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Keeping track of reality: Embedding visual memory in natural behavior

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Abstract

Since immersive virtual reality (IVR) emerged as a research method in the 1980s, the focus has been on the similarities between IVR and actual reality. In this vein, it has been suggested that IVR methodology might fill the gap between laboratory studies and real life. IVR allows for high internal validity (i.e., a high degree of experimental control and experimental replicability), as well as high external validity by letting participants engage with the environment in an almost natural manner. Despite internal validity being crucial to experimental designs, external validity also matters in terms of the generalizability of results. In this paper, we first highlight and summarize the similarities and differences between IVR, desktop situations (both non-immersive VR and computer experiments), and reality. In the second step, we propose that IVR is a promising tool for visual memory research in terms of investigating the representation of visual information embedded in natural behavior. We encourage researchers to carry out experiments on both two-dimensional computer screens and in immersive virtual environments to investigate visual memory and validate and replicate the findings. IVR is valuable because of its potential to improve theoretical understanding and increase the psychological relevance of the findings.

Keywords: Virtual reality; internal validity; external validity; visual memory; replication.

Keeping track of reality: Embedding visual memory in natural behavior

The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked. – Ivan Sutherland (1965), The Ultimate Display.

Since the development of the first virtual reality (VR) system by Ivan Sutherland and Bob Sproull, the aim of (computer) scientists and VR developers has been to make the virtual equal to the real. This search for realism is well exemplified in the above statement by Ivan Sutherland. Recently, VR has been extremely advanced in terms of technological innovations and used in a variety of areas. Current advances include an increased field of view, increased optical resolution, increased frame rates, wireless systems, decreased latency of displays, decreased weight of headsets, and the inclusion of senses other than just the visual, among other features. These technological developments bring VR closer to reality, making VR an even more valuable tool for experimental psychology research.

This paper encourages the use of immersive VR (IVR) in experimental psychology and neuroscience, as the technology allows for reducing the gap between laboratory and real-world experiments. VR further allows to carry out experiments that cannot be conducted in the real world; for example, it allows to access scenarios where the laws of physics are altered (e.g., a world with twice the gravitational force) or to simulate micro (e.g., formation of raindrops) or macroscopic aspects (e.g., solar systems and galaxies) of the real world. In this paper, we rely on investigations of visual memory as a case study to emphasize the beneficial features of IVR as a research method. Before reviewing recent visual memory research using IVR, we highlight the similarities and differences between the virtual and the real. We then propose that combining traditional laboratory studies with VR approaches can address certain methodological challenges, including external validity and replication issues. We close by highlighting promising avenues for future research.

Defining virtual reality

VR refers to the presentation of a computer-generated virtual environment by visualizing three-dimensional data via immersive (headsets) or non-immersive mediums (two-dimensional computer screens;

Jensen & Konradsen, 2018; Riva et al., 2016). However, it is important to note that immersion is rather a spectrum than a binary feature, and multiple dimensions within the concept of immersion seem to exist. For example, the question whether the presentation of a visual stimulus via high-resolution, monocular vision (e.g., a standard computer screen) is more or less immersive than through a low-resolution, binocular VR goggle is difficult to decide. Since the interrelationships between different dimensions (mono/binocular, high/low-resolution, etc.) are often unknown or undefined, the ranking of different technologies in terms of immersion appears challenging or arbitrary. In this paper, for simplicity, we refer to standard computer screens as non-immersive virtual-reality (N-IVR), and scenarios presented via head-fixed devices as immersive virtual-reality (IVR)[1]. While categorizing VR systems into a binary distinction is useful for clarity, it inherently simplifies the diverse range of available VR apparatuses. It is essential to consider the variations in equipment, as they can significantly impact study outcomes. Additionally, it is important to note that VR technology is continually evolving, which may result in changes to the definition of immersion itself.

Two concepts that are intrinsically related to VR are *immersion* and *presence* (Bowman & McMahan, 2007; Heeter, 1992). Immersion refers to the level of fidelity in surrounding the user with vivid sensory inputs through a technological system (Slater, 2003). By definition IVR blocks out visual access to the outside real world. A headset with a large field of view, high resolution, and associated multisensory stimulation (e.g., auditory and haptic) is typically more immersive than a headset with a small field of view, low resolution, and the provision of only visual information. Most research groups use consumer (e.g., HTC Vive, Pimax, Meta Quest) rather than high-end VR devices (e.g., Varjo). This decision seems to be driven by several factors. Firstly, consumer devices have dropped in price over the last few years, with the latest generation of devices costing only a few hundred dollars. Therefore, the required replacement of such VR devices every

[1] It is worth noting that other technologies, such as CAVE (Cave Automatic Virtual Environment), which consists of a room-sized cube with projection screens on multiple walls, have been proposed as belonging to a distinct category (Smith, 2019). In CAVE systems, the walls serve as screens onto which stereoscopic images are projected, creating a three-dimensional visual experience. Users typically wear glasses to perceive the stereoscopic depth, while a tracking system detects their position and orientation, enabling movement and interaction within the virtual environment. For the scope of this paper, we do not review research utilizing CAVE systems, but we refer interested readers to Smith (2019) for precise technological definitions, including distinctions between desktop VR, headset VR, and simulator VR (such as CAVE).

two or three years is affordable for many labs. A second factor is the widespread support of consumer devices, which enables the relatively simple integration of VR with game engines and modeling software, as the necessary drivers and interfaces are widely available and easily maintained, and a large community of users can provide help in the event of technical problems.

While *immersion* has been conceptualized as an objective measure that can be assessed and controlled, as it depends only on the technology, *presence* is subjective. Presence is related to any media, but visual input, as well as the multisensory experience, should enhance the feeling of presence (Balakrishnan et al., 2012). Generally, immersion and presence are positively related (Makransky et al., 2019; Moreno & Mayer, 2002; Rupp et al., 2019), however, at the individual level, the same VR system might produce different levels of presence (Ling et al., 2013; Weibel et al., 2010). There have been several discussions regarding the definitions of immersion and presence, as well as the factors that contribute to interpersonal differences, that we will not review in detail in this paper, and refer interested readers to e.g., Berkman and Akan (2018) for more details on these concepts.

In IVR, the participant is placed inside the virtual environment and is able to interact with it in real time, partially using her own senses and motor skills (Burdea & Coiffet, 2003). In contrast to computer experiments and N-IVR, the artificial separation between the participant and the stimulus is removed, unless the participant leaves the constraints of the virtual world, e.g., tries to walk stairs or climb on a box. In Table 1, we highlight the similarities and differences between reality, IVR, N-IVR, and computer experiments. The table shows a notable overlap between reality and IVR. In the next few paragraphs, we discuss these characteristics with a focus on reality and IVR.

Table 1. Similarities (high similarities are marked with an X, low similarities with a /) across reality, IVR, N-IVR, and computer experiments in terms of sensory inputs (visual, proprioceptive, and other) and experimental control

Characteristics	**Reality**	**IVR**	**N-IVR**	**Computer**
Visual input				
Natural visual information (dynamic)	X	X	X	/
Contextual embedment (visuospatial information)	X	X	X	/
Depth cues	X	X	/	
Vergence / accommodation conflict		X	X	X

Proprioceptive (body-based) input				
Natural vestibular input	X	X		
Natural perception of position and forces at muscles, tendons, and joints	X	/		
Postural stability	X	/		
Other sensory input				
Auditory direction cues	X	/	/	
Smell / taste	X	/	/	/
Somatosensory input	X	/		
Interoception	X	/		
Experimental control				
Presentation of stimuli (e.g., timing, repetition)		X	X	X
Manipulation of the laws of physics		X	X	X
Possibility to simulate micro- and macroscopic phenomena or systems not accessible in reality		X	X	X
No multisensory conflicts	X	/		
No cybersickness	X		/	X
Tracking of position, orientation, and gaze direction	X	X	/	/

Visual input

VR can simulate a *dynamic*, *contextually embedded*, rich world as a reality, which makes VR valuable in terms of external validity. VR is even capable of presenting stimuli that do not exist (e.g., unicorns) in a realistic manner, which expands its applications to address questions related to bizarreness or the capability to distinguish reality from fantasy. When compared to a computer experiment, VR is characterized by *efficient visuospatial information* as well as by greater *depth cues*, which is especially evident in IVR. With efficient visuospatial information we refer to the effective presentation of visual and spatial information in a way that maximizes the processing capabilities of the human brain. This includes features such as three-dimensional spatial positioning, realistic lighting and shading, and realistic textures and surfaces. When presented in IVR, efficient visuospatial information can create a highly immersive experience that closely simulates real-world scenarios. However, some authors have proposed that an inherent disadvantage of IVR is the presence of *reduced* depth cues compared to reality (Harris et al., 2019). With reduced depth cues, we are referring to the limited availability or fidelity of visual cues that provide information about distance and depth perception in the virtual environment. Several studies have shown an impairment in egocentric distance estimation in IVR, indicating that individuals tend to underestimate the distance between themselves and objects in IVR, also referred to as distance compression. To illustrate, Renner et al. (2013) found that egocentric distance estimates in IVR correspond to approximately 74% of the modeled distance. Harris et al. (2019) argued that reduced cues to depth in IVR elicit vision that relies more on the ventral pathway than on the dorsal pathway when compared to reality. This poses a disadvantage for using IVR in research, making it challenging to generalize findings from IVR to reality. However, more research investigating the hypothesized shift from the dorsal to the ventral pathways in virtual environments is needed, both in behavioral and neural terms. It is interesting to note that perceived flatness, which is a perceptual measure hinting at a shift from the dorsal to the ventral pathway, is lowered in more immersive displays (Harris et al., 2019). Similarly, more recent studies such as Feldstein et al. (2020), have not found a difference between distance estimates in the virtual and real environments, suggesting that the technological advancements are bridging the gap between the virtual and the real. However, the question of whether we use the same mechanisms in a virtual environment compared to the real world remains debatable.

VR is characterized by the *vergence/accommodation conflict* (VAC). In real-world viewing, the vergence and focal distance vary simultaneously. However, in stereoscopic head-mounted displays, these processes are decoupled: this leads to mismatched depth cues, causing visual fatigue (see Figure 1). Previous research has highlighted the negative consequences of IVR in terms of visual fatigue (Lambooij et al., 2009). However, current research suggests that the impact of VAC on visuomotor functions is minimal and/or reduced when using the most up-to-date VR systems. As an example, Tychsen and Foeller (2020) carried out a study with 50 children aged between four and 10 years, who were asked to participate in two IVR sessions of 30 minutes each of a first-person flying game requiring head movement to control flight direction. They assessed different dependent variables such as binocular corrected distance visual acuity, refractive error, binocular eye alignment, stereoacuity, and postural stability. No significant differences were found in these measures in the pre-, inter-, and post-measurement designs.

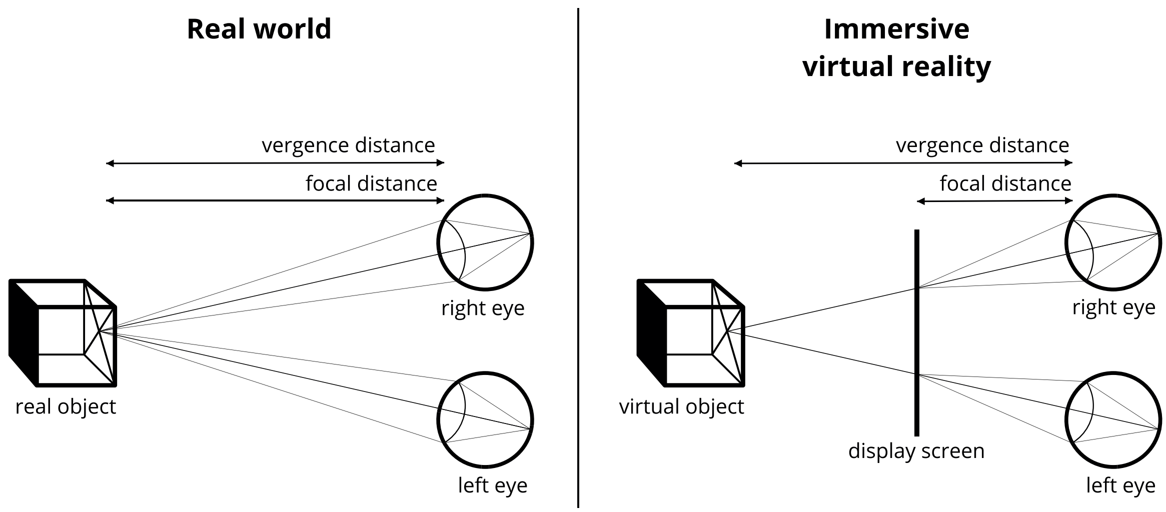

Figure 1. Different focal distances and vergence distances in an IVR setting causing VAC

Proprioceptive (body-based) input

In IVR, participants are active and become part of the environment. Furthermore, both in a real setting and in IVR, participants adopt a first-person perspective. Haptic information is provided; however, this information—usually simulated via vibration to signal contact between the hands and virtual objects—is reduced and artificial when compared to haptic feedback in the real world. Furthermore, interacting with the virtual world via controllers (or hand tracking) will draw attention to the fact that while picking an object, for example, the forces required are not the same as those in reality. Omnidirectional treadmills are sometimes used to extend the walkable area of a virtual environment beyond the size of the laboratory. Additionally, omnidirectional treadmills provide body-based inputs from the vestibular (balance), proprioceptive (in terms of the muscles, ankles, and tendons), and somatosensory inputs (in terms of feedback from the feet). They also allow for the effort needed to reach certain locations to be manipulated by changing the transfer between virtual and actual step lengths. In this way, the role of breathing or heart rate in spatial cognition can be investigated. In N-IVR, the participant can also interact with the environment; however, the experience is less immersive. The motor component via the mouse is often less similar to the simulated behavior than is the case with controllers (or hand tracking) in IVR (Smith, 2019).

A further characteristic that has been regarded as a difference between reality and IVR is *postural stability* (Horlings et al., 2009). However, in a recent study, researchers created a virtual room (equivalent to a real room) and showed that posture with body sway is reproduced in photorealistic, but not in abstract, virtual worlds (Assländer & Streuber, 2020; see also Tychsen & Foeller, 2020).

Other sensory input

The sensory input in IVR is high, however, not all senses can be adequately simulated. Usually, the most important sensory organ through which we experience the world is our eyes, and IVR can provide a highly immersive visual experience. Most VR headsets typically render a visual field of view that is more limited than the full field of view experienced by humans in the real world. However, advancements in technology have been improving the immersive visual experience of VR headsets, including the development of larger fields of view. The next generation of VR systems will likely continue to push the boundaries of visual immersion and provide users with even more realistic experiences. Auditory information can be partially simulated in IVR; while the emulation of natural auditory direction cues is challenging, they can be approximated through stereo headsets. Additional devices, such as haptic gloves or vests, target the somatosensory system and extend the simulated sensory spectrum (Dwivedi et al., 2022). While the olfactory or gustatory systems are relatively understudied compared to the other sensory modalities, there have been notable research efforts in this domain. For example, researchers are working on developing olfactory displays, including low-cost ones fitted to the controllers (Niedenthal, et al., 2023). These advancements are important as other sensory modalities play a role in several cognitive processes. Seminal studies have shown that sensory modalities other than vision can contribute to memory performance in IVR (Dinh et al., 1999). In their study, they manipulated visual cues, varying the level of detail, as well as the presence or absence of auditory, tactile, and olfactory cues. For instance, tactile cues involved the activation of a real fan when participants approached a virtual fan, while an olfactory cue was introduced through the scent of coffee delivered via an oxygen mask when near a virtual coffee pot. While there were no significant differences in memory for the overall environment layout, both olfactory and tactile cues enhanced recall performance for objects locations within the virtual environment (Dinh et al., 1999).

Sensory input and cybersickness

Cybersickness, which typically appears 10-15 minutes after entering an IVR environment, affects a significant number of participants (60-95%; Caserman et al., 2021). While the reasons for eliciting cybersickness are still matter of research, several factors increasing the likelihood of cybersickness have been identified. Among these factors are hardware and software inadequacies (Kourtesis al., 2019), and it has been speculated that technological advancements will help reduce cybersickness. Additional factors, such as vection (Keshavarz et al., 2015) contribute to cybersickness.

The empirical observations have led to a number of theories on the etiology of cybersickness, but none of them seem to explain all observations. One of the most popular theories is the sensory-conflict theory (Reason & Brand, 1975), initially developed in the context of motion sickness. According to this theory, motion/cybersickness is the consequence of a mismatch between the sensory information obtained by the various senses (visual, vestibular, proprioceptive). An alternative explanation, the postural instability theory (Riccio & Stoffregen, 1991) emphasizes the importance of maintaining postural control during the interaction with the environment. The theory proposes that motion sickness occurs in situations where individuals are unable to maintain postural stability, shifting the focus from sensory input to the interaction between the subject and the environment. A detailed discussion of cybersickness and related theories is beyond the scope of the paper but can be found elsewhere (Caserman et al., 2021, de Winkel et al., 2022).

Experimental control

Finally, IVR permits high *experimental control*, which entails a complete standardization of the visual setting, including construction, manipulation, and repositioning of the environment and virtual objects, as well as the precise measurement of behavioral responses, such as reaction times; body, head, and eye positioning of participants; or the distance between the participant and virtual objects. Modern VR systems allow for position tracking of the head-mounted display using a combination of accelerometers, gyroscopes, and optical components (i.e., embedded cameras or external lighthouses). This enables the inclusion of new variables in experiments. For example, in IVR, it is relatively easy to obtain the virtual distance between the participants and objects or avatars (del Aguila et al., 2021).

Visual memories *change* in different contexts

The methods used in experimental psychology aim at enhancing *internal validity* by simplifying the experimental context to reveal causal or correlational relationships between variables. The objective of these methods is to reduce the impact of extraneous factors that could change the relationship between the investigated variables. In other words, the focus is on minimizing complexity and maximizing experimental control. For example, when investigating visual memory processes, participants are presented with isolated objects on a two-dimensional computer screen and are asked to recall and visualize the stimuli on a white background (e.g., Martarelli et al., 2017). Laboratory studies conducted in highly controlled settings have an inherent disadvantage, which is reduced *external validity*. Enhancing internal validity reduces the possibility of generalizing the findings to other contexts, and thus the psychological relevance of the experimental research is called into question. The trade-off between internal and external validity has been highlighted since the advent of experimental psychology (Neisser, 1982). More recently, replication failures (e.g., Open Science Collaboration, 2015) highlight that previous findings in the laboratory can be replicated, but only under narrow conditions. For example, it has been shown that memory processes (and the use of distinct memory strategies) depend heavily on different aspects, such as stimulus material, instructions, expectations, and how memory is measured (Kingstone et al., 2008). In other words, *context* plays a key role, and ignoring it reduces the psychological relevance of such experimental research.

Others have put forward VR as a valuable method for bridging the gap between laboratory studies and real life. In their seminal paper, Blascovich et al. (2002) discussed the trade-off between internal and external validity and suggested that IVR might one day entirely eliminate the trade-off. Testing memory processes in real life (e.g., with field studies) enhances external validity but reduces experimental control. The advantage of IVR is its high experimental control *and* external validity. Researchers have highlighted the benefits of IVR for experimental research in the areas of linguistics (Eichert et al., 2018), visual search

(Draschkow & Võ, 2017), working memory (Draschkow et al., 2021), autobiographical memory (Kisker et al., 2019), context-dependent memory (Shin et al., 2021), and false memories (Romeo et al., 2019), to mention just a few areas. Also, theoretical papers have highlighted the benefits of IVR in terms of both high internal and external validity (e.g., Fanuel et al., 2020; Pan & Hamilton, 2018; Peeters, 2019; Smith, 2019). In a recent perspective paper Draschkow (2022) extended the discussion of IVR benefits for increasing external validity. First, with IVR it is possible to test the effects in different contexts to which one wants to generalize them (e.g., a classroom, a library, a café). Second, with *remote* IVR it is easier to test diverse participants and thus to generalize the findings to the whole population, and third, with *remote* IVR it is possible to diversify time points, i.e., to continuously collect data over different time points. In sum, Draschkow (2022) proposes *remote* IVR as an extremely promising method for increasing the diversity of settings, participants, and timing, which are all key aspects of external validity.

In our daily lives, we interact with the world via our gaze and by handling objects in a specific context. In IVR, the visual input is updated when the participant moves her head, allowing her to interact with the virtual world. Accordingly, VR allows for the study of human cognitive, visual, and physical behavior in natural contexts under controlled conditions. Here, we extend previous arguments with a focus on the investigation of *visual memory*. Visual memory research encompasses the study of how and what visual information is transferred from perception to memory, including visual working memory and the consolidation of information in visual long-term memory. In this sense, visual memory is connected to both perception and memory in a larger sense. In Figure 2 we illustrate the study of visual memory processes in three settings (with a computer experiment, N-IVR and IVR).

Figure 2. The study of visual memory in three settings. In a typical laboratory experiment the object to-be-remembered (e.g., a red hole punch) is presented on the screen. In a study using N-IVR it is possible to present dynamic visual information, and the stimulus (e.g., a red hole punch) is embedded in a context (e.g., a classroom). The user can interact with the virtual world via the mouse. In IVR there is no distinction between the user and the virtual world, and the user can interact with the virtual world in a naturalistic manner.

Investigating ***visual*** memory with IVR

IVR has been used in the past to study memory processes, particularly when it comes to spatial navigation and spatial memories. This is not surprising, because with IVR, it is possible to translate tasks usually used with animals (e.g., the water maze task) to the study of human behavior and the recall of location (see, e.g., the virtual water maze system of Commins et al., 2020) or kinesthetic spatial memory tasks (Wyssen et al., 2022). Despite the strong role of spatial information in non-spatial visual memory[2] (e.g., Ballard et al., 1997; Epstein et al., 2017), until recently, IVR has been rather neglected in its study. The use of IVR to investigate visual memory makes sense, both in terms of visual working memory, and visual long-term memory (see also Kristjánsson & Draschkow, 2021). Memories in real life are personal (i.e., to-be-remembered information occurs in immersive settings), dynamic, embedded in a spatiotemporal context, real (realistic), and multimodal. For example, episodic memory has been defined as entailing memories of personal experience in its spatiotemporal context, including perceptual information (Tulving, 2002). In other words, the key elements of episodic memory are *personal relevance*, *involvement*, and *embedment in a spatiotemporal context*, which are the inherent advantages of IVR methodology when compared to laboratory experiments. How do we remember in more natural tasks? Previous research has shown a benefit of immersion for episodic memory performance (Cadet & Chainay, 2020; Kisker et al., 2019; Krokos et al., 2019; Makowski et al., 2017; Schöne et al., 2019). For example, Schöne et al. (2019) presented participants with an IVR vs. video encoding situation and tasked them with an unannounced old-new recognition task 48 hours later. They found better memory performance and slower reaction times in the IVR conditions, thus

[2] Empirical evidence showing that spatial information is encoded automatically both in working memory (Cai et al., 2019) as well as in long-term memory (Martarelli & Mast, 2013) supports the special role of spatial information in visual memory. Furthermore, spatial information is also recalled with high precision in incidental memory tasks, and congruent spatial information between encoding and recall has been shown to improve performance in change detection and reproduction tasks (Treisman & Zhang, 2006; Martarelli et al., 2022). The special role of spatial information in visual memory is an important argument for the use of IVR in visual memory research.

suggesting that different memory mechanisms underlie IVR vs. video encoding. It seems that IVR via self-relevance is a condition for creating vivid memories.

We believe that IVR can advance the theoretical understanding of how visual information is processed and represented in the neural system. For example, feature integration theory (Treisman & Gelade, 1980), one of the most influential theories of visual attention, proposes that binding between non-spatial features (e.g., color and orientation) of an object is mediated by the object's location. Experiments using simple and isolated stimuli, such as colored bars on monochrome backgrounds, support the idea that spatial location plays a special role in visual working memory (Pertzov & Husain, 2014; Schneegans & Bays, 2017; Treisman & Zhang, 2006). However, the simplifications made in these studies to improve experimental control may not fully account for the processes that occur in natural behavior. In a recent study, Draschkow et al. (2022) investigated spatial frames used for visual working memory after self-movement, by combining IVR and eye-tracking technology. Even though participants were not explicitly instructed to recall the location of the information they were asked to remember, the gaze data obtained in the IVR setting revealed the presence of both relative and absolute spatial information in visual working memory. Such results would not have been possible to find in a simplified and static computer experiment.

Furthermore, IVR can be used to investigate the relative contributions and interactions of different features (e.g., temporal, contextual, semantic, and auditory information) in the processing and representation of visual information. For example, Martarelli et al. (2022) adopted an IVR approach combined with continuous measures to investigate the impact of object position location on the precision of subsequent color recall in IVR. They found that congruent location at recall (corresponding to the location where the object was previously encoded) enhanced color access, thus suggesting that spatial information embedded in natural behavior acts like a scaffolding structure that facilitates visual memory.

In real life, we experience visual information in a dynamic way, embedded in complex settings and accompanied by rich spatial and depth information, rather than being limited to two-dimensional space. Visually representing information in such situations thus requires not only the generation and maintenance of the to-be-remembered information, but also its protection from other distracting/interfering information. Moreover, we usually interact with our environment; both visual and motor behavior at encoding as well as at recall differ in real life when compared to laboratory experiments, and thus laboratory results might not generalize to everyday memory behavior. For example, Draschkow et al. (2021) showed that reliance on *visual* working memory is lower in natural behavior in IVR when compared to typical findings in the laboratory. Despite the large amount of empirical work on working memory, most of the research is done in a laboratory context, using computer experiments. In their study, Draschkow and colleagues adapted an object-coping task to IVR. Participants had to copy a model by selecting objects and replacing them in IVR. The researchers manipulated locomotive effort by varying the position of the model in IVR. They were able to show that locomotive effort had an impact on the usage of working memory, such that the higher the effort, the higher the usage of working memory. However, the capacity of the cognitive system was never fully used, and the participants relied more on external information than expected. Other studies exemplifying the importance of replicating classical findings in the laboratory are that of Chiquet et al. (2021; 2022), who investigated the looking-at-nothing effect in IVR. Instead of recalling and visualizing previously seen objects on a computer screen, the researchers asked the participants to recall and visualize previously seen objects in an IVR environment. Even though the results showed the typical looking-at-nothing effect (i.e., participants returned their gazes to the locations where the objects were previously presented), the results revealed that most of the time (89%), participants fixated on other areas of the room. While these results replicate the looking-at-nothing effect, they also suggest that the same effect found in computer experiments might be overestimated.

A research area where IVR has been used is the study of context and stimuli binding (Lamers & Lanen, 2021; Shin et al., 2021; Wälti et al., 2019). The idea of context-dependent memory (i.e., that memory performance is best when encoding and recall environments match) goes back to Godden and Baddeley (1975). It should be noted that this seminal work could not be replicated successfully (Murre, 2021). Godden and Baddeley (1975) used real-world environments (dry land vs. underwater), and the context-dependent memory effect has been investigated with several approaches over the years; it is thus not surprising that, more recently, authors used IVR to further investigate these findings. However, the results of these IVR studies were mixed. For example, Wälti et al. (2019) could not successfully replicate such findings in IVR settings. However, Shin et al. (2021) found a context-dependent memory effect in IVR. The two approaches differed, with Shin et al. tasking their participants to interact directly with the virtual environment during the encoding phase. Most importantly, Wälti et al. used word lists as encoding material (as was done in the original study), whereas Shin et al. used *virtual objects* as encoding material. These differences in methodology can explain the differences in the results and illustrate how IVR can be used to investigate and extend classical effects under controlled designs and, at the same time, with high psychological relevance.

Potential challenges and possible solutions

In the previous section, we have made the case for using IVR as a methodological tool in visual memory research. In this section, we would like to highlight three challenges associated with using IVR in research, as well as potential solutions.

A first challenge pertains to standardizing the presentation time, viewing angle, and order of critical stimuli, which can impact encoding and memory performance. As an example, the position of virtual objects may affect the level of detail of the object, and the object might go unnoticed if presented behind the participant. It is thus essential to track head/eye movements to ensure that participants have seen the stimuli. Solutions to this issue include tracking eye position and ensuring the same amount of encoding time or randomly presenting many stimuli in different positions to cancel out the impact of position on memory performance. Alternatively, it is possible to consider the position of virtual objects in the statistical models.

A second challenge involves task-irrelevant stimuli (that were included to enhance the realism of the environment) and that may distract participants from critical stimuli during encoding, thereby affecting memory performance. Addressing this challenge requires fully considering both task-relevant and task-irrelevant stimuli as well as the details of the graphics, especially of the elements that are not directly linked to the memory task. When compared to a computer experiment, extra time must be planned to design experimental conditions that balance realism with reduced detail that does not impact the memory task (Makransky & Mayer, 2022).

A third challenge pertains individual differences in familiarity with IVR technology, which can impact encoding and memory performance. Indeed, the novelty of IVR can increase cognitive processing and thus hamper memory performance (see e.g., Dall'Olio et al., 2023). A possible solution is to include habituation phases to the use of a VR headset. As an example, Meyer et al. (2019) found that participants benefited more from IVR when they had a longer phase of habituation (i.e., they added IVR pre-training phases to their IVR teaching approach). A further solution is the assessment of familiarity with the medium to test whether different populations or conditions that are compared in the experiment diverge regarding this aspect, and control for it if necessary.

Although not all experiments may encounter these challenges, avoiding these pitfalls is important when integrating IVR into research. It is worth noting that while IVR is in many ways more like real life than standard computer experiments, it is not equal to reality (Harris et al., 2019).

Outlook

To sum up, recent research investigating visual memory, summarized above, highlights the value of IVR as a methodological tool with high external and internal validity. We are convinced that IVR methodology can complement existing laboratory experiments. Most visual memory studies have been carried out on a computer; however, this static situation does not reflect everyday life, where recall and visualization are embedded in natural behavior. Further research is needed to fully understand the differences between classical results and those of IVR, as well as IVR results vs. real-world settings. We believe that studying the differences between the results obtained in different settings will advance theoretical understanding as well as support more applied approaches when it comes to enhancing memory performance or assessing everyday memory (Fanuel et al., 2020; Ouellet et al., 2018, Parsons et al., 2008, Varela-Aldás et al., 2022), especially in the elderly (La Corte et al., 2019).

Additionally, IVR has been used to investigate the role of social context on memory retrieval (Taylor & Dando, 2018). For example, Dando et al. (2022) conducted an experiment where participants watched a simulated crime video on a desktop computer. Interestingly, they found that subsequent eyewitness interviews conducted through avatars in IVR led to better recall compared to in-person face-to-face interviews. This finding suggests that physical co-presence can impact eyewitness memory, as in-person interviews may impose dual-task demands, thereby reducing the cognitive resources available for accurate recall (Dando et al., 2022). These findings have practical implications, such as enhancing self-disclosure in applied settings (Lee & Dryjanska, 2019).

It should be noted that there is an increase in complexity in virtual worlds when compared to classical experiments in the laboratory. This higher complexity is the advantage from an external validity point of view; however, increased complexity can enhance noise and thus have a negative impact on statistical computations (as more variables must be considered). It is therefore important to consider whether this complexity is needed to answer the research question at hand. We argue that when visual memory is the area of concern, psychological relevance is primordial, and the time has come to extend research to more naturalistic environments. Outstanding questions include, but are not limited to, the following: Do individuals intentionally use visual memory in natural settings? Does the use of visual memory depend on the age of the individual? How do visual memories unfold in natural settings? In a recent paper, Lin et al. (2021) discussed the importance of distinguishing the goals of research in terms of internal and external validity. Conflating these goals might lead to inaccurate theorizing. If internal validity is the main goal of the study, a computer experiment might be more suitable than a VR experiment.

A promising direction in VR research is the combination of IVR with additional methods, such as eye tracking or the simultaneous acquisition of EEG (Do et al., 2021; Gramann et al., 2021; Schubring et al., 2020; Stolz et al., 2019) or fNIRS data (Shi et al., 2020). These additional data provide further insights into brain processes, and the excellent experimental control in VR environments allows to conduct experiments that cannot be performed in the real world. IVR has limited compatibility with other neuroimaging methods (e.g., fMRI or PET), as both methods do not allow for head movements (Ertl & Boegle, 2019), and the participants are scanned in the supine position, which orientates them in an uncommon position relative to the gravitational field of the earth. Furthermore, the magnetic field of the MR scanner introduces a constant vestibular stimulation known as magnetic vestibular stimulation (Boegle et al., 2016; Roberts et al., 2011). All of these factors (e.g., restricted movements, unnatural body position, and vestibular stimulation) might interfere with tasks and reduce immersion.

Finally, the increased use of IVR in experimental psychology is accompanied by the development of platforms to program VR studies (Bebko & Troje, 2020; Brookes et al., 2020) and guidelines for IVR in psychological research (Vasser & Aru, 2020), as well as the development and validation of standardized virtual stimuli to be used in psychological research (Peeters, 2018; Popic et al., 2020; Tromp et al., 2020). Some researchers have also drawn attention to problematic data collection practices, statistical reporting issues, and the overall low transparency in VR research (Lanier et al., 2019). These further developments will increase methodological control and best practices, which is very much needed in experimental research. IVR is a timely methodology both in terms of external validity and the triangulation of methods. Priority should be placed on the use of multiple methods, as well as multiple data sources, that would further illuminate the underlying psychological, neuronal, and physiological mechanisms of visual memory. Interdisciplinarity across the cognitive sciences, neurosciences, and computer sciences will allow to test current theories and inspire new research. Although VR research is difficult to implement and not yet as standardized as desired (e.g., see the rarity of databases of standardized virtual objects), it is valuable because of its potential to improve theoretical understanding and increase the psychological relevance of new findings. Using IVR methodology comes with an additional benefit that has not yet been highlighted. IVR offers the possibility of changing contexts with ease, which is more challenging in laboratory experiments. A multi-context approach plays a crucial role in increasing the generalizability of research findings. By conducting studies in different contexts, we can determine whether the observed effects are specific to a particular context or whether they generalize. Additionally, a multi-context approach can increase the sample size, allow for computing mini meta-analyses (Goh et al., 2016), and potentially reveal moderators of the effect under investigation. Furthermore, discrepancies in the effects tested in different contexts can lead to more nuanced interpretations and refine theories. We believe such a multi-context approach to help the replication crisis mainly by increasing the generalizability of findings and identifying potential moderators. However, we encourage researchers to test their findings not only in multiple VR contexts but, whenever possible, also in real-world settings.

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