Firstly, three stimuli set (two in A; one in B) were excluded since they were not angled perpendicular. Secondly, the correct horizontal axis which could be either x or z depending on the room's angle in virtual world space had to be determined for each trial stimuli sets. The vertical axis y always remained constant.

$$2D\ distance = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \qquad (2)$$

Data were analyzed using repeated measures ANOVAs evaluating potential effects of Perception (2D; 3D) and Scene (A; B). Analyses were performed using R version 4.1 and Jamovi version 2.0.0.

Ethics

The experiment was not associated with any particular discomfort. For the purpose of scientific analysis, the project intended to collect and record information about participants, including responses and results on the experiment task as well as answers to personality questionnaires. To ensure participants' anonymity, all collected data were pseudonymized and stored on password-protected hard drives and computers so that only people associated with the project could have access to the information. Neither would any personal information be shared with any third party. All participants were informed of the general arrangement and handling of personal anonymity in the study such as anonymity and agreed to participate by signing an informed consent under full voluntary conditions, meaning they could abort the study and ask for their data to be withdrawn at any time without giving a reason why. Furthermore, all participants were debriefed verbally after they completed the study and were able to ask questions to the experiment leader. They were also notified about where to find the future results from the study.

4 Experimental results

When asked directly after completing the experiment, no participant admitted they noticed the manipulation of monoscopic vs. stereoscopic perception in the experiment. One indicated vaguely that the objects perhaps appeared slightly larger in one block.

Analyses of the first variable *accuracy of object recognition* yielded no support for **H1:** Stereoscopic VR perception will improve recognition memory for objects in naturalistic scenes.

The results of the first two-way repeated measures ANOVA revealed that there was no significant main effect of perception on participants' object recognition ($F(1,15) = 1.5$, $p = 0.24$, $\eta p^2 = 0.009$). Participants performed similarly when perceiving 3D ($M = 0.79$) and 2D ($M = 0.76$). In contrast, descriptive statistics revealed that participants' mean object recognition were better for trial rooms in Scene B ($M = 0.82$) compared to Scene A ($M = 0.73$), the ANOVA revealed that this difference was significant ($F(1,15) = 10.86, p = 0.005$, $\eta p^2 = 0.42$). There was no significant interaction between Perception and Scene on object recognition ($F(1,15) = 0.22, p = 0.64, \eta p^2 = 0.01$).

Table 1. Descriptive statistics – Object recognition.

Condition	*n*	*M*	*Median*	*SD*	*Min*
2D - A	16	0.73	0.73	0.15	0.45
3D - A	16	0.73	0.73	0.17	0.45
2D - B	16	0.79	0.77	0.17	0.55
3D - B	16	0.85	0.86	0.14	0.55

When looking closer at object recognition performance in response times as a secondary variable, support for H1 could be discerned. The results of the second two-way repeated measures ANOVA revealed that there was a significant main effect of perception on participants' response time (RT) for object recognition ($F(1,15) = 4.58$, $p = 0.049$, $\eta p^2 = 0.23$). Participants' was quicker when perceiving 3D ($M = 2.77$) than 2D ($M = 3.03$). And while descriptive statistics revealed that participants' mean RT were slightly lower for Scene B ($M = 2.84$ compared to Scene A ($M = 2.96$ the ANOVA revealed that this difference was not significant ($F(1,15) = 0.81$ $p = 0.38$, $\eta p^2 = 0.05$). There was no significant interaction between Perception and Scene on RT ($F(1,15) = 0.00$, $p = 0.985$, $\eta p^2 = 0.00$).

Table 2. Descriptive statistics – RT for object recognition.

Condition	*n*	*M*	*SD*	*Min*	*Max*
2D - A	16	3.09	1.23	1.47	5.51
3D - A	16	2.83	1.11	1.77	5.60
2D - B	16	2.98	1.20	1.46	5.71
3D - B	16	2.70	1.13	1.23	5.04

Next up was evaluating the results from the distance variables concerning **H2:** Stereoscopic VR perception will improve spatial memory for objects in a naturalistic scene. The results of the third two-way repeated measures ANOVA revealed that there was a significant main effect of perception on participants' spatial recognition ($F(1,15) = 21.96$, $p < 0.001$, $\eta p^2 = 0.59$). Participants placed the trial object closer to the target object when perceiving 3D ($M = 0.52$) than 2D ($M = 0.71$). Furthermore, descriptive statistics revealed that participants' spatial recognition were better in Scene A ($M = 0.49$) compared to Scene B ($M = 0.75$), the ANOVA revealed that this difference was significant ($F(1,15) = 22.73$, $p < 0.001$, $\eta p^2 = 0.60$). There was no significant interaction between Perception and Scene on spatial recognition ($F(1,15) = 1.19, p = 0.293, \eta p^2 = 0.07$).

Table 3. Descriptive statistics – three-dimensional spatial recognition.

Condition	*n*	*M*	*SD*	*Min*	*Max*
2D - A	16	0.51	0.19	0.20	0.84
3D - A	16	0.47	0.38	0.08	1.47
2D - B	16	0.91	0.56	0.35	2.10
3D - B	16	0.58	0.21	0.22	0.95

The results of the fourth two-way repeated measures ANOVA revealed that there was close-to but no significant main effect of perception on participants' two-dimensional spatial recognition ($F(1,15) = 3.79, p = 0.07$, $\eta p^2 = 0.20$). Descriptive statistics showed that participants' placed the trial object slightly closer to the target object when perceiving 3D ($M = 0.57$) than 2D ($M = 0.72$). In contrast, descriptive statistics revealed that participants' two-dimensional spatial recognition were better in Scene A ($M = 0.40$) compared to Scene B ($M = 0.77$), the ANOVA revealed that this difference was significant ($F(1,15) = 96.81, p < 0.001$, $\eta p^2 = 0.87$). There was no significant interaction between Perception and Scene on two-dimensional spatial recognition ($F(1,15) = 1.59$, $p = 0.23$, $\eta p^2 = 0.10$).

Table 4. Descriptive statistics – two-dimensional spatial recognition.

Condition	*n*	*M*	*SD*	*Min*	*Max*
2D - A	16	0.23	0.10	0.06	0.41
3D - A	16	0.27	0.24	0.03	0.82
2D - B	16	0.74	0.44	0.23	1.55
3D - B	16	0.51	0.22	0.19	0.88

5 Discussion

Returning to the first aim of the thesis presented in the introduction, I must conclude that I succeeded in my attempt to build a platform for rigorous cognitive memory assessment in VR with photorealistic naturalistic scenes. The platform is fully functioning and provides sophisticated data output of stringently defined memory variables. To my knowledge, I have produced a way more advanced, pertinent and integrated VR platform for data collection on memory than any other tool out there today. Most previous studies on spatial memory in VR, offer passive or interactive encoding but have spatial memory retrieval in a cruder form either verbally or post-VR (Smith, 2019). The current paradigm provides a fully interactable retrieval phase through intuitive position control apparatus with conscientious distance measurements revealing precisely how close participants were in their spatial memory retrieval. Furthermore, the platform is configurable so that e.g., stimuli can be exchanged and session settings like exposure times and event triggers can be adjusted with basic programming skills. Counter to common alternate paradigms, this build is also ready to be adopted in neuroimaging studies that are restraining movement, with the caveat that the hardware might have to be replaced to suit the scanning technology, such as non-magnetic HMD and controllers for fMRI.

Recalling my second aim with the thesis to investigate the difference between 2D and 3D on memory in VR, I will discuss the implications of the results concerning the two hypotheses.

Object recognition and spatial memory

If considering accuracy in object recognition alone, the first hypotheses could be rejected. This is consistent with the results from Bennett et al, (2010), however, I used substantially superior hardware and software in addition to having real-time visual interaction with the objects in the task contrary to having a postexposure questionnaire. What Bennet et al, (2010) was unable to capture with their methodology, was response times. Much like Amin et al, (2021) even though they did not use HMD VR I was able to register quicker object recognition in 3D. If 3D promotes object recognition memory remains not irresolute but just requires some sophistication to interpret and report consistently. More specifically it has to be clarified under what circumstances the encoding took place in respect to the objects' congruency to the scene. In this study all objects were native to the scene although some objects might have deliberately been placed at not the most typical place in the room, e.g., dustbin on the middle of the garage driveway behind a car instead of more typically on the street. This in part, motivated the spatial memory tests. As reported in the results there was a strong effect of perception on spatial memory. But regarding all the controversies around distance estimation in virtual environments eg. noted by Sinai et al, (1999) and the perhaps obvious fact that people should be better at telling the right three-dimensional position of objects if viewing it in three as opposed to two dimensions, further analysis was required. Considering only the three-dimensional distance measure, one is tempted to claim that 3D generated improved spatial memory retrieval and H2 was settled. However, it could be argued that the effect in this experiment is insufficient to generalize the improved skill of placing the object at its correct position in 3D to encompass memory retrieval. To control for this, I isolated the 3-dimensional axes, x, y and z and investigated if the proximal vector 3 Euclidean distance was driven by the z-axis alone. In other words, if participants still were better at positioning the object horizontally and vertically in 3D, the result can be confidently attributed to improved spatial memory retrieval in 3D. This investigation proved to be insightful, yet marginally statistically insignificant. Still, the lack of statistical significance does not rule out that spatial memory is invariable to depth cues, on the contrary, deemed in conjunction with the closer three-dimensional object placement, I find it sufficient to propose that spatial memory is in fact enhanced in stereoscopic viewing given the right circumstances. What those circumstances are is on one hand for future empirical data to decide but also for me to engage in some educated speculation on in the upcoming paragraph. The first possible explanation for the absent significance on the last test is inconsistency with object positioning in the room. No objects except arguably the lamps were placed mid-air. Therefore, objects were either placed on the floor/table or on a wall and therefore always locked in the x or y position. Meanwhile, the object could be placed towards a rear wall like a painting and thus locked in the z-axis, the vector3 Euclidean distance was always measured when including the z-axis. There are not many empirical data to draw on since the distance measurement in the context of spatial memory tests is rather original work. For deeper deconstruction, I revisited the perception literature and remembered the following passage from a book on 3D shape by Pizlo (2010, p. 124) "Adding binocular disparity does improve performance. However, binocular performance is not very good, unless monocular performance is very good, as well. This means that if simplicity constraints, such as symmetry, cannot produce a good 3D shape percept from a single 2D image, binocular disparity contributes nothing!" In stereoscopic perception (b) in Figure 4 appears more vivid and has greater depth cues than (a).

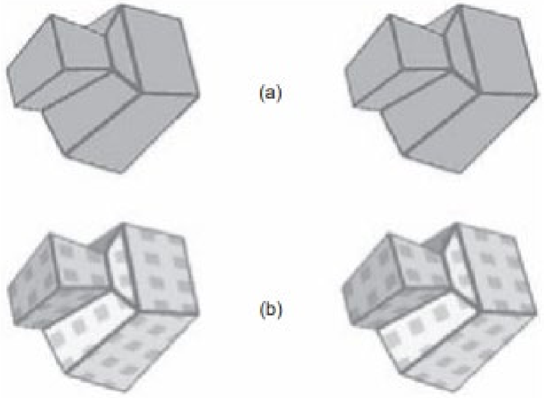

Figure 4. Two versions of the same 3D object. (a) has no binocular disparity, shaders or textures (b) has all three. Image from (Pizlo, 2010).

Therefore, the individual quality and textures of the objects might have been the determinant factor in the magnitude of performance improvements in the stereoscopic condition. Confusingly this is in direct contradiction to what my data suggests if we look closer at the within-scene differences between 2D and 3D (see Table 1-4) the 2D - 3D improvements seems to be slightly better for Scene B. Recalling that there was a significant performance difference between Scene A and B, and that Scene B were inferior in shader and texture quality. However my data sample was likely too small to carry out three-way ANOVA statistical analysis, therefore I will leave whether Pizlo suggestions are generally true as up for debate. I should also be clear to point out that features of specific trials such as average distance to target from the camera might have influenced the unexpected tendencies to better improvements in Scene B, this has as of today not been statistically controlled for. In addition, if we recall Mourkoussis et al, (2010) experiment showing that higher visual fidelity improves memory but only when objects are incongruent to the scene, it seems to explain why the better graphics in Scene A did not result in better memory performance. Almost all trial objects, at least the correct ones, were native to the scene and therefore had high congruency.

Most interestingly were that no participant explicitly noticed a perceptual difference between stereoscopic and monoscopic conditions. The subconscious element of added depth cues greatly augments the value of the present results.

Not included in the results section because it was quite irrelevant to the hypothesis, but interesting from a prototype evaluating perspective was the learning that occurred. (see Figure 5). Participants' object recognition and spatial memory scores were drastically improved from the first to the second round. This indicated that the platform showed proof of working as the cognitive memory assessment tool it was intended to become, and that the difficulty level was just about right in the current setting. What Figure 5 perhaps further reveals is that it could be most suitable as an encoding paradigm for a long-term retrieval study.

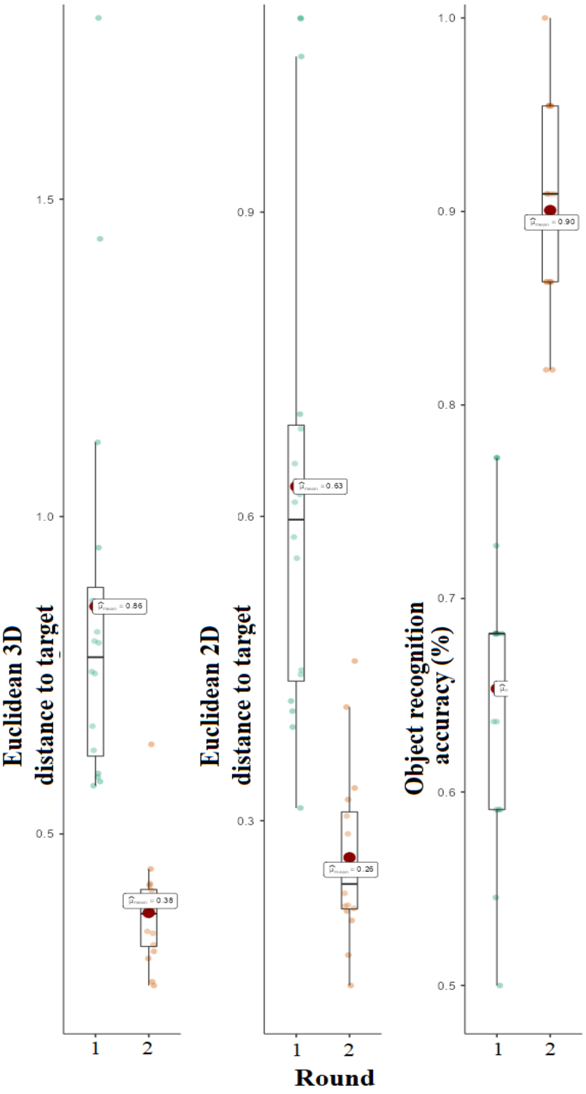

Figure 5. Learning effect from first to second time seeing the same room regardless condition.

Potential application in Alzheimer's research

A paramount motivation for building this platform was to improve cognitive memory assessment and hence neuroscientific understanding of Alzheimer's disease. The specific metrics of distance allow for a new and precise measurement of spatial memory able to upgrade the ongoing search for neural correlates of early-stage AD. In the introduction, I downplayed the impact of age-related concerns using VR in memory research. While some of these concerns lack empirical support (Plechatá et al., 2019), there could prove to be both foreseen and unforeseen challenges in using VR on cognitively impaired individuals. One concern is that the desired enhanced level of realism could prove to be counterproductive. Temporarily, blurring the lines between external and virtual reality could potentially be very confusing for already confused patients with memory deficits. Studies need to be made to ensure good precautionary paradigm configurations as well as ethical guidelines. Furthermore, using controllers with unsteady hands might be a problem in position placement tasks, although it could partly be tackled by adjusting sensitivity settings or avoided by replacing them with other tracking devices, eg. eye-tracking.

Limitations & future directions

Before pilot testing, there was no visceral way of preserving equal difficulty between stimuli since the stimuli sets were completely new untested. Meanwhile, the human FOV is approximately 200 degrees horizontally x 135 vertically I was limited to 104 horizontal x 98 vertical FOV provided by Oculus Quest 2. There exist HMDs with wider FOV that could possibly have contributed to greater immersion and synergistically stereoscopic promotion of spatial memory, but choosing HMD was a tradeoff between pure quality, tracking gear and software integration. The rooms in the paradigm however do not cut the edge of the FOV, making it feasible to use an HMD with greater FOV in the future.

What I would like to see in the future is taking tenacious advantage of interaction during encoding akin to (Jang et al., 2017). Applying it to the current paradigm, it would be most reasonable making the task as it stands to the encoding phase. Proposedly a day after you could have retrieval where a trial starts at object selection, alternatively or alternatingly showing the empty version of the room first. In the current within groups design, it was difficult if not impossible to reliably evaluate the perception and scene-based learning effects. A future between groups-design with cognitive control tests and a larger number of participants allows for a wider range of statistical analysis. If the platform proves to be valuable in neuroimaging remains to be determined. A proposed first study is to examine the neural correlates of 3D vs 2D perception of the same objects with EEG.

6 Conclusion

In conclusion, a robust, versatile, and unique VR platform has been built, ready to be applied to neuroimaging research on memory, and is perhaps of special interest for researchers focusing on cognitive memory decline such as Alzheimer's disease. In a first experiment using the platform, I found that stereoscopic 3D VR is preferable for optimal memory performance. In a within-VR memory encoding and retrieval task, stereoscopic VR improved object identification speed and spatial recognition in 3D.

Availability

In an open-source fashion, I aim to make the VR memory paradigm including documentation freely available to download via GitHub as a Unity package once script updates and bug fixes to the current prototype have been executed.

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