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Five canonical findings from 30 years of psychological experimentation in virtual reality

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Jeremy N. Bailenson[1], Cyan DeVeaux[1], Eugy Han[1], David M. Markowitz[2], Monique Santoso[1] & Portia Wang[1]

Virtual reality (VR) is an emerging medium used in work, play and learning. We review experimental research in VR spanning three decades of scholarship. Instead of exhaustively representing the landscape, our unique contribution is providing in-depth reviews of canonical psychological findings balanced across various domains within psychology. We focus on five findings: the benefit of being there depends on the activity; self-avatars influence behaviour; procedural training works better than abstract learning; body tracking makes VR unique; and people underestimate distance in VR. These findings are particularly useful to social scientists who are new to VR as a medium, or those who have studied VR but have focused on specific psychological subfields (for example, social, cognitive or perceptual psychology). We discuss the relevance for researchers and media consumers and suggest future areas for human behaviour research.

Virtual reality (VR) is a technology that provides perceptually rich, multisensory simulations that surround users and respond to naturalistic body movements. Early research on the medium was largely conducted by engineers focused on building the technology, but who would often make observations about user behaviour as well (for example, documenting simulator sickness). In 1992, however, formally trained social scientists emerged more prominently in the field. For example, the inaugural year of the flagship VR journal *PRESENCE* features several papers examining psychological and communication processes[1–3]. Since those early days, VR has progressed both as a medium and as an area of study for behavioural scientists.

As a medium, the technology has migrated from academic laboratories to living rooms. With over 25 million headsets in use worldwide and Meta spending over US $50 billion on the medium, corporations are investing heavily[4]. Meta and other companies are positioning VR (and related technologies, such as augmented reality and smart glasses) as a medium for entertainment, communication and work. Today, there is great variance in the terms scholars use for various types of virtual experiences, ranging from mixed reality to spatial computing to VR (see ref. 5 for an early explication and ref. 6 and ref. 7 for more recent discussions). In this Review, we use the term VR for two reasons. First, we are largely focusing on perceptually immersive experiences, as opposed to ones that augment the physical world. Second, given that we are studying findings over time, this term is most representative across the decades we review.

Figure 1 shows a timeline of influential research events in the field of VR. As an area of study, behavioural science research in VR can be roughly categorized into three main divisions. First, VR has been used as a tool to investigate basic psychological processes. Scholars can create rich, realistic experimental scenes in which people can interact naturally while still maintaining rigid experimental control. Second, VR has been studied as a medium itself; scholars have developed theories based on the medium and have researched the affordances of the technology as its own intellectual endeavour. Finally, the medium has a rich history of applications related to behaviour, including mental health and training. We briefly review each strategy independently.

An early paper outlined the advantages of using VR, which the authors referred to as immersive virtual environment technology, as a tool to study basic psychological processes[8]. They argued that VR would transform the field in a similar way to computers drastically

[1]Department of Communication, Stanford University, Stanford, CA, USA. [2]Department of Communication, Michigan State University, East Lansing, MI, USA. e-mail: Bailenson@stanford.edu

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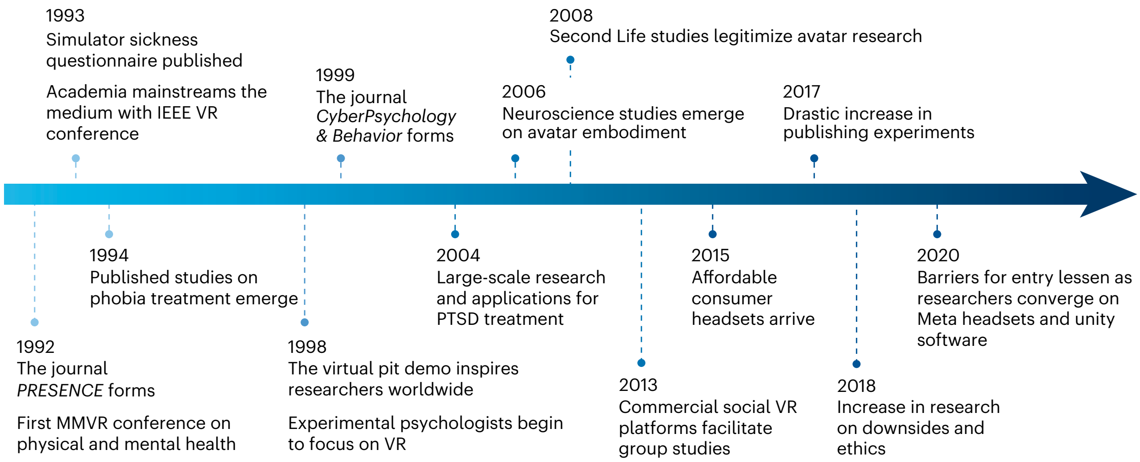

Fig. 1 | A timeline of selected influential research events. Trends that are not tied to specific calendar dates were estimated in consultation with an external panel of scholars. IEEE, Institute of Electrical and Electronics Engineers; MMVR, Medicine Meets Virtual Reality; PTSD, post-traumatic stress disorder.

changing psychological study by presenting text, images and videos in controlled sequences and measuring outcomes such as reaction time. Although computers offer great amounts of experimental control, seeing video clips flashing on a screen and clicking a mouse is not how people interact in the real world. Alternatively, VR can create realistic experimental activities for participants that still allow precise control by researchers. Although the number of psychologists using VR as a tool has grown since these early scholars made such bold predictions, the medium is still used sparsely compared with traditional two-dimensional (2D) screens[9].

VR is dramatically different from other media in that many scholars have dedicated research programmes for creating theories and collecting empirical data about the user experience within the medium itself. Early scholars[10–13], for example, explicated and studied the concept of presence. Although there are many instantiations and definitions of presence, the basic concept is the illusion of non-mediation: when people use VR, the medium tends to disappear and people behave in a similar manner to how they behave in the physical world.

Scholars study the process of experiencing presence, the technological and narrative features that cause it and the downstream effects of how presence impacts the outcome of VR simulations.

The third area of study is applying VR to solving real-world problems. Although VR technology has seen a massive transformation in its affordability, availability and quality of hardware and software in recent years, academics have anticipated this moment in time. Some of the earliest studies in VR focused on how to apply the medium across many general psychological domains. For example, after the 9/11 attacks in the USA, psychologists built a VR reconstruction of first-person views of planes hitting the towers to help first responders to overcome post-traumatic stress disorder[14]. Outside of clinical applications, one of the largest uses of VR has been in training scenarios, which leverage the embodied aspect of the medium to improve learning transfer[15]. From early flight simulators to virtual cadavers, the history of using VR for training and free repetitions is empirically rich.

If one counts 1992—the inaugural issue of the flagship VR journal *PRESENCE*—as the informal beginning of behavioural science research using VR, at the time of writing this Review there are 32 years of research to summarize. The best estimate on the number of human participant experiments focusing on people wearing a headset comes from a study using natural language processing and generative artificial intelligence to extract over 20,000 behavioural science research papers implementing experimentation in VR and augmented reality[16]. As Fig. 2 shows, the past decade has observed a massive increase in empirical work.

Scope of the current Review

In the current work, we focus on canonical findings in VR, which we define on the basis of two characteristics: (1) those with stable effect sizes in meta-analyses and/or studied over time; and (2) those that scholars central to the field suggest are stable and consistent. In writing this Review, we engaged in a three-stage process. First, we created a list of findings spanning several psychological disciplines that we view as robust based on our collective experiences researching VR. Second, when possible, we supported each finding with existing meta-analyses. Finally, to ensure we did not miss any obvious topics, we informally contacted a panel of 11 established VR scholars who are listed in the acknowledgements section (half men and half women, spanning the fields of advertising, communication, computer science, government, nursing, medicine and psychology) and asked them to suggest robust findings to augment and sanity check our list. By engaging in iterative qualitative discussions of their replies as a group, we honed our list and improved our discussions of the findings. This deliberation was useful for shortening the list by removing findings on which some of the scholars doubted robustness. For example, our initial thought was to include gender differences in simulator sickness as a finding, but recent research[17] raises some alternative explanations for this finding. As a further example, we initially considered the uniqueness of children in VR; although there was consensus this was an important topic, based on feedback we removed the section as there was not yet one clear directional finding. Within the explication of each of the five findings, feedback from the scholars helped to ensure that the experiments we present are representative of the field.

The resulting five findings feature scholars from and results relevant to various subfields of psychology, including perceptual psychology, learning science, neuroscience and social psychology. The five findings are depicted in Table 1.

Social scientists who focus on VR as their primary research area might find these five findings to be familiar. However, as Fig. 2 implies, there are many emerging scholars embracing this new medium. We envision this Review being a valuable research tool for those emerging scholars to help to frame and position their own research questions. Moreover, this Review will also be helpful for experienced scholars who seek to cross psychological disciplines in research. For example, a perceptual psychologist might be very familiar with how people process distance cues in a VR headset, but not as familiar with the social psychological implications of embodying avatars. Similarly, an education scholar may be well versed in the types of learning scenarios that are most effective in VR, but scholars outside of the subfield often measure learning as a dependent variable and can benefit from our discussion

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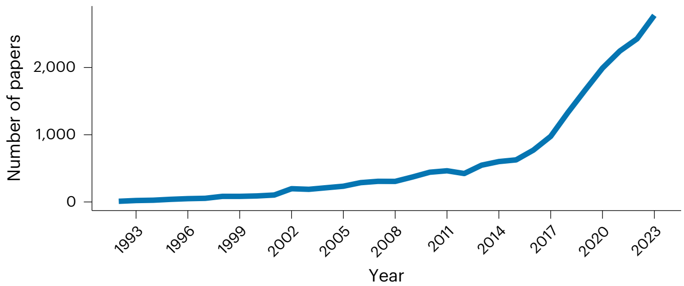

Fig. 2 | Publications over time. Number of experimental papers on VR and augmented reality published per year since 1992. Data from ref. 16.

of procedural versus abstract learning. Seasoned VR scholars may also benefit from seeing the depth of recent research on the extent to which body movements from tracking data can identify users. We therefore believe this multidimensional Review will have touchpoints for, and be useful to, different readers. We discuss each of the five findings in turn.

Five canonical findings

The benefit of being there depends on the activity

Presence is often informally referred to as being there[3]. One of the earliest studies documenting the experiential, visceral nature of VR validated a canonical VR demonstration[18]: when walking the plank over a virtual chasm, people showed real fear of heights and behaved as though the simulation was real, even with hardware that would be considered low fidelity by today's standards. Presence is a defining feature of VR that distinguishes it from other forms of media, but it turns out that not all media experiences can leverage presence equally[19]. High presence is a better fit for some media experiences than others.

Perhaps the best use case in VR's history is training, where a strong sense of presence is particularly beneficial. A number of meta-analyses have illustrated that in industries such as medicine, aviation and military procedures, VR allows trainees to experience realistic, high-stakes situations without the associated risks, allowing users to engage with the material as they would in a real-world scenario, solidifying their skills, facilitating learning transfer and honing decision-making[20–22].

Being there also has huge benefits in clinical applications. Exposure therapy is one of the most validated VR treatments for mental health, helping patients to confront their fears and decreasing avoidance of feared objects, situations or activities through desensitization[23]. Early work showed that VR exposure therapy could help patients to overcome a fear of heights[24]. Consider treating one's fear of flying. VR therapy reduces the cost of actually visiting the airport, it can simulate rare events, such as turbulence, and it protects the patient both physically and psychologically. Indeed, an early study from 2003 followed up with patients 3 years after treatment and showed that participants who received VR graded exposure therapy showed no recidivism in their fear of flying at the 3-year mark[25]. Recent meta-analyses have confirmed the lasting efficacy of VR exposure therapy[26,27].

Not being there (that is, psychological absence from the real world facilitated by high presence in VR worlds distinct from one's current physical location) provides benefits for pain management. One of the earliest studies on this topic demonstrated that VR alleviates pain in burn victims[28], effectively diverting attention from the painful procedure as a non-pharmacological intervention[29]. Indeed, a number of meta-analyses demonstrate medium-to-large effect sizes for pain reduction[29–31].

By contrast, two areas that have yet to show consistent efficacy are communication and entertainment. First, communication—defined for our purposes as using social VR systems in the metaverse to facilitate meetings and social interaction—has experienced only modest adoption, although it is important to note that a few VR experiences have gained traction. For example, in 2023, VRChat, one of the largest social VR platforms, reached over 92,000 concurrent users[32]. Gorilla Tag, a VR tag game where players don gorilla avatars and swing their arms back and forth to play among other gorillas, hit over one million daily users and three million active users[33]. At the same time, many VR scholars were surprised when the adopted medium during the pandemic was video conferencing as opposed to more immersive systems[34]. Metaverse systems, such as Roblox, are popular with children, but few adults are wearing headsets to leverage psychological presence during business meetings[35], and those who do in social contexts regularly encounter harassment[36]. Similarly, early scholars outlined a pathway towards success in entertainment[37] and although there was a flurry of energy after Facebook's purchase of Oculus, film festivals have recently turned away from the medium[38], in part due to the challenges involving viewer attention in VR[39].

Scholars who design research studies in VR should not always assume that high presence is a goal. As one chooses hardware and content for particular research studies, they should attend to both research findings and consumer trends that highlight the types of activities that benefit from high immersion (that is, the technical aspects of the medium) and presence (that is, the psychological feeling of being there), as well as the types that do not. For media consumers, it is important to understand that most VR headset owners use the devices infrequently after purchase[40]. Having a goal in mind for why one wants to use VR regularly, such as for fitness or social gaming, will help people to make the most of their purchase.

Self-avatars influence behaviour

Avatars are representations of people in VR[41,42]. A substantial thread of media psychology research on VR has investigated how avatars shape human behaviour. Avatars are central to VR user experiences, acting as the primary interface with the virtual world. Visuomotor synchrony, where physical movements sync with avatars' movements in real time using motion trackers, is a perceptual affordance of this medium with well-documented psychological effects. Body ownership illusion, for example, can occur in VR. This psychological phenomenon is characterized by the perceptual illusion of experiencing non-bodily entities as a part of one's body[41]. A canonical study illustrated body ownership of a physical rubber hand, in which synchronous visuotactile stimulation of a visible rubber hand and a hidden real hand induced the sensation that the rubber hand was real[43]. Scholars expanded this work by exploring the illusion of ownership over virtual bodies in VR[44,45]. One study reproduced the rubber hand illusion in VR, providing evidence of body ownership over a motion-synced virtual limb viewed through a headset using synchronous visuotactile stimulation[46]. Body ownership was also demonstrated in the absence of tactile feedback[47], highlighting the importance of VR's visuomotor synchrony in this perceptual illusion. The implementation of a self-avatar also has cognitive implications, as having an avatar with rendered hand movements improved recall over control conditions[48].

A precursor to body ownership research was the Proteus effect (first illustrated by ref. 49, but see ref. 50 for a recent example), whereby an individual's behaviour conforms to their avatar's representation. In their initial set of studies, participants embodying a taller avatar behaved more confidently during a negotiation task compared with participants embodying a shorter avatar[49]. This effect has been explored across a variety of contexts, showing that the visual characteristics of one's avatar can impact physical activity[51,52], attitudes[53] and interpersonal communication[49]. A meta-analysis found that effect sizes averaged between 0.22 and 0.26, which are comparatively larger effect sizes than other digital media effects[54]. Moreover, a second meta-analysis on the topic has shown that the Proteus effect is stronger in immersive VR than on 2D screens[55].

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Table 1 | Summary of five canonical findings

Finding	Early seminal paper	Scaled replication or meta-analysis	Implication for researchers	Implication for consumers
The benefit of being there depends on the activity	Rothbaum at al. (1995)[24]	Van Loenen et al. (2022)[26]	High presence is generally more effective for training and therapy than for communication and entertainment	Choose a headset with a specific purpose in mind; workout training apps have been particularly successful
Self-avatars influence behaviour	Yee and Bailenson (2007)[49]	Ratan et al. (2020)[54]	Avatar choice matters; even for studies not intended to study avatars, using default choices on platforms has consequences	VR apps that place users in avatars can influence one's self-attitudes and behaviour over time
VR works better for procedural training than abstract learning due to cognitive load	Moreno and Mayer (2002)[75]	Coban et al. (2022)[67]	Keep learning sessions short and spatial, and focus on procedural over abstract learning	2D content may be more effective than VR for schoolchildren, depending on the curriculum
Body tracking makes the medium unique, but also makes the user uniquely identifiable	Rizzo et al. (2004)[147]	Nair et al. (2023)[107]	When designing stimuli, facilitate head and hand movements and study the tracking data as an outcome variable	Understand the privacy risks around VR by reading the user agreement and remembering the device has many externally facing cameras
People underestimate distance in VR	Loomis and Knapp (2003)[113]	Kelly (2022)[117]	When computing variables based on movement, such as interpersonal distance and eye gaze, attend to the shortcomings of headsets	Apps that require accurate movements may be challenging depending on the headset model

For each finding, we present examples of early seminal works, recent meta-analyses or scaled replications, as well as implications for researchers and consumers. Although ref. 107 is not a meta-analysis, it offers an especially large sample size for VR research (n=50,000), which is why we included it here.

VR perspective taking—an exercise where individuals take the perspective of another—can promote empathy. Past work has documented the effects on implicit bias reduction[56,57], prosocial behaviour[58,59] and emotion recognition[60]. This endeavour has not been without its challenges or critiques. The effects of VR perspective taking on empathy tend to be context dependent[61] and have lacked longitudinal evidence (but see ref. 62 for an example of long-term effects). Scholars have also critiqued the hyperbole of VR as an empathy machine, citing the complexity of empathy, limits of simulation and spectatorship involved[63,64].

Scholars who design research studies must be aware of how strong an impact self-representation will have on participant behaviour, even in VR studies that are not designed to focus on avatars. Careful attention should be paid to avatar choices, regardless of whether those choices are intentional or simply a by-product of the often-limited availability of options on a given platform. Scholars should consider not only how participants are represented, but also how individual differences can shape perception towards their avatar and their degree of agency in customizing this representation. Consumers should understand that using avatars for long stretches of time has consequences; even in the 2D videogame context, avatar embodiment can impact behaviour over time[65].

Procedural training works better than abstract learning

Arguably one of the most popular and promising use cases of VR is learning and its variants, such as training. A number of meta-analyses have examined the extent to which VR affordances influence learning in classrooms, museums and other contexts[21,66–70].

Research has identified that the increased immersion, fidelity and a high level of participation provided by immersive virtual environments allow for unique affordances for learning[71]. These affordances have been shown to lead to the development of enhanced spatial knowledge[72], to facilitate experiential learning[73], to increase motivation and enjoyment[15] and to facilitate richer and more effective collaborative learning[74].

However, several limitations in the field have yielded modest or inconclusive results about the effectiveness of VR as a general classroom learning tool (see ref. 75 for an early example). These limitations include the difficulty of measuring appropriate VR learning outcomes, the lack of consideration of learning-theory-based research as a foundation for creating VR learning applications and the non-homogeneity of the term immersive technology being applied to non-immersive technologies such as desktop VR[76,77]. Furthermore, some works have identified that unique strengths of virtual experiences may undermine learning. For instance, although immersive VR may lead to positive outcomes such as greater presence, it can also lead to less learning and higher cognitive load[78,79]. The processing demanded by highly multisensory and interactive learning experiences in VR may exceed the processing capacity of people's cognitive systems, resulting in cognitive overload[80]. In particular, if learning tasks are poorly designed, they may lead to extraneous processing—cognitive processes that are not necessary for making sense of the new information—causing learners to waste cognitive capacity[81].

Other factors that influence the learning experience have been identified, such as individual differences (for example, gender[82] or neurodiversity[83]), learning level and subject[67], and pre-training[84,85]. Generally, the findings point towards the same direction: although VR may provide unique affordances that are promising for learning, the questions of who learns, in what context and using what material are critical in determining whether such affordances can foster meaningful learning[81].

Scholars who conduct research in VR can benefit from this previous work on learning in two ways. First, scholars should understand that porting learning materials from 2D media into VR can backfire due to cognitive overload. Second, time spent in VR should be shorter than for typical learning media to maximize comfort. For teachers administering VR in schools, it is important to be discerning when implementing VR content as part of a curriculum. It may sound obvious to VR scholars, but teachers without expertise are often led to believe that simply putting a headset on causes more learning regardless of content, and it is critical to limit headset use to content that leverages VR in a productive manner[86].

Body tracking makes VR unique

VR comprises a cycle of tracking, rendering and display. These occur continuously in real time, thus making the user uniquely identifiable.

The cycle starts with tracking, which involves sensors detecting one's movements and translating them into data that can be used to update VR content. Historically, tracking used sensors ranging from mechanical to magnetic, but today's tracking is mostly done with computer vision systems. These systems include cameras embedded within a headset that can accurately, quickly (that is, with low latency) and frequently (that is, with a high update rate) determine where a user is looking and how their body is moving by filming the room. Tracking information is critical because the system needs to know where someone is looking and how their body is situated to display their virtual location properly. One meta-analysis showed that improvements in tracking tend to have small-to-medium effect sizes on VR experiences[87].

Given that cognition is shaped by the body and grounded in the embodied experience and its context[88,89], VR offers fertile ground for understanding the relationship between the body and cognition. The medium allows researchers to isolate features of experience by manipulating how the tracked motion is perceptually reflected to the individuals. Research has shown that accurate, real-time body motion is critical for social cues of avatars of self and others[90,91]. The concept of altering how motion is mapped to a virtual body—known as homuncular flexibility[92]—captures much of the work done in this regard and presents possibilities for controlling new body parts or adopting non-human forms[93,94].

Tracking physical behaviours also allows for in-depth analysis of human behaviour[95]. VR works well for this purpose, as head, hand and eye movements can be subtly tracked by the headset and controllers, whereas additional sensors can capture physiological data such as heart rate and skin conductance. Physical movements, such as how an individual moves their head and hands and where they are looking, can reveal their intentions and level of attention[96–98] and can be effective in predicting embodiment[99]. Tracking data can also be used to create assessment tools for diagnosing attention deficit hyperactivity disorder in children using VR headsets[100]. Additionally, heart rate and skin conductance can characterize psychological states[101,102]. In networked VR, where groups of individuals share the same virtual environment, analyses can focus on social dynamics of body movements[103,104].

Importantly, motion-tracking data raise privacy concerns, particularly around the risk of re-identification. Information on how a user moves in a virtual environment is repeatedly found to be identifying across different settings, including training, 360° video watching and gaming[105–108]. A study using deep learning models showed that a VR user can be uniquely identified with over 90% accuracy among over 50,000 users using a model trained on 5 min of head and hand motion data per user[107]. That said, the identifiability risk of VR tracking data can vary across context, with a greater time delay between model training and testing reducing identifiability[105] and effective motion masking of tracking data increasing anonymity[109]. Although the ability to model individual differences from physical behaviour creates new opportunities for social science research, the potential for identity-based attacks demands further scrutiny.

Scholars who conduct research in VR can benefit from this previous work on body movement in two ways. First, when designing VR content, if high engagement is the goal, scholars should create virtual worlds that generally facilitate rich user movements, as well as moments along the timeline during the VR experience that intentionally cause specific user movements. Second, all scholars who run studies in VR should understand that the tracking data are uniquely identifiable and proceed accordingly with their internal practices of storing and anonymizing data. For practitioners, better real-time modelling of human behaviour will probably afford more adaptive and personalized immersive experiences[110,111], potentially augmented by the use of wearable sensors. The challenge here will of course be balancing privacy risks with the benefits of personalization (see ref. 112 for a thorough discussion of the risks of VR). As the field develops an understanding of the efficacy of privacy-preserving solutions, it is also crucial to quantify how potential downstream alterations to one's perceptual experience may affect psychological and social processes.

People underestimate distance in VR

VR is a fundamentally spatial medium. People move their bodies to navigate scenes; visual and auditory displays are generally rendered in stereo; and natural exploration of scenes is arguably one of the reasons one uses VR as opposed to a traditional 2D display system such as a desktop computer. When users experience high presence in fantastical VR worlds, assessing the accuracy of distances is probably not their first priority. However, when people are actually tasked with assessing how far away objects are, distances in VR can be underestimated by large magnitudes[113–115]. This perceptual shortcoming has consequences for spatial behaviours such as walking, jumping and throwing objects, putting the efficacy of VR-based training into question[116].

These effects have been consistent with early, low-fidelity headsets, as well as modern ones today. A meta-analysis[117] attributed possible causes, such as a restricted field of view, weight on the head, imperfect depth cues, shadows and rendering quality (see also ref. 114). To present 3D content, VR headsets use stereo displays that show two distinct images to each eye from perspectives that mimic the natural eye positions in the human head. A problem known as the vergence–accommodation conflict occurs when there is a discrepancy between focusing each eye on its corresponding display (accommodation) and adjusting both eyes to align with the object's correct depth (vergence)[118]. This conflict forces the brain to adapt in ways that feel unnatural and can negatively impact visual movement cues, suggesting that addressing this optical issue is vital to addressing the ongoing issue of distance underestimation in VR settings[117].

Previous studies in psychology and computer graphics have shown that shadows are a valuable cue for indicating ground contact[119]. Although VR systems generally do not incorporate shadows, they are important in its applications such as learning, where participants need to assess depth[120]. Recent studies on VR objects and shadows have found that dark objects with light shadows enhance accuracy when judging distance to the ground compared with dark objects with dark shadows or light objects with either dark or light shadows[121]. Furthermore, as shadows become brighter, depth cues are weakened, whereas chromatic shadows can improve depth perception of 3D objects in VR[122].

Distance underestimation increases when objects are further away[123]. This effect also occurs with headsets that show so-called passthrough video of the real world. One study found that people tended to underestimate distances in passthrough compared with when they were viewing the physical world without any cameras[124], and another showed that participants underestimated distance in passthrough and were less accurate when the target distance increased[125].

For researchers studying VR, distance underestimation could impact variables that rely on spatial relationships. For example, social psychologists who study VR will often use interpersonal distance or mutual eye gaze as variables in their studies (see ref. 95 for a review). Given that VR headsets change absolute measures of distance, psychologists should take this into account, especially when comparing virtual outcomes with norms in the physical world. Moreover, there are solutions to ameliorate this issue, such as augmenting a typical VR simulation with other sensors (for example, depth cameras), adjusting eye height or using virtual avatars[126–128]. For practitioners, the latest advancements in spatial computing enable the integration of both virtual and physical environments on headset screens, offering extended usage for both professional and leisure activities. Indeed, when Apple finally released its VR headset in 2024 it labelled the device as a spatial computer[129]. Distance underestimation errors could negatively impact cognitive performance and reduce the quality of in-headset experiences in these contexts[125].

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BOX 1

Future work recommendations for VR scholars

Use VR before studying VR. With webpages, videos, audio files, social media and other manners of delivering experimental content, scholars who are new to research typically have many years of experience with the medium itself. VR is complex, and the more one knows about hardware, platforms, content and the gestalt VR experience, the better. Researchers should spend at least a few dozen hours in-headset before spending the hundreds of hours it takes to run a rigorous study.

All VR scholars are perceptual psychologists. VR taps directly into the perceptual system in a way that is fundamentally different from other media. Small details matter immensely for the participant experience, and consumer technology varies. For example, should sounds be spatialized (that is, coming from the virtual location of objects), which increases presence but often at the cost of audio comprehension? How does one prioritize visual features that trade off due to processing power? A headset with a high field of view that approaches normal human vision is highly engaging, but rendering the periphery can require lower visual fidelity across the scene. Similarly, should one always render stereoscopically, as opposed to piping the same image to each eye, given that participants vary in their ability to see stereo, and that rendering in stereo (especially with video) can produce artefacts? Moreover, for hand tracking, should one use hand controllers, which are clunky and unnatural, or computer vision, which can be less accurate? VR is a complicated collection of many perceptual processes. One should make these decisions thoughtfully, not based on the default settings of platforms.

Longitudinal work is critical. A vast majority of VR studies look at only a single time point. Studying behaviour over time is critical to understanding any medium, but in particular with VR, which is a unique and novel experience for many participants. Longitudinal studies in VR often show that time as a variable accounts for as much variance in outcomes as the experimental treatment itself.

Study representative samples. Although all psychological research should strive to move from convenience samples to representative samples, VR has unique reasons to recruit diverse participants. Headsets fit people differently based on the size and shape of their heads.

Moreover, not everyone can stand for 30 min, use both of their hands, process stereo imagery or hold up a fairly heavy device using their neck muscles. Including diverse samples in experimentation is critical to fully understanding the psychological mechanisms at play and also to ensuring that research findings generalize to all people.

Include behavioural measures. Many of the constructs studied in VR are abstract and confusing; for example, what does it mean to be present in VR content, and how does one gauge what participants consider to be reality? Within the VR research community, questionnaires are still used regularly, but high-impact work typically also measures behaviour; for example, analysing verbal and non-verbal behaviour collected by tracking systems or examining what VR users do subsequently in the real world. Processing behavioural data can be labour intensive, but doing so is a critical aspect of understanding the psychological processes and implications of VR use.

Study the downsides. There is a paucity of scholarly work examining the negative psychological consequences of VR. However, understanding of psychological issues such as addiction, harassment or negative behavioural modelling is critical given the use cases gaining popularity in the consumer landscape. Designing experimental content in these areas can be challenging, and one needs to properly manage participant safety if studying difficult constructs such as harassment. Despite such challenges, this research area is in dire need of attention.

Discussion

The study of human behaviour in VR has flourished since its social science focus emerged in 1992. Indeed, as Fig. 2 shows, more than half of the total papers on the medium have emerged since 2018, and the current Review is written to highlight canonical findings that have replicated consistently over the years, are supported by meta-analyses and are useful for scholars who are beginning research programmes in VR, as well as consumers and practitioners who are implementing VR as a medium in their lives. Compared with the meta-analyses listed in Table 1, this Review does not present a systematic nor rigorous empirical analysis. Our goal was to engage in a balanced process to present our own perspective on the top five research findings that fit with the constraints we outline above. We sought out feedback from a panel of scholars to hone and refine the findings, but this was not a rigorous ethnography or survey, rather it just helped to increase the balance of our own perspective.

VR is often associated with videogames, films and the metaverse, where it has achieved modest success. In the current work, we focused on more psychologically useful applications and reviewed five robust findings, some of which indicate the applications where VR can apply epic wins, such as training[15], clinical therapy[23,24] and the use of avatars for empathy[56,58,60]. However, VR is not a free medium—using it can cause simulator sickness[130], cognitive load[78,79] and privacy concerns from tracked body movements[105–108].

One way to resolve the pros and cons of VR is to use a framework called DICE. This approach recommends that we primarily use VR for dangerous, impossible, counterproductive or expensive experiences that are not easy to implement in the real world[131]. Training firefighters[132], rehabilitating stroke victims[133], learning art history via sculpture museums[134] and having a visceral, perceptual experience of the Earth's future to understand climate change[135], for example, all fit squarely in DICE. Alternatively, one does not necessarily need to don a headset to check email, watch television and conduct general office work. Such applications work better on 2D screens. By not putting such use cases needlessly into VR, society can avoid some of its challenges. In Box 1, we present our recommendations for future work. This should focus on areas where VR is transformational and clearly the best medium for the job.

As the research field progresses, one striking characteristic is that few studies examine behaviour longitudinally (see ref. 136 for a survey of the studies that look at VR use over time).

Similarly, although some scholars have examined the psychological and social effects of the medium on children[137,138], this is an area that would benefit from additional research. Moreover, there are few studies that use reliable measures of brain activity, such as magnetic resonance imaging, to study VR, largely because good immersive experiences require large and abrupt movements, and even newer brain science tools have limited accuracy when extreme head movements

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occur (but see ref. 139 for a recent discussion of the use of functional near-infrared spectroscopy to study brain science in VR). Many scholars use traditional psychometric data and approaches (for example, self-reports) in VR research for good reason: self-report scales, for example, are typically valid and reliable in non-VR settings and are convenient to deploy. However, in VR it is a missed opportunity to not go beyond these measures (see ref. 140 for an early explication of this notion). A new frontier of VR research should include the prioritization of longitudinal and multi-method evaluations as we have indicated, but also the creation of new measures and ways of measuring to gain an understanding of human behaviour.

Scholars studying human behaviour in VR often prioritize non-verbal behaviours and self-report measures over speech[141]. However, speech is indicative of emotional and cognitive processes[142,143]. Additionally, speech is rarely examined, given that many studies tend to feature single participants in non-conversational settings. However, as discussed above, one of the more successful use cases of consumer VR is for social interactions, whether it is kids playing Gorilla Tag or adults perusing the world of VRChat[144,145]. Future work should address this disconnect, using the full spectrum of communication and human behaviour to measure constructs of interest.

When Sutherland wrote his seminal paper[146] describing this medium, he described a technology that “gives us a chance to gain familiarity with concepts not realizable in the physical world”, stating: “It is a looking glass into a mathematical wonderland.”[146]. Indeed, psychological research is now rigorously examining Sutherland’s vision, with scholars building and testing systems in consequential settings. Research on this medium has received a recent flurry of academic publications, building on the history that preceded it. Now that hardware and software are cheap and available, understanding the psychological processes and impacts of this medium as it scales is critical. We are optimistic that as access and affordability continue to improve, the field will provide insights into human behaviour and develop a deeper understanding of the uniqueness of virtuality.

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Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Jeremy N. Bailenson.

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