The Promises and Pitfalls of Virtual Reality

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Contents

Abstract Increasingly, Virtual Reality technologies are finding a place in psychology and behavioral neuroscience labs. Immersing participants in virtual worlds enables researchers to investigate empirical questions in realistic or imaginary

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environments while measuring a wide range of behavioral responses, without sacrificing experimental control. In this chapter, we aim to provide a balanced appraisal of VR research methods. We describe how VR can help advance psychological science by opening pathways for addressing many pernicious challenges currently facing science (e.g., direct replication, prioritizing ecological validity). We also outline a range of unique and perhaps unanticipated obstacles and provide practical recommendations to overcome them.

Keywords Ecological validity · Presence · Virtual reality

1 Introduction to the Volume

Imagine a continuum between physical reality at one end, and an entirely digitally mediated reality (for example, as depicted in the *Matrix* films), in which all interoceptive and exteroceptive signals are provided by a simulation, at the other end. Different technologies lie along this physical–virtual continuum, including augmented reality (AR), where digital objects are overlaid onto a video of the real world, and virtual reality (VR), which replaces sensory information about the real world with sensory information corresponding to a virtual environment (Milgram and Kishino 1994). Each technology on the "spectrum of virtuality" may contribute to psychological science; in this volume, we focus on VR and the many unique opportunities that it affords for the advancement of cognitive, affective, and behavioral neuroscience.

To this end, we have collected contributions from experts at the leading edge of VR research around the globe. In this introductory chapter, we describe some of the foundational features of VR and the contributions it can make to behavioral neuroscience research. We also outline some of the unique challenges (theoretical, methodological, and ethical) that arise when using VR in experimental paradigms. By doing so, we hope to help researchers capitalize on the opportunities provided by the technology while circumventing some of the pitfalls that can prevent VR research from delivering on its promise.

The first four chapters of this volume cover fundamental methodologies that combine VR technology with other tools in behavioral neuroscience. In this first chapter, we provide an overview of the technology and its potential applications, and the principles that guide its effective use. This chapter goes hand-in-hand with the following chapter "Launching your VR Neuroscience Laboratory" (Wu et al. 2023), which introduces the technological components of a VR neuroscience laboratory, and provides a collection of practical insights and strategies for different use cases. The next two chapters "Monitoring Brain Activity in VR: EEG and Neuroimaging" (Ocklenburg and Peterburs 2023) and Eye-tracking in Virtual Reality (Anderson et al. 2023) address some of the unique challenges involved in combining VR with these methods.

The following five chaptersdelve deeper into the many ways in which VR is used to uncover novel insights into mind, brain, and behavior. These chapters provide comprehensive overviews of specific research domains, including spatial navigation (Chapter “Virtual Reality for Spatial Navigation”; Jeung et al. 2022), vision science (Chapter “Virtual Reality for Vision Science”; Hibbard 2023), emotion (Chapter “VR for Studying the Neuroscience of Emotional Responses”; Andreatta et al. 2023), memory and cognition (Chapter “VR for Cognition and Memory”; Reggente 2023), awe and imagination (Chapter “VR for Awe & Imagination”; Chirico and Gaggioli 2023), and consciousness (Chapter “Using Extended Reality to Study the Experience of Presence”; Suzuki et al. 2023). Finally, the last four chapters describe new applications of VR to create practical interventions and improve lives. These chapters describe how VR can be used in classroom settings to improve engagement and learning (Chapter “Virtual Reality for Learning”; Checa and Bustillo 2023), distract people from pain using virtual embodiment techniques (Chapter “VR for Pain Relief”; Matamala-Gomez et al. 2023), aid in rehabilitation of motor control and cognitive abilities following a stroke or Parkinson’s disease (Chapter “Virtual Reality for Motor and Cognitive Rehabilitation”; Darekar 2023), and provide new diagnostic tools and treatments for psychological disorders such as post-traumatic stress disorder, specific phobia, and depression (Chapter “Virtual Reality Interventions for Mental Health”; Kothgassner et al. 2023).

2 How Psychological Scientists and Virtual Realities Have Worked Together from the Start

Although VR, as a technological medium, has only recently been adopted into psychological science, the practice of immersing participants in some carefully controlled context is fundamental to lab-based psychological research. Historically, these controlled environments (a.k.a. the “psychologist’s laboratory”; Danzinger 1994) provide conditions that differ from those in the “real world.” By rigorously and thoughtfully controlling the laboratory context, researchers aim to minimize irrelevant sources of variability (i.e., noise) and systematic factors (i.e., confounds) that may influence the dependent measures. The outcome of this process is an experimental design that is *internally* valid, which licenses one to conclude that significant differences in the dependent variables may be confidently attributed to the effect of the independent variable(s). However, the cost of this internal validity has always been external validity – the ability to generalize findings to other contexts.

Much like laboratory contexts, the virtual experiences that are designed today are also approximations (or analogs) of reality, where contextual variables can be carefully considered and controlled. The difference between the psychological scientist and the VR developer is the trade-offs that they need to navigate: while the psychological scientist must balance internal and external validity, the VR developer must balance the sophistication and realism of a given scenario with the computational costs of creating it. However, the VR developer and the psychological scientist share the goal of creating a context that biases participants to produce behaviors that mirror those in the real world's situational homolog. In science, when a study achieves this goal, it is said to be *ecologically* valid; that is, the results of the study will generalize to the real-world context it was meant to represent.

In principle, psychological scientists strive to design studies that are internally *and* ecologically valid. Unfortunately, the conditions necessary to achieve ecological validity seem at times diametrically opposed to the conditions necessary to achieve internal validity. Ecological validity can be achieved when there is verisimilitude between the testing conditions and the conditions of the real world. The trouble is that, often enough, what makes testing conditions naturalistic is precisely the presence of many sources of undesirable variability (Kingstone et al. 2008). The world outside the lab rarely presents internally valid conditions for evaluating theoretically motivated hypotheses, just as laboratory conditions rarely resemble the "real world."

This ecological validity problem is a pernicious one (Holleman et al. 2020). It threatens to reduce the value of every laboratory finding in psychological science – no matter how robust, replicable, or widely cited that finding may be – to nothing more than a "laboratory curiosity" (Gibson 1970). Without ecological validity, findings cannot shed light on real-world phenomena. Lacking any clear solution to this problem, we can forgive scientists of the past for determining that their best course of action was to focus on what they *could* control and prioritize internal validity. The hard problem of ecological validity became a problem for another day. But that day may have arrived; VR could be the solution that finally allows psychological scientists to ask: "do these laboratory findings replicate in naturalistic contexts?"

3 How Immersive Devices Create an Illusion of Presence

We define a VR system as one that uses a head-mounted display (HMD) to fully replace visual information from the "real world" with digitally rendered visual information. This visual input is provided stereoscopically via display screens in front of the participant's eyes, creating a three-dimensional visual landscape. Depending on the system, the simulation may be rendered by a computer tethered to the HMD (via either a cable or wireless receiver), or by a computer inside the HMD itself. A VR system must perform many computations in order to successfully replace a user's sensory experience and generate a compelling simulated environment (Bouchard and Rizzo 2019). These computational demands are not trivial and different companies have leveraged multiple technological innovations to overcome them. For example, whereas Meta's line of Quest headsets overcome certain computational demands using computer vision algorithms, HTC's line of Vive headsets overcome those same demands using infrared light sensors and time-division multiplexing. Regardless of how impressive a simulation may be, the VR system itself is primarily responsible for accomplishing two tasks: (1) capturing human motion and (2) rendering an image from a virtual camera whose position and rotation in the virtual environment is animated by that incoming motion data. When these tasks can be completed at a high enough speed, a VR system is said to be "immersive"; achieving the conditions necessary to induce a stable illusion that the user is looking, not at a series of two-dimensional images, but rather, that they are looking *into* a three-dimensional environment within which they are physically situated. This illusion is referred to as "presence" (Cummings and Bailenson 2016).

Presence is most often defined as the psychological experience of "being there" (Slater and Wilbur 1997; Schubert et al. 2001). Mel Slater attributes "presence" to two distinct yet simultaneous illusions. The first illusion is that the user is in a place (and is therefore called the "place illusion"). The success of the place illusion is primarily a function of the technological properties of the VR system. Features like the visual resolution, frame rate, field of view, and the number of sensory modalities that a system can deliver determine the immersiveness of the virtual environment, resulting in an illusion that the user is embodied within some three-dimensional space. Until recently, only very expensive computers were equipped with graphical processing units capable of meeting the computational demands necessary to reliably induce a place illusion, and the systems that were available were orders of magnitude more expensive than today's VR systems.

Although the place illusion is an essential condition for generating the subjective experience of presence, a second "plausibility" illusion further enhances VR's potential for tapping into human behavior (Slater 2009). It is important to acknowledge that "plausibility" illusion is something of a misnomer, as it does not reflect how much the virtual world looks like a plausible representation of the real world. Instead, the plausibility illusion is experienced when a participant feels that the events in the virtual environment are *actually* happening but are outside of their control. These illusions can be induced in a variety of ways. Borrowing an example from Pan and Slater (2007), imagine that you enter VR and find yourself sitting at a table in a cafe while facing a virtual avatar. If the avatar shifts her posture and gazes around the space naturalistically, and yet she never directs her gaze toward you, then you may feel that you are *physically situated* in the cafe (a place illusion), but you remain orthogonal to the events that occur in that world. If the avatar then makes eye contact with you, you become part of the simulation and experience the plausibility illusion. The distinction between illusions of place and plausibility can also be illustrated using the story of Ebenezer Scrooge from Charles Dickens' *A Christmas Carol.* When the Ghost of Christmas Present allows Scrooge to attend the Cratchit family's party, Scrooge learns that although he can walk amongst the attendees, their behavior indicates that he is not a member of their reality, and that the events he is observing do not refer to him.

3.1 Why Presence Is So Important

Irrespective of the psychological phenomena under investigation, it is pivotal that research participants feel present in the virtual world. The rationale for using VR to study real-world behavior depends on participants feeling present in the virtual environment, just as they do in the physical world. Therefore, it should come as no surprise that presence features in every chapter throughout this volume (and why an entire chapter is devoted to attempts to understand it; Suzuki et al. 2023).

Given its relevance, it is surprising that we do not know much about how presence works, or the mechanisms that give rise to it. We know that a VR system is capable of inducing presence when it incorporates sufficient immersive technological properties (Cummings and Bailenson 2016), and we know that presence can "break" when participants' sensory expectations are violated (Kokkinara and Slater 2014). We also know that simulator sickness disrupts presence (Weech et al. 2019). However, we do not yet know how long it takes to re-induce presence following a "break," and we do not know whether individuals' familiarity using VR technology may facilitate or limit the extent to which people feel present in a virtual environment. We also do not know how other processes impact (and are impacted by) changes in presence.

One reason why presence has proven such an elusive topic of research is because it is quite difficult to measure (Slater et al. 2022). Typically, presence is measured using either self-report ratings while participants are in VR, or questionnaires administered after exiting VR. Commonly used questionnaires include Witmer and Singer's (1998) "Presence Questionnaire," a retrospective state measure that operationalizes presence using subscales measuring realism, possibility to act, and quality of the interface, and the "Immersive Tendencies Questionnaire," a trait measure of an individual's tendency to be immersed in virtual environments and narratives across different types of media. Many attempts have been made to identify reliable objective measures of presence (Van Baren and IJsselsteijn 2004). However, results are mixed. For example, while some earlier research (Meehan et al. 2002, 2003) reported relatively strong correlations between measures of physiological arousal (heart rate and electrodermal activity) and self-reported presence, more recent studies have not observed any relationship (Bailey et al. 2009; Maymon et al. 2023).

Despite these measurement limits, some progress is being made. For example, recent research has demonstrated that presence may be driven by subjective changes in people's emotional experience. In this study conducted in one of our labs (Maymon et al. 2023), we developed a VR simulation inspired by a commercial VR game called *Richie's Plank Experience*. Participants stepped inside an elevator that took them high above a city street. When the elevator door opened, participants saw a wooden plank extending precariously from the elevator and were asked to walk across it. At different points throughout the simulation, participants provided verbal ratings of the extent to which they were experiencing different emotions, as well as how present they felt in the virtual environment. We observed robust increases in measures of physiological arousal (heart rate and electrodermal activity), along with increases in self-reported fear ratings. Interestingly, presence also increased during height exposure, and was related to fear ratings, suggesting that presence may be influenced by particular emotional states.

In a pre-registered follow-up study, we adapted the simulation to include a control condition where the elevator rose but then returned to the ground floor where participants found a wooden plank lying on the pavement. By manipulating the scenario in this way, we were able to control for potential confounds in the design. Specifically, we realized that the environment included some additional immersive features during the height exposure which could explain why presence increased at height (e.g., being able to operate the elevator by pressing a button, feeling a real wooden plank beneath their feet). This control condition was highly useful, as we discovered that while presence *did* significantly increase in both conditions, the magnitude of that increase was much larger in the height condition and only in that condition did we replicate the finding that fear ratings and presence were related. Further, by simultaneously collecting physiological recordings throughout the experiment, we were able to determine which changes in the emotional experience (subjective, physiological, or both) were driving presence. We found that presence was predicted only by changes in self-reported fear and was not related to changes in physiological arousal.

Presence is a tricky construct to study, but it is a worthwhile endeavor. Understanding the mechanisms underpinning presence can enable VR developers and researchers to simulate experiences that correspond more directly to real-world experiences, stimulating more naturalistic and ecologically valid behaviors. Because presence may be causally linked to other cognitive and affective processes, researchers should think carefully not just about the ways in which a simulation is sufficiently immersive, but also about the way in which participants' experience of the content may lead to changes in, for instance, the emotional intensity of the environment, and how those changes may shift presence.

4 The Potential of Virtual Reality for Behavioral Neuroscience Research

Recent years have seen rapid development in the accessibility and practicality of virtual reality for cognitive, affective, and behavioral neuroscience research. State-of-the-art VR systems are affordable and can be powered by desktop computers; headsets are becoming lighter; and new models are equipped with multiple sensors that can track eye movements, facial expressions, and physiological signals. These systems can also interface with conventional neuroscience tools such as EEG or other recording systems. Software is maturing, making it possible for non-specialists to create virtual environments that are suited to their research needs. In the next section of the chapter, we describe several ways that VR systems are changing the research landscape.

4.1 VR Puts Our Participants in Highly Controlled Multisensory Environments

The ability to create alternate realities in which people feel present solves several problems that researchers face when trading off internal for ecological validity. Well-constructed environments can be highly ecologically valid (Parsons 2015), substituting for real environments that would be impossible, impractical, or unethical to produce in laboratories. Virtual environments exist in three dimensions, providing a major advance for vision scientists who have (until now) been largely constrained to the study of visual processing of two-dimensional images presented on a computer screen (see Hibbard 2023). Complex scenarios can be created in which the participant is an active agent, allowing researchers to move away from hypothetical situations in which people estimate how they would behave in a particular situation, and test how they actually do behave (Rosenberg et al. 2013; Schöne et al. 2023). Emotion researchers can create situations that induce genuine fear, or awe, or anger (see Andreatta et al. 2023; Chirico and Gaggioli 2023), and need not rely on pictures, words, or films that induce only pale facsimiles of the real thing. Presence can be enhanced by the addition of other sensory modalities including stereo sound, smells, or tactile feedback via vibrations (e.g., in gloves, or a hand controller) or with real objects (Wu et al. 2023). At the same time, these ecological environments can be highly controlled, allowing researchers to manipulate independent variables while holding all other aspects of the environment constant, and ensuring that all participants experience the same experimental context.

Conversely, VR also allows researchers to import ecologically valid paradigms into the virtual world, increasing their internal validity. For example, Hale and Hamilton (2016) used VR to test the effects of mimicry on prosocial behavior. Earlier studies suggested that mimicry increases prosocial behavior (van Baaren et al. 2004), and that people find mimickers to be more trustworthy (Maddux et al. 2008) and more likable (Kouzakova et al. 2010). These original studies made valiant efforts to achieve ecological validity by employing trained confederates to imitate participants' movements. However, it is unreasonable to expect even professionally trained confederates to precisely replicate the timing of their mimicry equally across all participants and to treat each participant the same way. Hale and Hamilton (2016) replaced the human mimicker with an animated virtual avatar, precisely controlling the timing of movements, while holding potentially confounding social factors like interpersonal warmth constant. The virtual avatar was directly animated by motion data recorded from the participant, which made it a more reliable mimicker than any human partner. Replicating previous findings, participants reported better rapport with avatars who mimicked their actions; however, mimicking avatars were not rated as being more trustworthy or more similar to the participant. These results indicated that previously reported effects may have been the product of confounding social variables introduced when mimicry was performed by real humans, and not caused by mimicry itself.

Another example is provided by the well-validated Trier Social Stress test (Linares et al. 2020). In the conventional version of the task, participants are asked to write a speech which is then evaluated by a panel of judges. In another subtest, participants must perform a series of mental calculations while being evaluated by a stern examiner. The task reliably induces anxiety and stress, but places a large burden on researchers who must enlist the help of a number of confederates, and train them to behave consistently across participants, and across labs. A VR version of the test provides a virtual panel of examiners. Although people on the virtual panel are obviously not "real," the VR version of the task induced stress as indicated by both subjective and endocrine responses (Zimmer et al. 2019). VR therefore reduces the costs of such research, and also makes it possible to fully control the experimental manipulation, making it replicable across participants and across labs.

4.2 VR Facilitates Translational Neuroscience Research

Much knowledge in behavioral neuroscience derives from animal research. This is because it is possible to directly manipulate animal brains (e.g., through lesions, the administration of pharmacological agents, through genetic manipulation, through manipulations of stress, hunger, social isolation, etc.). These animals are then tested in well-established behavioral paradigms, allowing researchers to draw causal links between brain and behavior. These brain-behavior relationships can then be extrapolated to humans, often tested with non-invasive technologies such as EEG or fMRI.

One of the barriers to effective translation is that the tasks that are commonly used with laboratory animals are behavioral, while the tasks that are used with humans are often cognitive. For example, in a delay-discounting paradigm, a rat might have to choose (by pressing a lever) between receiving a small reward now or a large reward in the future. Importantly, they receive the reward. In the human analog, participants are asked if they would prefer a small amount of money now, or a large amount of money in the future. But they don't actually receive the reward. Numerous studies have shown that humans do not behave as predictably as rats in these situations, in part because the hypothetical reward decision lacks ecological validity (Vanderveldt et al. 2016). But in VR, it is possible to create a situation for humans that more closely matches the characteristics of animal paradigms, producing reliable discounting functions, and facilitating the translation of research findings from animals to humans (Bruder et al. 2021).

There are many other examples of animal research paradigms that can be implemented for humans in VR. One is the Morris Water Maze (Morris 1984) that is widely used in animal research on the neural substrates of learning and memory. The Virtual Water Maze task is really a collection of paradigms that capture the basic task – navigating to a "safe" place using either landmarks or egocentric trajectory (for a review, see Thornberry et al. 2021). In humans, the task has been combined with single cell recordings in epilepsy patients (e.g., Kunz et al. 2019) and with mobile EEG (e.g., Do et al. 2021), replicating animal studies that link spatial navigation to hippocampal theta activity. Similarly, fear conditioning paradigms, often used in animal research to study the neural mechanisms of fear and anxiety, can be safely and ethically simulated using VR (see Andreatta et al. 2023). VR is well-suited for replicating animal experiments on contextual conditioning, as different contexts (e.g., rooms in a virtual house) can be associated with the conditioned stimulus. A wide range of contexts can be tested by simply altering the simulation, making VR ideal for isolating factors that are associated with conditioning and extinction. These contexts can also be made to resemble real-world contexts (such as a bar, a hospital, etc.), increasing the ecological validity of research findings.

4.3 VR Affords Ecologically Valid Behaviors

The illusion of presence means that people do not just experience the virtual world as real, they also behave within it as they might in physical reality. Traditionally, cognitive and behavioral neuroscientists, particularly those who work with humans, have adopted paradigms that require their participants to remain still. Vision researchers use chin rests, attention researchers constrain eye movements, EEG researchers restrict movement to obtain clean recordings of neural activity. Behavioral responses in these experiments are limited to small movements that can be measured in such circumstances, such as pressing a button or saying a word. But brains (and cognition and emotions) exist in the service of action, and therefore just as it is important to create virtual environments that resemble the real world (i.e., ecologically valid contexts), future research must also afford participants the ability to coordinate action in ways that are similarly unrestricted (i.e., ecologically valid behaviors). Participants in virtual environments are free to move, and the VR system automatically tracks their movements. This freedom to move greatly increases the range of actions that participants can perform, and the dependent variables researchers can collect.

One example of a more complex behavioral response is reaching. In a reach-tracking experiment, participants don't use buttons to indicate a yes/no response. Instead, they reach toward a location in space that corresponds to the response. Because a reach is a continuous action (as opposed to a discrete button press), it is possible to use the reach trajectory to track online conflict resolution and decision-making processes. Reach-tracking can be easily implemented in VR (e.g., Morrison et al. 2023) because the VR system already tracks the movement of the controller. Reach-tracking can then be implemented in a range of virtual environments to determine how contextual factors affect the cognitive processes of interest.

4.4 VR Yields Rich Multivariate Data

VR also affords researchers the ability to collect rich datasets across several systems simultaneously. The VR system itself tracks head position, and further motion tracking can be obtained using hand controllers, foot trackers, or complete motion capture (a.k.a "mocap") suits. Its rich motion tracking capabilities make VR an ideal tool for studying navigation and other aspects of spatial cognition (see Jeung et al. 2022). It is even possible to use treadmills or other devices to extend the range through which participants can move (Hejtmanek et al. 2020). The nature of movements in VR can also be informative. In our plank-walking studies, participants who walked the plank high above the virtual ground took smaller steps and walked more slowly than those in a control condition who walked a plank that appeared to be on the street. These changes in gait were so large as to be apparent to naive observers who watched videos displaying point-light avatars of the participants (Crawford et al. 2023). Other behaviors that might be tracked in VR include head and eye movements (see Anderson et al. 2023), manipulation of virtual (or real) objects, or a wide range of choice behaviors.

In addition to features of body movement, many VR systems on the market today offer a range of tools for detecting and recording diverse metrics related to attention, arousal, emotional state, and more. It is possible, for instance, to capture the participant's field of view on video, providing a real-time record of their experience that can be synchronized to other measures. Headsets can be fitted with eye-trackers that capture eye movements and pupil responses. Wearable sensors can capture a wide range of peripheral responses including cardiac activity, respiration, electrodermal activity, skin temperature, muscle movements, and facial expressions (for more detail, see Wu et al. 2023). Mobile EEG systems with online artifact rejection can be used to capture neural activity during the simulation. Triggers sent from the VR system can be used to synchronize neural and physiological sensors to events in the simulation, allowing for signal averaging and other analytical approaches.

These multiple data streams can be used both to test the effectiveness of a VR scenario and to address fundamental neuroscientific questions about their relationships. For example, a researcher may be interested in determining whether high-arousal fear affects attentional scope. The researcher first needs to reliably manipulate fear. However, fear responses manifest across multiple dimensions (i.e., subjective, physiological, and behavioral channels). The researcher could check that the manipulation worked by (1) asking for subjective ratings at different time points, (2) continuously measuring peripheral physiological signals using wearable technologies, (3) continuously measure root motion in the environment by saving the same positional and rotational coordinates that are used by the game engine to update the virtual camera in real-time, and (4) capture frontal asymmetries that are associated with fear using mobile EEG (El Basbasse et al. 2023). These multiple data streams not only allow the researcher to test that the fear manipulation was successful, they also make it possible to address long-standing theoretical questions about the causal relationships amongst subjective, physiological, and behavioral components of emotion (Cannon 1927; James 1884; Panksepp 1982; Schacter and Singer 1962).

Of course, the sheer amount of data that can be obtained increases the complexity of the research. Continuous recordings across multiple channels create very large datafiles that must be stored and manipulated. Multivariate statistical approaches are necessary, and machine learning algorithms may be more appropriate than conventional statistical analyses in some situations (e.g., Winkler-Schwartz et al. 2019). The synchronization of data streams is also not trivial, although basic principles are not different from those in other neuroscience applications such as EEG or fMRI.

4.5 VR Promotes Direct and Conceptual Replication

Another benefit of VR for addressing current challenges facing psychological science is that simulations can be easily shared with other labs. Doing so has clear advantages for replication studies, and studies that aim to extend research paradigms in ways that closely preserve the testing conditions of an earlier study. Sharing VR simulations between labs can also improve the efficiency of those investigations. Traditionally, researchers are expected to use the "Methods" section from a given empirical study to ascertain the necessary information to replicate the paradigm in their own lab. This practice is often slow and does not ensure that the new stimuli match the stimuli used in the original study. Consequently, if an effect does not replicate, this can spawn debates, not about the robustness of the effect itself, but about whether the new stimuli adequately matched the original.

VR provides a solution to this problem, as the testing conditions of one experiment can be directly matched in replication studies, so long as the simulation is delivered using similar hardware and software. Indeed, sharing simulations can help to meet several key goals outlined in the Association for Psychological Science's strategic plan (Bauer 2023). First, making VR simulations available to labs anywhere in the world encourages researchers to examine the robustness of a given effect across diverse study populations. Second, the ever-increasing affordability and availability of VR technology means that teams with limited funding for research will be able to afford the technology necessary to present even the most impressive VR simulations, thereby promoting a more globally representative psychological science. Finally, Bauer (2023) highlights the need for an increased focus on *authenticity* in psychological science, encouraging a shift toward a science that concerns itself with the extent to which findings can explain behavior in the real world, even if that shift incurs a cost to a study's internal validity. VR not only provides a way to achieve these goals, but it can also do so without sacrificing internal validity. Therefore, we think that VR will play a major role in how psychological science overcomes the replication crisis and will become an increasingly common methodology in cognitive and behavioral neuroscience laboratories.

4.6 The Impact of VR on Research Ethics: Challenges and Opportunities

VR engenders new concerns about the ethical treatment of research participants. A number of adverse experiences can occur when a person enters VR, including eye strain, headaches, dizziness, and nausea (i.e., simulator sickness; Weech et al. 2019). Additionally, VR poses a risk of bodily injury. Because participants cannot see objects in the real world when they are in VR, any objects left in the VR "play area" present a hazard. Fall risks are particularly dangerous for a participant in VR because they also have no way of knowing where the walls are. Therefore, they have no way of knowing whether they may be stumbling toward a wall or the edge of a table as they try to regain their footing.

Currently, no "gold standard" exists for mitigating these risks. As with any psychological research, researchers must ensure that the experiment does not cause physical or psychological harm to participants. In our labs, we have developed protocols for minimizing these risks. For example, in our research into fear using height exposure (Maymon et al. 2023), we ensure that experimenters stand beside the participant while they walk across the wooden plank, and that experimenters are hypervigilant to signs that they may lose their balance and be prepared to catch the participant if they should lose their balance. Experimenters are also trained to respond to instances when a participant reports feeling nauseous or dizzy, by erring on the side of caution and ending the experiment. In our experience, simulator sickness does not subside while the participant remains in VR. Rather, participants who try to "muscle through" those symptoms and remain in VR will usually experience worsening symptoms and will take longer to recover after exiting VR.

Interestingly, VR may also provide a means of overcoming particular ethical restrictions. The idea here is that some in vivo research paradigms that have been deemed unethical, may be ethically permissible when participants experience the paradigm in an environment that they know is not real. Perhaps the most famous example of this comes from Slater et al. (2006) who developed a VR analog of Milgram's obedience study. The original procedure involved the use of deception, whereby a participant was instructed by an experimenter to deliver increasingly dangerous electric shocks to another person (the learner). Participants were led to believe that the learner was just another participant in the experiment, and that if the outcome of a coin toss were different, the participant would have been the one receiving the shocks. The world was astonished when Milgram (1963, 1974) reported that 65% of participants proceeded to deliver shocks that were clearly marked as lethal, despite the learner screaming in protest. Of course, no shocks were being delivered, and participants were (eventually) made aware that the learner was an actor pretending to be shocked. Nevertheless, participants later reported experiencing considerable psychological distress as a result of their actions during the experiment. Since then, direct empirical replications have been impossible.

Slater et al. (2006) developed a VR scenario whereby the confederate receiving the shocks was a computer-generated avatar. Although the avatar was programmed to behave as if they were experiencing pain following each shock, participants were regularly reminded during the experiment that the avatar was not real and could not experience pain. Therefore, this replication study did not involve the use of deception. Nevertheless, participants who saw and heard the avatar suffering, showed patterns of subjective, physiological, and behavioral responses consistent with experiencing stress and caring for the well-being of the virtual avatar. Interestingly, despite knowing full well that the avatar was not experiencing pain, 27% of participants asked to stop the experiment before reaching the end of the study.

With this VR paradigm, it is now possible to evaluate the proposed mechanisms underpinning obedience to authority figures, in ways that are perhaps less ethically dubious. In a follow-up study from the same lab, Gonzalez-Franco et al. (2018) used the same paradigm to critically examine Milgram's "agentic state" interpretation for his original findings. According to Milgram, people were willing to cause harm to the confederate because people are inclined to focus on efficiently doing what is commanded of them by an authority figure, even at the expense of harmful consequences. If it is the case that participants are submitting to authority without considering the harm to the confederate, then participants should be equally likely to obey when the avatar is not visible. In this study, Gonzalez-Franco et al. (2018) demonstrated that when an avatar was present, participants spontaneously adapted their tone to emphasize the correct response, in an apparent attempt to help the avatar avoid receiving a shock. Furthermore, they found that participants who identified more with scientific pursuits displayed more concern for the avatar, were more likely to provide help and (perhaps due to having attempted to provide help) exhibited less stress.

This demonstration has inspired others to imagine ways to study behaviors in VR that would be unethical to study otherwise. However, VR should not be viewed as negating ethical scrutiny, and there is ongoing debate about the kinds of criteria that ethics committees should apply when reviewing VR research. Ramirez (2019) proposes an *equivalence* principle, stating that "If it would be wrong to subject a person to an experience, then it would be wrong to subject a person to a virtually-real analog of that experience. As a simulation's likelihood of inducing virtually-real experiences in its subject increases, so too should the justification for the experimental protocol." Returning to the plank-walk, it would certainly be unethical to put participants in physical danger by walking a real plank suspended at extreme heights (or to require participants to escape from a burning building; Bernardini et al. 2023). VR analogs remove the physical risk, but not the fear. Ethics committees must therefore evaluate the risks arising from experiences that manipulate emotional states or beliefs using VR, independent of the physical risks that would be present in the real world.

5 Experimental Research Using VR: Recommendations for Best Practices

VR brings with it a variety of novel and unapparent challenges. In this section, we provide five recommendations from our own experiences adopting VR technology into our neuroscience laboratories.

5.1 Recommendation 1: Anticipate That People May Differ in Their Response to Being in VR by Adding a Baseline Measure of the Dependent Variable

VR studies are often designed such that participants, drawn from a common population, are randomly assigned to one of two simulations which the researcher predicts will be associated with differential patterns of responding. The researcher may improve this experimental design by adding a within-subjects variable, allowing them to demonstrate that these randomly assigned groups are indeed similar on relevant measures *prior* to entering VR. If researchers observe an interaction effect in this 2×2 mixed model design, they can more confidently attribute that difference to the effect of their manipulation. However, it is often worth extending the levels of the within-subjects variable further to include a measurement taken after participants have entered VR but before the events differ as a function of the independent variable.

This practice can be particularly helpful when VR is used to demonstrate effects of emotional change. In such studies, it is recommended that participants enter VR and are first immersed in an "emotionally neutral" environment where they can acclimate to this new simulation. Studies interested in manipulating emotional states should collect baseline measures both before participants enter VR (to account for individual differences at the trait level), as well as during the neutral environment (to account for individual differences in participants' response to being immersed in VR) before proceeding to the environment where groups differ as a function of condition. This neutral environment can also be used to help participants learn the rules of the new reality, like whether and how they can move through the environment, which objects they can interact with, and how. When a study aims to measure naturalistic behavioral responses (like which of two buttons a participant reaches toward or how quickly participants can navigate a maze) providing ample opportunity to interact in the virtual world prior to the task can ensure that participants are similarly familiar with being embodied in the virtual environment.

5.2 Recommendation 2: Avoid Tasks That Require Participants to Remain in VR for Long Periods of Time

When designing a VR study, it is important to take into consideration how long participants will be expected to remain inside the headset. This is especially pertinent for cognitive researchers who may rely on tasks that require participants to complete a large number of trials in an experimental session. While it may be reasonable to ask participants to remain in front of a computer for an hour or more, this regimen is not reasonable for those in VR. Being in VR for long periods of time (i.e., more than 20 min) can have a number of deleterious effects on participants' impression of the virtual environment, their physical comfort, and their task performance (Souchet et al. 2022). Over longer periods of time, participants' neck muscles may fatigue from supporting the weight of the headset. VR headsets also tend to generate heat and this may cause participants to become overheated and dizzy. Additionally, if that heat causes participants to sweat in the headset, this sweat can become condensation across the lenses, compromising visual clarity. Some of these difficulties may be overcome by future technological innovations, but presently, the best course of action for ensuring the best experience and data quality is to design studies that keep participants in VR only as long as is necessary.

5.3 Recommendation 3: Conduct Rigorous Pilot Studies of New VR Scenarios to Help Identify Potential Nuisance Variables

By design, VR studies introduce more contextual nuance relative to traditional laboratory studies. Although VR allows every aspect of a virtual environment to be controlled, knowing how to set each potentially relevant parameter is no trivial task. Furthermore, in our experience, it is quite difficult to predict which features of a virtual environment may have an undesirable impact on participants. We have found that the best practice for identifying potential nuisance variables is by conducting pilot studies. Additionally, it is often helpful to plan these pilot studies in such a way that participants can provide open-ended feedback about their impressions of the environment and especially about what in the environment may have attracted their attention.

Pilot studies can test several assumptions about participants' experience in a virtual environment. For example, imagine that you create a VR scenario in which participants are expected to press a button on a wall using their hand controller. It may seem obvious that participants would realize that they could interact with the button; however, participants are often surprised to learn that they can operate a button the same way they would outside of VR, by reaching their hand toward it until the button has been depressed. It is also common to encounter the opposite situation, where a participant incorrectly assumes that objects in VR can be interacted with as if they were physically real. For example, in our early fear studies (Maymon et al. 2023), we were surprised to observe that some participants reached out to grab the edges of the doors of the elevator, only to remember that there was no wall there to grasp. We responded to this observation by widening the elevator so that the edge of the door was further away. Finally, pilot testing can help identify where there may be disruptions in the performance of the VR system during the experiment. VR technology can be disrupted by even momentary errors in motion tracking or if some event causes an increase in the real-time computational demands. These disruptions typically result in a visual glitch (where the headset may default to presenting a gray screen or may render images from an incorrect point-of-view) or a lag in the framerate, which can break presence, interrupt data collection, and cause simulator sickness. Therefore, it is important that researchers are also recording when and where technological glitches may be occurring so that they may be addressed before collecting data for the main experiment.

5.4 Recommendation 4: Don't Try to Go It Alone

The creation of even seemingly straightforward virtual environments capable of inducing presence can be a daunting and unfamiliar technological challenge for cognitive and behavioral neuroscientists. It is one thing to expect that researchers can pick up some skill in MATLAB to program tasks with relatively few parameters; it is an altogether different thing to expect researchers to simulate context in a way that compels participants to behave naturalistically. Moreover, in multi-modal paradigms, detecting heterogeneous streams of data and synchronizing them with virtual world events typically requires at least some degree of iterative design and testing. When it comes to developing the virtual environment, it is best to reach out to artists and game developers working with VR who can translate your idea into a quality environment. Consulting with developers and artists can also reveal alternative ways to create a scene that may be more efficient, higher quality, and more affordable, than how you may envision creating the environment.

5.5 Recommendation 5: Recognize When Using VR Is Not Appropriate

Scientists should think critically about whether an idea for a VR study makes appropriate use of VR. It is certainly not the case that all behavioral research would be improved simply by embedding a study in VR. It helps to ask what specific value VR adds to the interpretation of your data. This is also a helpful exercise for ensuring that the way you are using VR makes the best use of the technology. One of the biggest challenges when designing psychological experiments using VR is ensuring that the virtual environment is actually capable of representing the intended real-world situation. While VR technology has made significant advancements in recent years, the technology struggles to fully replicate some sensory experiences, such as touch and smell, which may contribute meaningfully to the experience that a study aims to simulate (Vasser and Aru 2020). Even visual experiences in VR may not sufficiently replicate visual experiences in the real world. The field of view in virtual reality is typically constrained (Ragan et al. 2015), and the frame rate may not be sufficient to simulate real motion. Finally, it is important to consider whether your specific research question may contraindicate the use of VR. For example, VR may not be well-suited for investigating special populations such as those suffering from psychosis, depersonalization/derealization disorder, or specific phobia. In such cases, it is important to assume that the VR experience may be appraised as real, which may have lasting impacts on the individual. For more information about contraindications of VR, see Kothgassner et al. 2023.

6 Conclusions

VR is making waves throughout psychological science, and we have only just begun to appreciate its unique potential to improve scientific pursuits across nearly every domain. When utilized appropriately, VR could help researchers overcome some of the most pernicious challenges facing the field. Virtual environments can be both precisely controlled and naturalistic, providing a solution to the otherwise intractable compromise between internal and ecological validity. VR can also improve the accuracy and efficiency of replication studies and unlocks new methods for translating animal research paradigms for human participants. By leveraging positional tracking data collected by the VR system alongside wireless wearable recording devices, VR studies can permit researchers to pre-register stronger, more specific predictions across a multitude of dependent measures. In this chapter, we have endeavored to provide a balanced account that tempers the technology's many promises with some of VR's new and in some cases unavoidable challenges. The many promises of VR are achieved when researchers carefully consider whether VR is appropriate for their use case, consult with specialists to develop quality simulations, and conduct rigorous pilot studies.

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