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EDITED BY
Carolin Wienrich,
Julius Maximilian University of Würzburg, Germany

REVIEWED BY
Richard Skarbez,
La Trobe University, Australia
Thomas A. Stoffregen,
University of Minnesota Twin Cities, United States

*CORRESPONDENCE
John Porter III,
jjporte@clemson.edu

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Lingering effects associated with the consumer use of virtual reality

John Porter III* and Andrew Robb

School of Computing, Clemson University, Clemson, SC, United States

Since the release of the Oculus Rift CV1 in 2016, millions of VR headsets have made their way into consumers' homes. Since then, users have created large quantities of data about their experiences in VR through posts made to online discussion forums. We examine this data to gain insights on what sorts of "lingering effects" users report having experienced after VR, and on the progression of these effects over time. We found three major categories of lingering effects (besides simulator sickness) during our qualitative analysis: perceptual effects, behavioral effects, and changes in dreams. The perceptual and behavioral categories were further divided into sub-themes: disruption of body ownership and proprioception, loss of a sense of depth in the real world, visual aftereffects, the need to verify the reality of the real world through touch, hesitation when moving in the real world, and attempts to apply VR interaction metaphors to real life interactions. Users were nearly unanimous that these lingering effects only occurred after spending at least 1 h in VR, and that these effects completely disappeared several weeks after they first appeared (assuming the user continued to spend time in VR). There was less agreement about how long these effects lasted after exiting a specific VR session. The results of our analysis suggest that users feel that there are no long-term side effects to the use of VR. We pair this analysis with an analysis of interviews conducted with 20 novice users who were loaned Oculus Quest HMDs to use for 4 weeks. Semi-structured interviews with participants further substantiated the findings of our analysis of online discussions.

KEYWORDS

virtual reality, reddit, lingering effects, long-term use, games, qualitative, over time

1 Introduction

Virtual Reality (VR) has undergone a major transformation since the release of the Oculus Rift CV1 and HTC Vive in early 2016. Whereas VR was previously largely confined to laboratories and training facilities, millions of headsets are now used in homes for entertainment and other applications. A major consequence of the widespread availability of VR is that more people are experiencing VR, and for longer periods of time. When VR was confined to the laboratory, few people had the opportunity to spend any meaningful amount of time in VR. Now, it is not uncommon for users to spend hours in VR for weeks on end. As such, it is more important than ever that we understand how

prolonged exposure to VR affects the people who use it. In this paper, we specifically seek to understand what types of "lingering effects" are common after prolonged exposure to VR, and how these effects evolve over time.

We follow Laviola's definition of cybersickness, which we refer to in this paper as simulator sickness, and how it often results in a range of symptoms including nausea, disorientation, headaches, sweating and eye strain (LaViola, 2000). Outside of this realm of simulator sickness, relatively little work has considered how time spent in VR may continue to affect user's experiences in the real world after exiting VR. A few early studies considered how VR could affect memory formation, in particular considering whether VR could promote the creation of false memories. Segovia and Bailenson examined false memory formation in pre-school and elementary aged children, and found that elementary aged children were significantly more likely to form false memories about experiences they had had in VR, as compared to when children merely imagined being in the situation that was shown in VR (pre-school aged children were equally likely to form false memories in both conditions) (Segovia and Bailenson, 2009). Hoffman et al. considered false memory formation in both real and virtual worlds, and found that the characteristics of the memories were influenced by whether participants situated the false memory as having occurred in real life or in VR (Hoffman et al., 2001). Steinicke and Bruder reported on a case study where a participant spent 24 consecutive hours in VR and reported on their experience; of particular interest to this paper was the observation that "several times throughout the experiment the participant was confused about being either within the VE (virtual environment), or in the real world, and also had mixed certain artifacts and events between both worlds", which demonstrates the potential for confusion between real and virtual worlds during periods of prolonged exposure to VR (Steinicke and Bruder, 2014).

Each of the above studies sought to understand how exposure to VR may continue to affect the user later in the real world. Though the Steinicke and Bruder study considered how a singular prolonged session of VR exposure impacted their participant, few other research studies have included a meaningful longitudinal component in their research looking at how exposure to VR impacts human behavior (once again, with the exception of simulator sickness research). When considering the question of how long-term exposure to VR affects the way people are affected by VR, it is important to recognize the distinction between studies that conduct longitudinal research *on* VR, and studies that conduct longitudinal research *using* VR. Studies in the first category inform us about how users with more experience using VR technology will respond to VR differently than users with less experience. Studies in the second category inform us about how users who have gone through a structured program using VR will be different from users who have not, in some other context (such as phobias, or performance).

While many longitudinal studies *using* VR have been conducted, little longitudinal research has been conducted *on* VR. The only aspect of VR that has received a significant amount of longitudinal research is how users' response to simulator sickness changes as they gain experience using VR technology over time (this research has largely been conducted in the context of military training simulations) (Kolasinski, 1995; Dużmańska et al., 2018). Almost every other longitudinal study involving VR has focused on the *application* of VR to a specific context, such as phobia (Parsons and Rizzo, 2008) or PTSD treatment (McLay et al., 2010), training behavior (Crochet et al., 2011), or social behavior (Moustafa and Steed, 2018).

After conducting an extensive search for other studies that have conducted longitudinal research *on* VR, we are only aware of three studies that investigated how behaviors (other than simulator sickness) changed as users gained more experience with VR over time. The first of these studies was conducted by Bailenson and Yee, who followed nine participants across 15 laboratory sessions involving social activities in VR (Bailenson and Yee, 2006). Simulator sickness decreased significantly over time, but no effect was observed for presence or copresence. Participants also spent less time looking at the faces of other avatars as time progressed. In the second study, Porter et al. conducted a brief longitudinal study (three 45 min sessions) using a VR version of the game Minecraft (Porter et al., 2018). Porter et al. also found that there were no longitudinal effects on presence; with regard to simulator sickness, interviews with participants suggested that they felt simulator sickness decreased with time. However this was not supported by an analysis of the Simulator Sickness Questionnaire (SSQ). In the final study, Meehan and Brooks conducted between-subjects studies where physiological reactions, such as heart rate, were used across multiple sessions as potential measurements for presence (Meehan and Brooks, 2001).

There are many challenges associated with longitudinal research, especially when this research must be conducted in laboratory settings, as opposed to in the field (Taris and Kompier, 2003; Thomson and Holland, 2003; Ployhart and Vandenberg, 2010). While controlled, experimental longitudinal studies are essential for answering some questions, we argue that other methods can also be used to gain insights into how users' responses to VR evolve as they gain experience with the technology over time. In particular, users have generated large quantities of data about their experiences with VR in online forums devoted to VR games. These forums can be used as a lens to investigate how community beliefs and attitudes toward VR have evolved over time. They also provide researchers with the opportunity to identify self-reported information about how a particular user's response to VR has evolved over time. There are

limitations with this method, notably a lower degree of control as compared to experimental studies. Additionally, the results of these studies may pertain to the beliefs of the community, which may differ from actual relationships. However, this approach can enable research that would be nearly impossible to conduct experimentally, due to either the rarity of the phenomenon or due to the amount of participants required.

In this paper, we attempt to understand what lingering side effects the general population of users report experiencing after using VR games and applications, and on how these lingering side effects evolve over time as users spend more time in VR. We do not consider simulator sickness in this analysis, as this has been well studied in other contexts. Instead, we focus on effects that are less well understood from laboratory studies and that are also more difficult to study in laboratory contexts, either due to their relative rarity, or due to their long temporal timescale (e.g., an effect that emerges only after a long period of exposure to VR, or that slowly evolves over the course of several days after exposure). We identified three major categories of lingering side effects: effects on perception in the real world, effects on behavior in the real world, and changes to dreams. Several sub-themes also emerged within the perceptual and the behavioral categories. After identifying the major categories of effects, we considered how these effects progressed over time. In particular, we coded data according to four temporal concepts: 1) how long must be spent in VR to trigger an effect, 2) how long until the onset of the effect upon exiting VR, 3) the duration of a specific effect, and 4) the total duration that side effects can occur. We found that users almost unanimously agreed that these lingering effects only occurred after spending at least 1 hour in VR, and that all lingering effects would disappear within several weeks of beginning to use VR. We conclude with suggestions for how this work can be applied.

2 Analysis of online discussions

2.1 Reddit overview

As of 2019, Reddit was ranked as the sixth most visited website in the United States, and 15th globally [1]. The site describes itself as a "home to thousands of communities, endless conversation, and authentic human connection" where there are currently over 330 million active users, over 138 thousand active communities, and over 14 billion monthly screenviews [2]. On Reddit, users can submit textual content directly as submissions, allowing for others to comment, as well as create their own subcommunities named "subreddits." These subreddits are independent, dedicated to a specific topic, and moderated by other volunteer 'Redditors' - a neologism combining 'Reddit' and 'editor.' Within these subreddits, users generally stay within their own community (Buntain and Golbeck, 2014), and are often vetted by bots, moderators, and other redditors when posting content or answers in their respective forums. This signifies a generally cohesive and trustworthy base of information that can be gathered from these users. Currently, some longitudinal research concerning Reddit posts has been done, though only relating to Reddit data as a whole, not focusing on any one particular subreddit (Singer et al., 2014).

2.2 HTC vive description and terminology

To aid the interpretation of user's comments in the next section, we provide a brief description of important aspects of the HTC Vive system. It is comprised of a the Vive head mounted display (HMD), two handheld controllers, and two Lighthouse base stations (these are used to track the motion of the HMD and the controllers in the real world). The HTC Vive is connected to a computer by a 5 m cable that runs out the back of the HMD and (typically) down the user's back.

The HTC Vive's field-of-view is roughly 113° diagonal; this is significantly smaller than the typical human FOV of roughly 200°. As such, the periphery of a user's vision in the Vive is blocked out. The resolution of the display is 2,160 × 1,200, which is sufficient to provide a great amount of detail, but insufficient to replicate the typical resolving power of human vision. Due to this, and to the structure of pixels in the displays, the HTC Vive suffers from the "screen door effect," where the user has the impression of looking through a fine mesh (like a screen door), due to the gaps between pixels and the pixels' visible size.

The HTC Vive supports motion within up to a 5 m × 5 m space, supported by the Lighthouse base stations. As users in VR are not always aware of when they are approaching a boundary in the real world (e.g., a desk, or a wall), the HTC Vive displays "chaperone bounds" when the user is near a boundary. Chaperone bounds usually take the form of a brightly colored vertical grid that stretches from floor to ceiling. These bounds appear once the user is close to the boundary, and disappear once the user moves away.

Users interact with virtual objects through the use of two handheld controllers. The controllers contain several buttons, including a trigger, a grip button, and a touch-pad. As these controllers cannot detect finger motion, interactions are typically initiated by pressing a button while the controller is in contact with a virtual object. As the HTC Vive cannot track a full human body, very few VR applications visualize the user's body in VR. While some may show virtual hands at the location of the controllers, it is more common to simply show the controllers in VR without any hands, or other elements of the user's body.

1 https://www.alexa.com/siteinfo/reddit.com

2 https://www.redditinc.com/

2.3 Methods

To gather consumer discussions about lingering effects in VR, we turned to the popular discussion forum Reddit, specifically the subforum/r/Vive subreddit. We chose to focus on the HTC Vive, as opposed to other available headsets, such as the Oculus Rift, due to the more advanced capabilities of the HTC when it was originally released. Specifically, the HTC Vive supported motion input controls and wide area tracking upon release, whereas these features were only made available at a later date to the Oculus Rift. Furthermore, the/r/Vive subreddit was more active than other subreddits devoted to VR in general, meaning that more data was likely to be available.

All conversations made within 2 years following 5 April 2016 (the day the HTC Vive was released) were included in our search. Conversations on Reddit are composed of an initial post followed by a nested threads of comments. Posts are made by an initial user and comments can either be made to that post, or to other comments already made in the conversation. This results in a more complex conversation structure than is common of most online forums. During the 2 year period we sampled, 121,550 posts and 2,183,924 comments were made on/r/Vive. We performed our search using the Reddit API, specifically through the portal hosted at *www.Redditsearch.io*. We included both posts and comments that met our search criteria, which enabled us to identify both root discussions of interest, as well as relevant tangential discussions that emerged in the comments.

Prior to performing a structured search, we engaged in an exploratory phase where both authors tracked posts made to the forum, with the goal of identifying conversations that were relevant to our topic of interest. Based on the conversations identified in this phase, we identified phrases and words that were often present in the majority of the relevant observed conversations. These phrases include: 'feels weird after', 'side effect after', 'disassociation', 'disoriented after', and 'weird dreams'. These search terms were then used to identify more conversations made in the first 2 years following the HTC Vive's release that involved discussion of lingering side effects. We began reaching saturation when searching with the fourth and fifth term (meaning that most of the returned posts had already been identified). In total, 1,710 comments were retrieved using these search terms. Though this number is small in comparison to the total number of comments made during the searched period, discussions concerning lingering effects were rare overall and did not constitute a major topic of discussion in this subreddit.

During the search, each phrase was independently input into the Reddit API, which was configured to return all conversations where all the individual words in the search phrase occurred somewhere within a single post or comment; the exact search phrase was not required to be present in any particular order. Using this 'bag of words' search criteria, all conversations returned were identified as relevant to our topic. After all relevant conversations were identified, comments made in each conversation were reread individually while notes and relevant quotations were extracted. After notes had been made on each individual comment, we then categorized this data into our major themes: perceptual aftereffects, behavioral aftereffects, and changes in dreams.

2.4 Qualitative analysis

The three major themes identified within consumer discussion of lingering effects that they attributed to their time spent in VR were: perceptual aftereffects, behavioral aftereffects, and changes in dreams. From these major themes, sub-themes were identified that captured the nuances of all discussions pertaining to these themes. We consider each of these themes, and their sub-themes, in the following section. After which, we discuss what can be inferred about the duration of these effects, and also discuss the explanations users proposed for these effects.

2.4.1 Perceptual aftereffects

The first theme that emerged from users' conversations dealt with perceptual aftereffects. In these cases, users' perception of their own bodies and the world around them was altered. These effects were predominantly visual in nature, however a haptic after effect was also reported, as were proprioceptive aftereffects. Users generally felt that these effects were mildly disconcerting, but not grossly unpleasant like the experience associated with simulator sickness, and one of the effects was actually reported to be enjoyable by most users.

2.4.1.1 Disruption of body ownership and proprioception

Many users also reported disrupted feelings of body ownership. This phenomenon typically manifested itself either across users' entire body, or specifically in their hands. Disruption of the hands was more commonly reported than disruption of the entire body. With regard to disruption of the hands, two sub-themes emerged: feeling that their hands were not their own, and feelings that their hands were in the wrong position. We argue that the first sub-theme indicates disruption of body ownership, and the second disruption of proprioception.

Disrupted Hand Ownership: In these discussions, users reported feeling surprised that they could see their hands, and that they did not feel like they belonged to them: "I feel like my hands are not part of my body anymore." Another user described this feeling as though the hands he saw moving in front of him belonged to a puppet: "It is just such a powerful feeling of seeing my real hands and they don't feel like my real hands . . . just like puppet hands moving in front of me." Being able to see ones' hands was also linked to more general feelings of unreality, such

as this user's comment stating that, "After jumping out of VR, I get in the car and feel my brain debating if it is still in VR, looking at my hands and such." Users also expressed surprise at how their hands physically interacted with the world around them saying, "When I interact with real objects, I'm surprised that my hands don't go straight through them."

Users frequently linked this effect to when they were holding their phones (one user generalized this to any held object that kept his hands in view). Examples include: "When I hold up my phone my brain expects no hands to be there," "When I text on my phone my hands seem to go out of focus and it feels like my hands are not part of my body anymore," and "When holding my phone sometimes randomly my hand seems to not be my own hand. It looks like my hand but it feels like a random third ghost hand holding it." In these cases, users do not feel that their hands are generally unreal, but only when holding or manipulating an object. This potentially can be attributed to a common convention in current VR games called "tomato presence" (Steed et al., 2021) in VR (such as a phone), the controller model representing the hand was replaced by the object being grasped. As such, when manipulating objects in VR users saw the object where their hand was located without any representation of their hands (or even the controller that stands in for the hands).

Disrupted Hand Proprioception: Users also reported moments when their hands merely appeared to be in the wrong location, rather than being completely unreal stating, "My hands feel like they are in a slightly incorrect position in the real world from where it was tracking in the game." Users sometimes also reported the feeling that their hands were lagging behind their actual motion, "I was driving around in LA Noire VR the other day for a couple of hours. The next day my hands felt weird for a split second on my actual steering wheel, like my brain was waiting for lag or something." Other users described their hands as seeming to go out of "focus," or saying that they have "lost track of depth" when looking at their hands.

One user reported an experience where he was unable to successfully grasp an object in the real world due to the misperception about the location of his hands. During the game Job Simulator, the user explains that "your 'hands' in are positioned at the end of the wand, extending unnaturally longer than your normal hands." While in VR, he "completely accepted this," but when returning to the real world "his mind rejected the position of his normal hands." This then led to his experience where he was unable to accurately interact with the world around him stating, "I found myself unable to grab a carton of milk from the fridge on the first try after playing for an extended session, which immediately made my mind reel inwards in recoil to this . . . I needed to sit down and re-evaluate before feeling better." When attempting to grab a carton of milk, the user found that he under-reached and missed the carton. He attributed this to the time spent playing a game where his virtual hands were positioned further from his body than his actual hands.

Bodily Disruption: With regard to their entire bodies, some users reported moments when they "would bump into stuff because [they] forget [they] had a body." Others experienced moments when they felt like they "lost tracking in real life" and had to "freeze for a second until [they] reacquired [themselves]." For one user, this experience went beyond mere body ownership to complete loss of self, saying that "When I laid down after very long vive session I felt like I was not there." While most users did not link these events to specific conditions, one specifically mentioned "going down the stairs" as a cause for this feeling, in addition to "just moving around." Several users felt the need to stop and focus for a time to restore their normal sense of body ownership: "I just felt strange mentally, somewhat detached, and felt like I had to try to be myself for a while before it became natural."

Self-avatars are currently rare in VR games. As such, most reports about disrupted body ownership were concerned with feeling detached from their body. However, one user reported on an experience he had with an early VR game that attempted to simulate a self-avatar using the Oculus DK2, the Razer *Hydra*, and inverse kinematics. He reported that "after getting out of the game it would usually take me to up to half an hour for my mind to accept that my RL arms were actually my arms, and not some 'foreign' part (pinching my arms helped my brain to accept that they were part of my body)." This suggests that additional forms of body ownership disruption may be experienced as consumer VR applications begin to simulate self-avatars.

2.4.1.2 Loss of a sense of depth in the real world

Many users reported that the having experiences where something about the real world seemed "off" after spending time in VR. This "off-ness" was typically linked to difficulty judging the distance to real objects, or feelings that the world has somehow because more two-dimensional. These experiences varied in terms of intensity, ranging from a user who reported "[their] depth perception was a tiny bit off," to users who said that "I feel like my brain can't tell distance anymore in real life." Another user mentioned things appearing two dimensional. "People and things lack a sort of presence and weight. They look almost two dimensional, and it is hard to tell things apart from their surroundings." No clear pattern in the direction of the misperception was present in the data; different users reported feeling both that people and objects were closer and further away than they knew them to be, and other comments simply described the difficulty without indicating the direction of the misperception (as was seen in the quotes reported earlier in this section).

Onset of this effect was not necessarily immediately after exiting VR. While the feeling of "off-ness" could occur immediately, others reported it suddenly occurring while engaging in other activities, e.g. when "sitting at my desk looking at my keyboard typing, when I just [had] this sort of removed feeling. Feeling further away than normal." External stimuli could sometimes trigger this feeling, such as how "flickering fluorescent lights made [them] feel like [they were]

in low fps VR" or how "when I closed my eyes, or blinked, I felt like the world around me was jumping or lagging."

2.4.1.3 Persistent perception of VR elements in the real world

In addition to distortions in depth perception, participants also reported other categories of visual aftereffects. The first group focused on how constant visual elements of VR could appear to persist in the real world. These sorts of effects included feeling like the outline of the HTC Vive's lenses could be seen in the real world, persistence of the screen door effect in real life, and seeing the HTC Vive's chaperone bounds appear in real life.

When speaking of the lenses, users seem to be referring to the restricted field of view created by the HTC Vive, with the periphery of their vision being blocked and darkened. One user described this, saying "everything looked as if I was looking through the Vive lens." Another linked this to night, potentially due to the associated darkness: "Especially at night, when I close my eyes I could see the outline of the [HTC Vive] lenses." Users compared this effect to how very bright lights can linger after looking away, until the pupil adapts: "It is like light persistence, where you're looking at something really bright then close your eyes and keep seeing it." However, unlike pupillary adaptation, the duration of this effect could be highly variable, sometimes "going away in a minute" and sometimes "lasting for hours and even into the next day." The potential for this effect to persist for a prolonged duration, and for delayed onset (such as appearing at night) suggests that this effect cannot be solely attributed to the response of the retina to prolonged dimming of the periphery.

Many users reported seeing something like the screen door effect, where the real world appears to be composed of pixels: "I felt like I could see pixels in real life." In a similar fashion, other users reported that "[the real world] seemed kinda rendered." Sometimes this effect could be triggered by seeing a grid in real life, such as when one user reported that they "noticed a screen door effect in real life, which was caused by a grid pattern messing with my eyes." The community also referred to this effect using the term "grid eyes." In addition to seeing pixels, one user also referred to seeing Fresnel patterns in real life, saying they could "see pixelation and Fresnel lines up to 12 h after [they] stopped VR." This effect could persist for a long duration in some users, even to the extent that users would "see grid eyes when they wake up [the next day]" after long play sessions spent in VR.

A similar effect was also reported with the HTC Vive's chaperone bounds. Unlike the lens outline and the screen door effect, the chaperone bounds are not necessarily always visible. They are also not fixed in the visual field, as they are spatially situated and will move in the visual field as the user moves. As such, this does represent a slightly different effect than those discussed previously. Some users reported "seeing chaperone bounds where they would have been in VR, but within [their] real life rooms," while others also reported that this could occur in environments other than where they normally play in VR. This effect was convincing enough that it can affect user's behavior, as in the case of the user who said that the effect"was really weird, and has made me make a dead stop in the middle of a stride, because for a second or two I thought I was going to hit my wall."

2.4.1.4 Additional visual aftereffects

In addition to aftereffects related to persistent visual elements of a VR display, users also reported two other unusual aftereffects pertaining to vision in the real world: a heightened sense of dimensionality for 2D text or images and a strong awareness of the individual pixels present in a display.

Some users spoke of "visual glitches" that occurred outside of VR, where "text would randomly appear 3D." This included "floating text when browsing the web" and seeing "stuff on regular 2D TV appearing a bit like 3D-glasses." This effect was frequently linked to text, with one user specifically referencing the "text on your screens created a 3D effect against contrasting backgrounds." It may be that this effect was tied to high contrast situations, of which text was one of the most frequently encountered examples. However, like the earlier reference to 2D TVs, other users felt that "everything just seemed to pop out in 3D." This effect is an interesting contrast to the first perceptual after effect we discussed, where depth perception becomes difficult and the world appears more flat. In this case, flat images and text seemed to take on an additional sensation of dimensionality. It is also worth noting that many users reported enjoying this effect, telling new users who mentioned it to "enjoy it while it lasts. I kinda miss it."

Another unusual visual effect was a heightened awareness of the pixels present in a display. This was distinct from the previous instance of observing the screen door effect in real life; where rather than seeing pixels where there are none, users instead become more aware of pixels when they are present, even in high density displays. One user reported being able to "notice pixels on an iPad Pro from a normal lap-resting viewing distance," which is notable given the "retina" resolution of an iPad Pro. Other users did not make reference to specific devices, but reported the same effect, saying "I now see the pixels on high density mobile displays, which required a bit of work to see clearly before," and claiming that they could "easily distinguish between all of the pixels."

2.4.1.5 Persistent haptic aftereffects

The final perceptual after effect that we noted was not a visual effect, but a haptic effect of an ongoing sensation that the HTC Vive's cord is running down their back, even after removing the HMD. Users often referred to this effect as the "phantom cord." Many users reported that "after using [their] Vive [they] could still feel the cord down the back of [their] neck even when the HMD was off." This effect became so familiar to some users that "it just felt like there SHOULD always be a cable coming out of the back of my head." This effect could also manifest itself behaviorally, where if users were to "run over some wires with a chair at work" they would "rush to make sure my HMD wasn't about to fall over."

While this effect seems less notable than some of the previous effects, it was unique in that it was the only non-visual after effect we observed. Even the aftereffects related to body ownership and proprioception contained a visual component, as these conflicts were created when users saw their bodies. Additional haptic aftereffects may be expected in future VR systems that provide additional haptic stimulation, especially if this stimulation is provided consistently, or with high frequency.

2.4.2 Behavioral aftereffects

The second theme that emerged from users' conversations dealt with behavioral aftereffects. In this theme, the aftereffects led users to alter their behavior. While perceptual effects inevitably would also alter behavior, users did not frequently discuss these changes, instead preferring to focus on the altered sensation. The sub-themes discussed here are different in that they were always linked to explicit behavioral changes.

2.4.2.1 Verifying the reality of the real world through interaction

Users commonly reported a sense of unreality associated with the real world after exiting VR: "Especially right after I take off the headset, I have a hard time figuring out whether I am in reality or not." In order to verify the reality of their experiences after removing the headset, users would deliberately touch objects to confirm their real nature, e.g., "I would often touch things (my desk, the wall, my phone, etc.) just too reaffirm they are indeed real," and "I would touch or pickup objects IRL and question if they were real". It is notable that users fall back on the haptic sense to verify that the objects they are seeing are in fact real. While current VR systems are capable of simulating visual input with high accuracy, haptic simulation remains crude, at best. As such, users have grown accustomed to virtual objects not providing any haptic feedback, which ensures that if an object does provide haptic feedback, it is real. This may have interesting implications for future VR systems capable of more accurate haptic simulation. In this event, it seems likely that users would not fall back on haptic sensing to reassure themselves of the reality of the real world.

2.4.2.2 Hesitation when moving in the real world

In addition to verifying their world's reality through touch, users also reported they would "walk a bit slower in their house to make sure the chaperone system didn't pop up." Others attached emotional significance to this change in behavior, expressing "[fear] to walk because I feel penned in by the imaginary cage of the chaperone bounds." In addition to moving slowly due to feelings that they might encounter a chaperone bound, users also expressed hesitation about attempting to support themselves using physical objects. One user reported that he "never shifts my weight onto anything unless my hand is on it for about a second for my brain to make sure its real." This behavior emerges from the risk of "just falling through it" associated with attempting to support oneself on objects in VR, which have no real existence. This hesitation was then carried over into the real world after exiting VR.

2.4.2.3 Attempts to use VR interaction metaphors in real life

While the previous two effects dealt with new interactions with the real world, the final effect users describe involved instinctively attempting to use VR interaction metaphors in real life. These included both locomotion metaphors and interaction metaphors.

Users regularly report attempting to teleport in real life after spending time in VR. As the inverse to users hesitancy to walk due to fear of encountering a chaperone bound, users "feel like [they] should just teleport somewhere instead of walking." Users felt this instinct for both general motion throughout a space and for motion intended to facilitate interactions with the local environment: "I try to teleport to things I need to pick up." As teleportation is one of the most common locomotion metaphors used in consumer VR experiences, attempts to teleport were the most frequent VR locomotion metaphor applied to real life. However, at least one user also referred to an attempt to use sliding locomotion, saying he would "put my hand out with the non-existent wand that was no longer in my hand to point at the part of the room they wanted to 'walk' to." This suggests that the frequency of references to the metaphor of teleportation was more likely to be due to its prevalence in consumer VR applications, rather than any inherent aspect of the metaphor. As other locomotion metaphors become more common, it seems likely that users will also experience instincts to use them to move in the real world.

Interaction metaphors from VR were also applied to real life interactions. Users would "try to press the trigger button to pick up objects in front of me in real life," or "try to pick up a drink by pointing my 'controller' at it and pressing the grip button." Going beyond attempting to initiate interactions by pushing an appropriate button, another user reported an event where the rules governing ongoing interactions in VR were carried over to the real world stating that, "After a few hours in VR, I got some coffee, and then just let the cup drop from my hand, spilling all over my carpet. I think I had been in a game where you only pull the trigger once to pick up an object and then it stays bound. My brain just forgot to hold on." VR games will commonly allow some objects to be held by pulling a trigger once, rather than requiring users to continuously hold the trigger down. The object can then be released by pulling the trigger again. This lowers the strain placed on users' hands while holding these virtual objects, that otherwise would be held for a significant amount of time.

While the majority of attempts to use VR interaction metaphors in real life centered on attempts to use controller-based interactions, one user reported changes in his physical motions used while engaging in an activity:

> "I've been having a whole lot of fun with 2MD VR Football lately. After a few weeks of playing an hour or so a day, I went to throw [an American football] with a coworker in between shifts. Even with only a few weeks of play in VR, I noticed my

> release was way earlier than it had been. I'm pretty sure it's because the Vive wand is significantly lighter than [an American] football, so I accidentally trained myself to release faster since I go through my throwing motion faster in VR. I had to re-learn my throwing motion a bit after that. This is particularly interesting to me because I work in athletics (totally different sport) and proprioceptive response training is a big part of my work."

While the previous application of VR interaction metaphors to real life are relatively harmless (and even humorous), the disruption of a user's muscle memory required to perform a physical activity is more concerning. While we only observed a single user describing how their muscle memory for an action in the real world had been disrupted due to learning a different motion for the same action in VR, this anecdote suggests that it may be very important to carefully engage the same muscle systems and motion patterns in training systems where skills with a muscle memory component are being learned, even if the primary goal is to train a cognitive component of the task.

2.4.3 Increased vividness and lucidity in dreams

Unlike the first two major themes, which focused on changes in perception and behavior in the real world, the final theme that emerged focused on changes in users' dreams. At the most basic level, some users reported dreaming about VR experiences, either in general (e.g. "I had dreams about VR the first few days after I got my Vive") or in part (e.g. "the interface of my dreams is different, almost like playing VR in a dream."). Given the brain's tendency to integrate recent events into dreams, it was not particularly notable that these sorts of dreams were reported. Of more interest are instances where specific interaction metaphors from VR are incorporated into non-VR dreams. Users spoke of how they "definitely teleport around in dreams now," how "all of a sudden a chaperone grid popped up [in my dream]," and how "the dream I had last night involved a climbing mechanic from the game I played." In these cases, specific interaction mechanics, locomotion techniques, and safety features of VR experiences are integrated alongside more mundane experiences in users' dreams.

Going beyond the mere content of the dreams, other users spoke of how their dreams had become more vivid: "The more time I spend on VR, the more vivid my dreams become. I've dreamt all kinds of things. They're not always related to the games I play, but it feels like my brain is more used to be in dreamlike environments so I'm more aware and even in control sometimes." Dreams were not only more vivid, but could also become lucid. In lucid dreaming, the dreamer is able to control what happens in the dream, rather than merely experiencing it: "The only thing that happened to me [when I started using VR] is I had these really lucid, vivid dreams where I was in VR, but they only lasted a few weeks." In users who already experience lucid dreams, they felt that VR increased the number of lucid dreams they had: "I have many more lucid dreams (where I know I'm dreaming). Presumably as a product of my mind constantly reminding me that VR is not real."

Out of all of the aftereffects reported by users, the dreams associated with VR were the most well received and enjoyed. These vivid dreams were described as "amazing" and "the best side effects in my opinion." One user said he "kind of digs the dreams actually. Some really wild entertainment is going on in my head at night now." One user, who no longer experienced vivid dreams after spending time in VR shared how he missed them: "God it was so beautiful having VR lucid dreams. I miss those the most from my first VR experience."

Past research has found that playing non-immersive video games can influence the dreams of the players, and that this influence can grow stronger the more immersed players feel in the game (Van den Bulck, 2004; Gackenbach et al., 2010; Poels et al., 2015). Based on this research, it was not surprising that users reported dreaming about VR, or that their dreams had become more vivid. However, the increase in the rate of lucid dreaming goes beyond previous observations with non-immersive video games. It may be that the increased agency afforded by direct manipulation in fantastical VR settings prepares the mind to exert more agency within dreams as well.

2.4.4 Reports on the duration of lingering effects

While discussing the type of aftereffects experienced when using VR, users frequently made reference to the duration of these effects. During our first pass through the comments, it became clear that the community agreed that these aftereffects eventually stopped occurring once users had spent enough time using VR. As such, we coded all comments made by users pertaining to lingering aftereffects for four temporal concepts: 1) the amount of time required to spend in VR before lingering aftereffects emerged, 2) when aftereffects began after ending a session, 3) the amount of time aftereffects lingered after ending a VR session, and 4) the amount of time that lingering aftereffects could be experienced at all.

2.4.4.1 The amount of time required in VR for effects to manifest

Users were nearly unanimous in that the aftereffects described above only occurred after extended play sessions in VR. The shortest duration mentioned in association with aftereffects was 1 h. One user specifically said he did not play for longer than 40 min at a time, so as to avoid a "VR hangover." While the lower threshold set by users was 1 h, the longest duration mentioned by users lasted an entire day. Between these limits, users mentioned other durations, including "2 hours," "a few hours," "a long session," "extended use," and "a long session of 5 h" Several users obliquely mentioned that they had engaged in shorter VR sessions prior to their first "longer" session (exactly how long was not stated), which is when their first aftereffects began to appear: "It started after I started to play longer sessions," "the first time I got it, I had spent hours in

VR playing games," "it started after my first day of extended use," and "they usually start after a users initial extended use." As such, it appears that side effects are triggered by the amount of consecutive time spent in a single session, not cumulative time spent across multiple sessions.

2.4.4.2 The time required for onset of effects upon exiting VR

We found few explicit references to when aftereffects began after exiting VR. This seemed to be because users generally understood these effects to begin immediately after a play session had ended. Comments to this effect included "[they started] after getting out of the game" and "especially right after I take it off." However, other users reported that the effects could start later, such as when "I laid down after very long Vive session," or "when I saw a grid pattern [in real life] messing with my eyes." Of all of the temporal questions concerning the aftereffects discussed in this paper, this question was the least discussed by users, and the most uncertain.

2.4.4.3 The duration of aftereffects upon exiting VR

Users discussed the duration of these effects more frequently than the time required for onset. There was also little agreement for this topic. Users reported aftereffects lasting from only "a few seconds" to "12 h" or more. Some users also reported that these effects can persist through sleep, such that they are still present the next day after waking up: "Even on the next day, e.g., during car traveling, I still have this insecure feeling, that somehow my depth sense is distorted." As such, it is difficult to draw conclusions about the "typical" duration of these aftereffects. It may be that different aftereffects are associated with different lengths, or the time spent in VR prior to the aftereffects appearance is related to the duration the effect lasts. Work by Champney et al. suggested that the time to recalibrate after performing a pointing task in VR was related to the amount of time spent in VR (Champney et al., 2007). It may be that a relationship of this sort is generally true for the aftereffects we observed here, which would account for the lack of agreement among users concerning how long these effects last.

2.4.4.4 The time required for aftereffects to completely disappear

Users were also unanimous in their agreement that these lingering aftereffects eventually stopped occurring. Some users reported effects disappeared in as little as two to 4 days. However the most common length of time reported was after "a couple of weeks" of regular VR use. Most users reported that these effects completely disappear: "It went away and has never returned to me," "I don't get a hint of it anymore," and "your brain adapts and these feelings go away." Rarely, people would speak of the effects mostly disappearing, where they would infrequently reappear: "You will get used to it and it will go away. It is pretty rare for me now." The one exception to this claim was dreams. Some users report that their dreams have remained exceptionally vivid: "Vivid dreams are a noticeable side effect and have persisted to now." Other users, who once had vivid dreams but since lost them, reported that these vivid dreams reappeared when they returned to VR after taking a break of several weeks: "[The vivid dreams] all go away after a while, but if you take a break for a few weeks they could return." There was also shown to be a significant drop in discussion regarding all of these topics in the second year, when compared to the initial year when the Vive was released. This could possibly be attributed to new users encountering these effects for the first time and reaching out to see if other users had experienced the same. Upon enough discussion, as well as a majority of these novices no longer experiencing these effects, it can be inferred that a large enough portion of the community had by then exhausted their opinions on these subjects. A significantly smaller amount of discussion was still found, but became more centrally focused around expert users sharing their past experiences and comforting new users of what is to come for them.

2.4.4.5 Discussion on the duration of lingering aftereffects

Users unanimously reported that these lingering effects only occurred after spending a significant amount of time in VR, and that they eventually seemed to disappear, typically over a period of several weeks (with the assumption that the user continues to spend significant amounts of time in VR during this period). With the exception of changes to dreams, these effects were rarely observed to reappear, even if the user took a prolonged break from VR.

It is important to draw a distinction between users *reporting* that the effects disappeared, and the effects *actually* disappearing. It is possible that the unanimity expressed in the eventual disappearance of these effects can be attributed to these effects actually disappearing, or to the users adapting to their presence. This determination would require controlled experiments that examine users' perception and behavior after prolonged exposure to VR. Ideally, this would be carried out in a longitudinal experiment. However, experiments could also shed light on this by comparing the perceptions and behavior of inexperienced VR users to experienced VR users.

We observed that few users attributed these temporal effects to specific aftereffects, but instead more generally referred to feelings of "off-ness' after VR. As such, we were unable to identify different temporal patterns for each of the aftereffects discussed above. Instead, we consider the duration of each of these effects as a whole. While we found significant agreement in the minimum amount of time required for temporal concept 1 (see Section 2.4.4), users reported significant variability in the amount of time associated with the other temporal concepts. While many factors could explain this variability, including individual differences between users, the time spent in VR, and the activities engaged in while in VR, it may also be that each of the aftereffects identified here have unique temporal properties.

2.4.5 Users' understanding of VR aftereffects

Users referred to these side effects using a range of different terms; including terms coined by the community (such as "VR hangover", or "the Matrix effect") and terms imported from medical or scientific literature, including the "Tetris effect", "dissociation", and "derealization." Other users simply referenced these effects descriptively, speaking of "weirdness", or experiencing an "off" feeling.

Regarding the Tetris effect, which was first described in association with the game Tetris, prolonged exposure to repeated stimuli resulted in continuing to experience this stimuli even after ceasing that activity (de Gortari et al., 2011). In the original context, people who played Tetris for extended durations (i.e. multiple hours) reported feeling like they could still see Tetris blocks falling in real life. Users regularly referred to this Tetris effect within plausible contexts, such as when discussing how users continue to see chaperone bounds in real life. We did not observe any instances where the Tetris effect was applied inappropriately, such as to problems with perceiving depth in the real world. The Tetris effect has been observed in VR before (Lin, 2017), however this study reported on users' seeing the environment of a specific game when they closed their eyes, not aspects of the supporting technology while acting in real life, as was reported by our users.

Others used the terms "disassociation" or "derealization" when describing these effects as well. Users were more likely to reference scientific experiments, or scientific experts when employing these terms. One user compared this to the disassociation experienced in the rubber hand illusion, where a participant can be convinced that a rubber hand is their own hand (Botvinick and Cohen, 1998). With this in mind, the user said "I think being in a new reality without seeing my hands dissociates them in real life." Another user referenced speaking with a friend who has a masters degree in psychology, who said this sounded like a form of sensory disassociation. Derealization was used in a similar context (e.g., a user said that "people do report symptoms similar to derealization"). When speaking of "derealization", another user expressed concerns as to whether this was at the root of these experiences, and what impact this could have at a societal level. Interestingly, these users never defined the terms disassociation or derealization, but instead leave the user to infer their meaning, or search out a definition themselves. This makes it difficult to gain more insight into the specific meanings applied to these terms, beyond the observations of the contexts they are used in.

By characterizing these effects as the "Tetris effect", or "disassocation/derealization", users implicitly attempted to explain these effects using these phenomenon. Other users put forward additional explanations that were not explicitly linked to a term describing these phenomenon. Possibly the most common basic explanation was that these side effects were believed to be linked to inaccurate interpupillary distance (IPD) settings on a users' HMD (e.g., "If your depth perception feels weird after taking off the Vive, your Pupillary Distance is set incorrectly."). Users' awareness of the importance of setting the IPD accurately can most likely be attributed to instructional material provided with the HTC Vive, both in paper format, online materials, and tutorials shown to the user when setting up the system. This is useful information, as it suggests that the (current) VR community may be receptive to scientific information that can help to explain or improve their experiences with the technology. Users also attributed these effects to how "your brain adjusts to the slight lag in VR tracking in intensive games, and that in real life it tries to apply what it knew in VR, which causes a slight disparity resulting in a real life ghost hand." This user demonstrated not only an awareness of the importance of minimizing latency, but also the concept of calibration in the human perception-action system (although not the terminology). The idea of calibration (Altenhoff et al., 2012) was widely accepted in this community, although terminology such as "reprogramming" was typically used instead. One concept that was notably missing was the accommodation-vergence conflict problem (Hoffman et al., 2008). While this problem was tightly linked to distance misperception issues within the scientific literature, this concept was not invoked by the community when discussing these issues.

2.5 Discussion of online themes

The analysis of consumer discussions on the/r/Vive forum suggested that VR does create lingering side effects in users after they finish a VR session, but that these effects seem to completely disappear within a relatively short period of time (at the most, several weeks). The most commonly reported side effects were perceptual side effects, which included altered perceptions of body ownership and proprioception, altered depth perception, an assortment of unusual visual phenomenon, and a lingering haptic sensation from the cord connected to the HTC Vive. We noted that behavioral side effects were also reported, including feeling a need to verify the reality of the real world through touch, hesitancy when walking or leaning against objects in the real world, and attempts to use VR locomotion and interaction metaphors in real life. Some users also reported experiencing more vivid and lucid dreams. Overall, these users agreed that these effects only seemed to occur after spending at least one continuous hour in a VR application, though the duration of any effect could vary considerably from mere moments to lasting into the next day. Most users were noted to agree that they eventually stopped experiencing reported side effects of any kind anywhere between one to several weeks after their initial occurrence. VR consumers believe this to be a by-product of the brain attempting to delineate between the transition of reality and virtual reality after experiencing increased exposure within a virtual environment during a user's first few weeks in VR, but no laboratory studies have been conducted to confirm this.

3 Interviews with twenty novice users

3.1 Methods

After completing our analysis of online consumer discussions, we sought to take the themes and lessons identified from the findings mentioned above and verify them through direct contact with novice users. Twenty students were recruited (5 females) with ages ranging from 18 to 33. These participants met a certain preset of criteria including: having experienced less than 1 h with any form of virtual reality, being housed local to the surrounding area, having enough space in their home to use the device, affirmation that they would be the sole user of the device, consent in the use their personal Facebook account to login to the device, consent to participate in two separate interviews, and affirmation that they would return the device in working condition at completion of the study. Participants were encouraged to purchase any games or applications that were of interest to them, which would remain their property even after the 4 weeks, although it would not be required.

Upon enrollment, we explained the procedures and our expectations to participants before requesting their informed consent. After consenting, each participant completed a demographic survey and given a $50 visa gift card. Participants were then loaned a single Oculus Quest device which included a head-mounted display and two controllers in order to play any virtual reality games or applications of their choosing over the course of 4 weeks. Participants were asked to spend anywhere between five to 10 hours of time engaging in VR each week, and were informed that they would be contacted for two distinct interviews across the 4 weeks. Ten participants were interviewed after their first and third weeks of receiving their device, with the remainder being interviewed after their second and fourth weeks. After taking their headsets home, participants were emailed a link to a 15 min orientation session explaining how to navigate the menus of the Oculus Quest in order to find games and applications. After conducting both interviews and returning their devices, participants were compensated with an additional $75 Visa gift card.

3.2 Qualitative analysis of semi-structured interviews

As part of the semi-structured interviews, participants were asked if they had "noticed anything interesting or strange" after leaving a VR session; participants were specifically *not* asked about any of the phenomenon we observed in our analysis of online discussions. Fourteen users mentioned experiencing something similar to the lingering effects we observed in online discussions. Brief quotes from each of these participants are reported in Table 1. The types of after-effects experienced varied between participants. Most experienced an effect that was unique to them, however, several reported experiences that shared a common theme of disruption in body ownership (see P2, P5, P12, and P18). Participants discussed both lingering effects that happened right after removing the HMD (see P3, P7), as well as effects that occurred significantly later (see P6, P20). The amount of time spent in VR before exiting seemed to be relevant as well;

TABLE 1 Participant quotes that highlight a variety of lingering effects that were experienced.

Participant ID	Participant Quote
P1	"*after I picked up my box of goldfish, I was just like, 'I wonder what would happen if I dropped it right now'. I just wanted to let it go*"
P2	"*now I'm questioning even basic things and it's like, making me step down harder on myself being like, 'I know where my hands are!*"
P3	"*in the headset, you get used to the images with the graphics not being super high def, like HD, and then when you take the headset off, you can see like, so crisp and so clear*"
P4	"*like the peripherals, while I'm looking at the screen, like the background, kind of just makes me think of VR*"
P5	"*when I'm, you know, looking at a screen in my hands, I get this sense that my thumb's are like, not part of my body. Which is very strange*"
P6	"*right after I went to sleep, and then I want to have my eyes shut, I guess I felt like I was looking into a screen type thing*"
P7	"*definitely feel like you're opening your eyes more when you come back out of VR. So just like realizing how things are like far away like the walls I guess*"
P10	"*it just feels like when you try to grab something or you try to reach for something it's like, your arm's extended or your grabbing motion is kind of more game like*"
P11	"*The world seems less detailed than I feel like the game is with having brighter colors and more detail. . ..I'll look and I'll be like, Oh! it's not as bright anymore*"
P12	"*I feel a disconnect with my hands and the rest of my shoulder . . . like they're the disembodied hands that you see, when you're playing in the Oculus*"
P15	"*I start to adjust in the real world with moving my head as slow or as fast as I would in VR because that's what my eyes are used to*"
P17	"*when I closed my eyes, it definitely felt like I was, I don't know, just like rolling around. It wasn't like, nauseous or anything, it was honestly quite fun, but it was just like I felt moving*"
P18	"*a second I was like surprised that I had legs that were carrying me instead of just standing in place and then I felt myself moving the joystick in my finger even though I was walking*"
P20	"*but now it's like, my dreams are kind of in VR a little bit*"

P2 specifically referenced spending hours in a single VR session prior to saying "*I know where my hands are! This is stupid I have to say this, but I know where they are in proximity to myself!*".

Across participants, the most common types of effects mentioned included perceptual effects such as a questioning of body ownership, questioning of hand ownership or proprioception, distortion of depth perception, and increased visual sensitivity to real world imagery. Participants also mentioned behavioral lingering effects, such as attempts to use VR interaction metaphors in real life, and increased lucidity in dreams. These mirror the three major types of lingering effects we observed in our analysis of online discussions. Similarly, we saw that the lingering effects experienced by one person could vary wildly from another. In contrast, six of our participants never discussed anything akin to our findings from online discussions, indicating that these effects are not necessarily a universal phenomenon. For those who did experience lingering effects, many were shocked or intrigued by them (as P3 said, "*it is kind of exciting*") and referenced attempting to further understand or recreate them. However, apart from dreams, participants again referenced instances of these effects disappearing anywhere between a few seconds to minutes after having noticed them, and that they disappeared completely "*after that first week, upon which I felt kind of sad about it because it was pretty cool*" (P2). Participants generally either referenced these effects in the first interview, and then indicated they had grown less common or disappeared completely by the second interview, also supporting our observation that these effects tend to disappear a few weeks after they begin.

4 Conclusion

Within both studies, a variety of lingering effects was shown to be experienced across users regardless of how they spent their time in VR. These effects were typically met with surprise, confusion, or excitement, persisted briefly after exiting VR, and stopped manifesting completely over the course of several weeks. These effects most commonly manifested as perceptual effects (e.g., uncertainty about where one's hands are located) or behavioral effects (e.g., attempting to teleport in real life), and also sometimes manifested as changes in the vividness of participants' dreams. While our primary findings come from our analysis of 2 years of online discussions on the/r/Vive subreddit, these were substantiated by our interviews with twenty novice VR users who we followed over the course of 4 weeks. The primary element missing from the online analysis was a sense of how common and consistent these lingering effects are. While not definitive, the results of our interviews suggest that people often experience lingering effects (in our case, 14 out of 20), but that these effects can differ wildly from one person to the next. The interviews also gave some clarity concerning when these lingering effects typically completely disappeared, as participants were in general agreement that these effects had grown significantly less common, or ceased altogether by the end of the 4 weeks.

These findings illustrate how the experiences of novice users can differ from users with more prior experience. This has implications for both how we introduce VR to new users, and for how we study the effects VR has on users. When introducing VR to novice users, it may be helpful to caution them about the possibility of these lingering effects, but also to explain their typical course of progress (namely disappearing over the course of several weeks). This may potentially be of help to new users who experience stronger lingering effects that they find unpleasant, and are thus more likely to stop using VR. It also underscores the need for researchers to understand and report how much prior experience their users have had with VR in the past. While these effects occurred upon leaving VR, it is plausible that similar differences may occur while using VR; while these may not stand out to individual users, as everything they are experiencing is novel and somewhat strange, if such differences occur they may make it more difficult for researchers to draw firm conclusions that pertain to their intended audience. These findings also open up new, interesting questions, such as why lingering effects occur, what experiences lead to the different sorts of effects reported, and whether these effects truly become extinct after several weeks, or if users have merely adapted and grown accustomed to them.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Clemson University IRB. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2022.880634/full#supplementary-material

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