Barriers to Photosensitive Accessibility in Virtual Reality

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ABSTRACT

Virtual reality (VR) systems have grown in popularity as an immersive modality for daily activities such as gaming, socializing, and working. However, this technology is not always accessible for people with photosensitive epilepsy (PSE) who may experience seizures or other adverse symptoms when exposed to certain light stimuli (e.g., flashes or strobes). How can VR be made more inclusive and safer for people with PSE? In this paper, we report on a series of semi-structured interviews about current perceptions of accessibility in VR among people with PSE. We identify 12 barriers to accessibility that fall into four categories: physical VR equipment, VR interfaces and content, specific VR applications, and individual differences in sensitivity. Our findings allow researchers and practitioners to better understand the meaning of photosensitive accessibility in the context of VR, and provide a step towards enabling people with PSE to enjoy the benefits offered by immersive technology.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**; *Accessibility design and evaluation methods.*

KEYWORDS

accessibility, virtual reality, photosensitive epilepsy

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1 INTRODUCTION

Photosensitive epilepsy is a neurological condition characterized by recurrent seizures in response to certain visual stimuli, particularly flashing or strobing lights and repeating patterns. Interacting with technology can be challenging for people with photosensitive epilepsy due to the persistent threat of flashing or strobing lights suddenly appearing and potentially causing a seizure while partaking in common activities of reading social media [39, 65], playing video games [24], or watching films [66]. Immersive forms of technology such as virtual reality (VR) have the potential to be even more hazardous from the perspective of photosensitive accessibility than traditional 2D systems [71] for several reasons. Light sequences that cover a greater proportion of the field of view are more likely to induce seizures [25], which means that VR headsets occupying a wider range of the visual field than standard 2D systems are potentially riskier for people with photosensitivity to use safely. Additionally, maintaining background ambient room illumination is a key technique used by people with photosensitivity to manage sensitivity and reduce contrast [25], but VR headsets eliminate ambient room illumination and increase overall relative screen contrast [71]. Exposure to seizure-inducing flashes for people with photosensitive epilepsy can have long-term negative effects on physical and mental health [74], and can even lead to death [29]. As VR becomes more prevalent in the activities of everyday life, such as education [23], entertainment [8], and employment [75], understanding how people with photosensitive epilepsy can safely participate in immersive VR worlds is imperative.

Many VR games and platforms come with a general warning encouraging anyone who has experienced seizures to consult a doctor before participating (e.g., Meta Quest[1]). People with photosensitive epilepsy have historically been excluded from VR studies out of safety concerns (e.g., [32, 33, 47]), limiting the potential for future research that directly benefits people with photosensitivity. Data about incidence rates of seizures triggered while participating in VR are limited. In a review of medical literature, Tychsen & Thio point out that there are no reports of photosensitive epilepsy evoked by VR headset usage despite the rapid proliferation of commercial VR products in the past five years [71]. Nevertheless, people with photosensitive epilepsy are often left out of conversations about VR, despite the potential benefits this technology might offer if it could be used in a safe and accessible manner.

The benefits of VR systems are apparent across many domains. Virtual reality applications have been used in medical capacities to aid in exposure therapy [5], stroke recovery [41, 58], and pain management [68]. Job training is quickly growing as an application area for VR in domains such as hospitality [45] and construction [31]. Recent projects have even used VR systems to ease users with

[1]https://www.meta.com/legal/quest/health-and-safety-warnings/

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disabilities such as schizophrenia [62] and autism [13] into the workforce through virtual job training sessions. Social VR platforms such as VRChat and RecRoom can be an important source of social support for LGBTQ individuals [43] and can support positive mental health outcomes by encouraging socialization to combat loneliness [21]. Certain diseases, such as depression, anxiety, dementia, and arthritis, are up to eight times as likely for people with epilepsy compared to the general population [40]. The high rate of comorbidity among those with epilepsy suggests that many individuals with photosensitive epilepsy would likely benefit from being able to take part in virtual reality systems built to address challenges associated with other disabilities in terms of medical treatment, job training, socialization, and more. All of these VR applications could hypothetically benefit an individual with photosensitivity, but it is unclear whether they could inadvertently provoke seizures and therefore be inaccessible. To better understand the meaning of photosensitive accessibility in VR, we focus our inquiry on two research questions:

- **RQ1**: What are the current perceptions of VR accessibility for people who have photosensitive epilepsy?
- **RQ2**: What changes in design would make people with photosensitive epilepsy feel safer in VR?

In order to address these questions, we conducted a series of semi-structured interviews with people who have been diagnosed with photosensitive epilepsy or experience symptoms consistent with photosensitivity. We conducted a thematic analysis of interview transcripts and identified 12 barriers to accessibility that can be grouped into four thematic categories: physical VR equipment, VR interfaces and content, specific VR applications, and individual differences in sensitivity. We additionally generated two themes related to positive perceptions of VR among people with PSE and participants' ideas for improving VR accessibility. Our paper makes the following specific contributions:

(1) Identification of barriers to accessibility in VR for people with photosensitive epilepsy
(2) Summary and contextualization of participants' ideas for improving accessibility
(3) Discussion about future research directions for photosensitive accessibility in VR

2 RELATED WORK

Our work builds off of prior research on accessibility for people with photosensitivity and prior work on safety and accessibility in VR.

2.1 Photosensitivity and photosensitive epilepsy

Photosensitivity is a broad term used in medical literature to describe skin, eye, or neurological reactions to light. Following convention in photosensitive epilepsy literature (e.g. [25]), we restrict the meaning of the term "photosensitivity" to only neurological response to light, color, and patterns. The term "photosensitive epilepsy" is used to refer to a formal diagnosis of visually-provoked seizures or epilepsy. We will use person-first terminology throughout this paper (i.e., "person with photosensitive epilepsy"), as Noble et al. found that this usage was preferred among people in the epilepsy community through an online survey [51]. The Web Content Accessibility Guidelines (WCAG 2.0) [16] define seizure-inducing light sequences according to four characteristics: area, frequency, color, and duration of a flash. If a flash exceeds specific thresholds for all four characteristics, it is considered potentially seizure-inducing and should be avoided in online content. These thresholds are based on empirical results from a series of EEG-based medical trials where patients with photosensitive epilepsy were exposed to certain light stimuli on a television screen seven feet away [26, 34, 73]. Brain responses were recorded after exposure to the stimuli and aggregated standards were developed from these results. It is not clear to what extent these standards are applicable to immersive VR headsets, as they were developed before modern head-mounted displays (HMDs) were commonly used. Fisher summarizes current research on photosensitive epilepsy across a range of topics including characteristics of seizure-inducing light sequences based on medical trials, seizure prevention methods, and the history of light-induced seizures triggered by modern technology [25]. Several works over the past ten years have examined methods for reliably detecting seizure-inducing light sequences in films and videos [4, 7], GIFs [65], and interactive data visualizations [64]. South et al. additionally conducted qualitative interviews to understand people with photosensitivity's perspectives on safety and accessibility within social media sites such as Twitter (X) and Reddit. In this work, we apply qualitative methods to better understand the barriers to accessibility that people with photosensitivity face when attempting to participate in VR.

2.2 Safety and accessibility in VR

As VR has matured into an active field of HCI research, researchers have examined barriers to accessibility in VR across different dimensions of ability. A significant amount of prior work has focused on accessibility for users with low vision or blindness in VR [19, 38, 60, 72, 76–78]. Accessibility in AR/VR for users who are deaf or hard of hearing (DHH) has been examined in the context of live theater [69] and education [22, 54], in addition to recent work exploring the design space of tactic and visual methods to replace sound cues in VR [37, 44]. Managing the physical equipment associated with current VR technology, such as controllers, headsets, and cords, can be barriers to accessibility for people with mobility impairments [48]. Several methods have been proposed for improving comfort and level of control within VR systems for users with limited mobility [27, 46, 53]. Gerling & Spiel characterize the inherent ableism present in modern VR technology that makes access challenging for users with physical disabilities (i.e., limited mobility) [30].

Research into VR accessibility for cognitive, neurological, and developmental disabilities has been relatively more limited than other types of disabilities. Hodge et al. explored the design and use of VR experiences for people with dementia through interviews [35], while Moyle et al. found that a VR intervention had a positive effect on level of pleasure and alertness felt by patients with dementia [49]. Ahsen et al. designed a customizable AR application intended to be used by therapists in conducting learning activities with autistic children [1]. Some studies in VR accessibility account for more than one disability type. Through a series of multidisciplinary workshops with stakeholders from various domains, Creed et al. identified distinct barriers to access in AR and VR for people with physical, visual, and auditory impairments, in addition to barriers to access for neurodivergent populations [20]. We build on prior work in VR accessibility by using qualitative methods to examine the experiences of a community that has not previously been the focus of VR research: people with photosensitive epilepsy and other conditions related to photosensitivity.

Our work additionally draws from recent research into safety and harassment in VR. While our work is not explicitly about harassment behaviors, prior work in this field is relevant due to the physical safety consequences of encountering seizure-inducing content for people with PSE. Harassment behavior in VR is prevalent and often targets marginalized groups, such as women [59]. Freeman et al. examined online harassment in social VR with particular emphasis on marginalized communities, including people with disabilities, and highlighted the emergence of *embodied harassment* within immersive VR environments [28]. Blackwell et al. summarize challenges in platform governance for limiting harassment in social VR, including the subjective and highly personal nature of what constitutes harassment, a lack of standardization among platform controls, and increased intensity of harassment due to the embodiment and immersiveness associated with VR [10]. Due to the inherently social nature of harassment, prior work in this area has primarily focused on harassment in social VR environments (e.g., AltspaceVR, VRChat, Meta Horizon). Our work encompasses both social and non-social applications of VR with a focus on safety for people with photosensitivity.

3 METHODS

We conducted a series of semi-structured interviews with five people with varying levels of photosensitivity to understand their perceptions of accessibility in VR. Interview transcripts were then examined with inductive thematic analysis [14] to generate themes corresponding to barriers to accessibility in VR.

3.1 Recruitment & Participants

We recruited five participants with photosensitivity for interviews (1 male, 4 female). All five interviews took place remotely via voice or video call, according to each participants' preference, and lasted between 30 and 45 minutes. Interviews were conducted by a single experimenter. Participants were recruited through social media (Twitter/X, Reddit, and Facebook) in collaboration with local and international nonprofit organizations dedicated to supporting epilepsy research (Epilepsy Foundation and Epilepsy Society) and were compensated in the form of a $25 Amazon gift card upon interview completion. Participants had to be at least 18 years old and self-report having symptoms consistent with photosensitive epilepsy or photosensitivity. Table 1 summarizes participant demographic information. Our sample size was limited due to the small pool of potential participants who simultaneously have photosensitivity, are active on online support networks for photosensitive epilepsy, and are physically able and willing to participate in a virtual call with researchers.

Due to the wide range of conditions possible under the umbrella term of "photosensitivity", participants were asked to describe their experience with photosensitivity in their own words, using details such as their level of sensitivity, specific triggers, symptoms, or formal diagnoses. P1 developed photosensitive epilepsy in her forties after a car accident. She describes her sensitivity as "exquisite" and has trouble navigating public spaces, participating in video calls, and watching films due to her extreme sensitivity to flashing lights. P1 experiences "auras" [63], a term that is used by individuals with epilepsy to describe a "warning" they feel before they have a tonic-clonic ("grand mal") seizure. Auras are described as taking different forms for different people – to some they manifest as a sudden, intense feeling while others might experience an aura as a visual disturbance or an unusual smell or taste. P2 was diagnosed with photosensitive epilepsy at a young age and experiences visual auras that serve as a warning before tonic-clonic seizures. P2 has been on medication and seizure-free for approximately 20 years, but remains particularly sensitive to rapidly flashing lights on the periphery of computer screens. P3 was diagnosed with photosensitive epilepsy at eight years old and experiences both absence ("petit mal") and tonic-clonic ("grand mal") seizures triggered by many different types of flashing lights. P4 was also diagnosed with photosensitive epilepsy at eight years old and experiences absence seizures triggered by flashing lights (e.g., strobe lights, camera flashes) and 3D images (e.g., optical illusions). P5 was diagnosed with severe hemiplegic migraines and focal seizures triggered by photosensitivity in her early 40s. She remains sensitive to strobe lights, flash photography, sudden movement on screens, and green flashing lights.

In terms of participants' experience with VR, four out of five participants reported limited prior experience. P1 has never used VR. P2 occasionally uses a family member's Oculus headset to play games and hopes to eventually purchase his own VR system. P3 used a family member's VR headset to play games once several years ago and has intentionally avoided using VR ever since. P4 once played games in VR using a PlayStation with a group of friends and feels hesitant to try VR again due to safety concerns. P5 tried VR once with family members and has not attempted to use VR since.

3.2 Interview protocol

Participants were first asked to provide background information about their experience with photosensitivity, including details such as their specific diagnosis, the number of years they have experienced photosensitivity symptoms, the severity of their symptoms, and their level of sensitivity to common triggers (e.g., flashes, colored lights, stripes). We then asked participants about their level of familiarity with VR. Participants who said they had used VR before were asked to recall as many details as possible about the hardware and software used during these experiences. Participants with no prior VR experience were asked to provide additional context about their decision to not use VR, with experimenters asking guiding questions about whether they had ever considered using VR before and, if so, how that decision was made. As the final step of the initial questioning, all participants were asked about their

ID	Gender	Age	Ethnicity	Diagnosis	Prior experience with VR
P1	Female	50+	White	Photosensitive epilepsy	None
P2	Male	25-34	White	Photosensitive epilepsy with auras	Limited experience
P3	Female	18-24	White	Photosensitive epilepsy	Limited experience
P4	Female	25-34	White	Photosensitive epilepsy (absence seizures)	Limited experience
P5	Female	35-44	White	Hemiplegic migraine and focal seizures triggered by photosensitivity	Limited experience

Table 1: Demographic information for five participants included in semi-structured interviews about VR accessibility.

general perception of the current state of accessibility in VR for someone with PSE. When developing our interview protocol, we anticipated that participants might not have experience with VR due to barriers to accessibility. To help guide discussion among participants without VR experience, we created a video elicitation protocol consisting of four videos explaining various aspects of the process of participating in VR and accompanying questions related to the content of each video.

The first video explains common applications of VR and showed clips of users participating in different VR applications such as gaming (e.g., Beat Saber), social platforms (e.g., VRChat, Rec Room), virtual co-working spaces (e.g., Horizon Workrooms), job training (e.g., construction simulations), and medical treatment (e.g., physical therapy). Participants were asked to describe their level of comfort with various applications of VR, including those shown in the video and applications participants had used in the past, for participants with prior experience. Participants were also asked to discuss whether there were certain applications of VR that seemed riskier or less safe than others. The second video covers the physical equipment associated with VR, including headsets, controllers, and body-tracking. Participants were asked to talk about any accessibility concerns they had related to the physical equipment or setup process required for VR systems. Participants were explicitly asked to discuss the accessibility of HMDs if the topic was not organically brought up by participants in earlier responses. Finally, participants were asked to describe any changes to physical VR equipment they could imagine that might improve photosensitive accessibility. The third video focuses on different kinds of user-generated content in social VR platforms. We chose to include this video because several instances of seizures triggered by VR have occurred in response to user-generated content on social VR platforms (e.g., [3, 36]). Participants were asked about their accessibility concerns related to social VR and custom user-generated content. Participants with prior VR experience were asked to recount any experiences they may have had with encountering harmful content in social VR. Finally, participants were asked to talk about any ideas they had for improving safety and accessibility in social VR. The final video summarizes safety mechanisms that are currently implemented in social VR platforms to help users remove themselves from hazardous situations, such as the "talk to the hand" gesture for blocking users implemented in Rec Room [2], Safe Mode [3] in VRChat, and Safe Zone[4] in Horizon Worlds. Participants who had prior VR experience were asked about their awareness and degree of satisfaction with the safety mechanisms identified by the experimenter. All participants were asked to talk about the usefulness of current safety mechanisms in VR from a photosensitive accessibility perspective. Participants were also asked to describe any other ideas they had for safety mechanisms that would be beneficial for people with PSE in VR.

All four videos were tested for safety using PEAT[5], a photosensitive risk detection program. However, we still gave participants the option to skip the videos if they had safety concerns about watching the videos. Only one participant had no prior experience with VR (P1). This participant opted to not watch the videos out of safety concerns due to their extreme sensitivity, so we instead gave verbal summaries of each video to the participant to guide the discussion. For participants with prior experience in VR, we prepared a list of questions to better understand participants' perceptions of VR accessibility and ideas for improving VR accessibility in the future. Our interview protocol, questions, and videos are available at https://osf.io/gp53t/.

3.3 Thematic analysis

We chose to use an inductive thematic analysis method due to the flexibility these methods allow for when generating themes from the data [15]. We follow Bowman et al.'s recommendations for reporting methodology and results of thematic analyses [11]. The aim of this work is experiential, with a focus on reporting the lived experiences and perspectives of five people who have photosensitivity. The thematic analysis was completed by the lead author, following the six phases identified by Braun & Clarke [14]. The familiarization process took place first during manual transcription of interviews, which was done by the lead author, and then during a subsequent phase of reading through the complete interview transcripts. The coding process was iterative, with codes being added or merged as the lead author repeatedly examined the five transcripts. Initial themes were generated from the codes by the lead author and refined through comparison of themes and discussion among the authors. We conceptualize our final six themes as *patterns of shared meaning* [14] uniting potentially disparate data that share a central concept (Table 2). The first four themes describe barriers to accessibility, while the final two themes are related to photosensitive accessibility in VR more broadly. In the next section, we describe the six themes generated through our analysis process and include quotes from participants illustrating each concept.

[2]https://recroom.com/comfortandsafety
[3]https://docs.vrchat.com/docs/vrchat-safety-and-trust-system
[4]https://www.oculus.com/horizon-worlds/community/

[5]https://trace.umd.edu/peat/

4 RESULTS

4.1 Physical VR equipment

The most frequently mentioned barrier to accessibility was the physical equipment associated with using VR, such as HMDs and controllers. Of the four participants who had prior experience with VR, three mentioned feeling uncomfortable with the physical headset they used when trying VR. P5 explained that the heaviness of the headset caused an uncomfortable feeling of disorientation, saying *"[The VR headset] was just an incredibly heavy and I felt something was moving but my body wasn't moving and it was very, very disorientating to me."* Several participants shared concerns about how **wearing a VR headset could worsen the impact of a fall** if someone were to have a seizure while wearing the equipment. As P4 explained, the headset and hand controllers could complicate the emergency response after having a seizure: *"Especially because not only you could lose your balance, but you've got things in your hand and you got something on your head, that if you start having a full seizure, then it adds to the impact of not only do you hit the floor, but then you've got equipment on your head that someone's got to get off. It creates more chaos than is necessary."*. Similarly, P3 explained how a laptop would feel safer than a VR headset if she were to have a seizure and fall: *"But also say I have a seizure now.* ***The laptop's not going to crash on my head.*** *I'm not going to hit my head on the laptop whereas the VR headset, obviously you're completely immersed in it. You're don't really know exactly what's happening around you, so you're more likely to have some sort of accident. And if you do, if I had a seizure I'm going to hit my head and the headset's on my head."* One participant (P2) reported that he felt comfortable with the physical VR equipment that he has used in the past and did not feel that the equipment was a barrier to accessibility.

P3 mentioned that **VR headsets make it more challenging to remove herself from flashing light on the screen**, in comparison to a laptop: *"I think the difference is like — say I'm looking at a laptop now — it's not all around me so I can still see actual reality and if I need a break from the screen, I can literally just turn away from it and I'll be fine."* Similarly, P5 described instances of *"putting a pillow over [her] face every five seconds"* while watching films with flashing lights to remove herself from the hazardous light stimuli. Both participants pointed out that this approach of removing oneself from flashing lights is less practical in a VR environment due to the physical equipment. It is worth noting that individuals with photosensitive epilepsy cannot simply close their eyes within the VR headset to avoid the light stimuli, as closing the eyes can cause a diffusion of light that increases photosensitivity [42]. Covering one eye with a hand or other solid material as soon as pre-seizure symptoms are felt may reduce the risk of seizures [25], although this action is once again impractical when the individual is wearing a VR headset.

P1 had never tried a VR system but felt very strongly that wearing a VR headset would be detrimental to her health due to her sensitivity to screens with 60 Hz refresh rates: *"I suspect that that just takes a regular screen resolution 60 Hz or a multiple of 60 Hz and* ***puts it even closer to your eyes*** *and I – I'm not putting that on my face. I cannot do 60 Hz again. It's within seconds and I will literally throw up on the keyboard and that assumes I'm well medicated. If I'm not well medicated then I'll likely fall over. I don't have grand mal seizures, I have partial seizures but I do fall so I'm not looking at – I'm not going to put something on my face that has 60 Hz."*

4.2 VR content and interfaces

Several participants explained that content viewed in VR felt less predictable than content viewed in a traditional 2D context, particularly when other users are involved. This **unpredictability made VR seem less accessible**, as P4 states: *"I think because it's not a platform that I regularly use and so I don't know what to expect. And with other people I feel like the more people you put in a situation that's more creative, that can be triggering for me. I'd be more cautious about [VR] than say looking on Twitter or looking on Instagram when there's not necessarily gonna be as much – as many variables to kind of affect me."* P5 felt concerned about being exposed to unpredictable movements beyond her control when using VR: *"That's fine if I'm in charge of the movements but if a lot of movement is coming from different places on the screen which I am then supposed to orientate myself in relation to, I would find that hard so I don't know if it would work for me or not."* Two participants referenced negative experiences with video calls on Zoom to explain the importance of predictability when interacting with other users in virtual environments. As P1 explains her reasoning for not using VR: *"The very first reason is the unpredictability. I have been on Zoom calls where somebody just pops an Excel spreadsheet on the screen while they're screen sharing and I'm out for a week. So I need to have some predictability."*. Similarly, P5 explained how the unpredictability of the green outline indicating the current speaker on Zoom calls triggered her symptoms: *"I struggled with Zoom stuff when you have people in boxes and when I struggled was when they were highlighted in green."* Both participants used these Zoom examples to illustrate how it can be hazardous to participate in online spaces where fellow users produce sudden flickers or color changes that may show up on the screen of someone with PSE. Because changes to the light stimuli are tied to another user's actions, the interfaces are unpredictable and more hazardous for people with PSE. Participants explained that predictability is crucial because their photosensitivity symptoms can often be triggered within seconds of being exposed to hazardous light sequences [26].

Even though four out of the five participants had tried VR before, none of the participants considered themselves to be particularly familiar with VR interfaces. The participants' lack of familiarity led them to feel concerned about their **ability to quickly take action to remove themselves from a situation with hazardous light stimuli**. To demonstrate this point, P1 described her ability to quickly remove troublesome patterns in Microsoft Word and Excel: *"I can at least look at that and I know how very quickly to make the lines and columns disappear so I can work with that."* P1 did not feel the same level of confidence in her ability to quickly remove hazardous stimuli in an immersive VR environment. As P1 explains, her discomfort comes from both a lack of familiarity with VR systems and prior experiences where other individuals have not been sensitive to her accessibility needs: *"Some of that is about the fact that I don't have experience with it and some of it is because of the things I do have experience with. I deal with people who have who just do things. I go to the doctor and he's supposed to know all of my problems but his habit is to turn on the lights so he does.*

Theme	Codes
Physical VR equipment*	Risk of complicating a fall during a seizure Screen refresh rate triggering seizures Size and position of screen near eyes Inability to quickly break immersion Disorientation caused by heaviness of headset
VR interfaces and content*	Unpredictability of content and social interactions Lack of familiarity about how to quickly remove hazardous content Additional degrees of freedom compared to 2D content
Specific VR applications*	Seizure risk heightened by stress or exhaustion in work, training, or medical applications Pressure to use VR continuously for extended periods of time
Individual differences in sensitivity*	Difficulty making educated decisions based on vague flash warnings Applying non-immersive standards to VR
Positive perceptions of VR usage	Greater control over surroundings than in real-life scenarios Social and health benefits
Ideas for improving VR accessibility	Automated testing for flashes Warnings about flashing lights Customization for visual displays Interdependence

Table 2: Six themes generated during the thematic analysis process. The first four themes (indicated by *) relate to barriers to accessibility in VR that were discussed by participants during our interviews. Two themes relate to VR more broadly, representing positive perceptions of VR among participants and ideas for improving VR mentioned by participants.

It's just people behaving automatically or without thought generally or specifically not being able to truly understand the implications of a condition like this, so they just do things they don't think are a problem."

4.3 Specific applications in VR

Our interview protocol explicitly asked about a handful of commonly encountered applications for VR, including video games, social VR, virtual workplaces, job training, and medical treatment or therapy. When participants were asked to describe their perceptions about the accessibility of remote work in virtual environments facilitated through VR equipment, such as Meta's Horizon Workrooms [6], participants voiced **concern about the accessibility of a VR workplace**. P4 explained that because her photosensitive epilepsy symptoms tend to be worse when she is stressed or tired, a workplace in VR could be more dangerous for her than other recreational VR applications: *"I feel like I'm still approaching with caution because when we're in a working environment, it's easy to get stressed and if your tired and then add that on, it feels more like a recipe for disaster than even playing a game when I'm awake and I can have a coffee or anything like that. Like sometimes you feel like your brain is tired even when you do regular work. Let alone when you put a VR on it and my brain is trying to figure out what's going on."* P4 felt that other applications of VR that require high mental effort or stress, such as job training or medical treatments, could also be particularly risky for people with photosensitive epilepsy whose symptoms are exacerbated by stress and exhaustion. P3 was optimistic that a work VR application might involve less movement and flashing lights than recreational VR applications, but remained cautious about the expectation for her to spend long periods of time in a VR workplace: *"I guess the work one would be a bit more accessible mainly because it would be less movement, if you want to call it that. I still – I think if someone said 'Oh you have to work in total VR the entire time' I'd be like, I don't think that's a good idea. I feel like I'm going to make myself unwell."* P5 was concerned about the accessibility of a virtual workplace due to her sensitivity to movement outside of her control: *"I haven't done anything like that. I imagine it would be difficult. [...] If someone says 'Look there, look there, look there' it gets difficult. Because even with work, I mean I'm pretty functional now, I can do pretty much do most things, but I do find it quite difficult if somebody is standing over me and pointing and making me point. If on a screen, if I'm continually having to follow someone else's lead rather than my own and things are coming out and coming at you – if it's very self-directed I have a better chance."*

[6]https://forwork.meta.com/horizon-workrooms/

4.4 Individual differences in sensitivity

Participants frequently qualified their statements about VR accessibility with acknowledgements that other people with photosensitivity may have different experiences or perspectives depending on their **personal triggers and degree of sensitivity**. Individual differences in sensitivity make it challenging for someone with epilepsy to make educated decisions based on vague or generic warnings about flashing lights. For example, P5 explained that she is not sensitive to white flashes that seem to affect other people with photosensitivity: *"I don't know why but for me the white strobe is very tolerable. But what would completely get me is green. Suddenly someone throwing in loads of green."* A generic warning about flashing lights within a VR world might not apply to P5 if the flashes only involve white lights, but she would have to risk entering the world and being triggered to know with confidence.

This poses a barrier to accessibility that is not necessarily unique to VR, as it is challenging to reliably determine whether a light sequence will be triggering for a specific individual across all media types. Accessibility standards such as WCAG 2.0 define thresholds for what can reasonably be considered "seizure-inducing", but these guidelines are drawn from aggregated responses to EEG-based medical trials (e.g., [26, 73]) and will not always align with an individual person's sensitivity. For example, P2 describes being triggered by a very small flashing light that falls below the area threshold used in WCAG 2.0 to identify seizure-inducing content: *"I've watched YouTube videos where they had like a thin strip, just a tiny strip of a health bar at the bottom of the screen and when it got really low it started flashing red, yellow, red, yellow, red, yellow. Sometimes other blues and colors in there as well. And even though that was like 1% of the screen that still bothered me and I could not look at that particular thing portion of the screen at all."* Furthermore, the studies from which these standards are drawn measured brain responses while participants were watching experimental stimuli on a television set seven feet away and are not guaranteed to generalize to immersive environments where a screen is inches from the user's eye. This means that even efforts to automatically test VR content for adherence to formal web accessibility standards would require **applying non-immersive 2D standards to 3D VR content**. The complexity of VR worlds suggest that two people might have completely different experiences in the same VR world, making it challenging to produce reliable, consistent warnings for immersive virtual content.

4.5 Positive perceptions of VR usage

After being asked about their perceptions of VR accessibility and describing barriers to accessibility, several participants additionally mentioned **positive aspects of VR usage** that they see for people with photosensitive epilepsy. P2 was the most comfortable with VR out of the five participants. He attributes his comfort to an awareness of his triggers: *"I figure I know my triggers, like I know everything that affects me. So if I ever feel like I'm in a situation where things are going wrong or I mean a flashing zone or whatever. I'm most likely just going to try and take the headset off and leave as quickly as possible."* P2 expressed that he is well-medicated and has been seizure-free for 20 years, which plays into his confidence in safely using VR. Additionally, P2 experiences auras that appear in his visual field before a seizure, effectively giving him a warning that allows him to safely remove the VR headset and go to a safe location before he is in danger. P2 explained that he felt that VR offered him more control over his surroundings than he would find in real-life scenarios with flashing lights: *"This is different from going to a club in real life. Like if I go to a club in real life I can't just tell them to stop strobing the lights. But if I'm in VR I can just take off the headset and turn off the power and then I'm gone."* P2's experience suggests that for individuals who have their symptoms under control and are aware of their triggers and auras, virtual experiences in VR might even be safer than their real-life counterparts. Despite her concerns about barriers to accessibility, P5 felt optimistic about the potential for positive VR experiences in the future for people with epilepsy: *"The temptation is to give up but it's possible that, you know, VR might have some kind of application that helps people, that helps to create connections in the brain, or helps people who are not mobile to visualize themselves as mobile. So it's an uncertain area."*

4.6 Improving VR accessibility

Participants had several ideas for how VR might be made more inclusive and accessible for people with photosensitivity.

Automated testing for flashes: Automated testing for flashing light in VR environments has the potential to make the environment safer and improve user confidence. P3 said that she would want to try VR again if she could feel confident that the system had been thoroughly tested for flashing lights: *"Yeah, I mean, if there was no sort of flickering, you know, if it had been fully tested to make it safe. Because then I'd be like 'Oh 100% let me do it, give it a shot.' Why not? But without that it's a bit dodgy."*. Testing content for flashing lights is common practice in film and television [7, 17, 50] but is less commonly used with interactive media due to the unpredictability of interactive content [65]. Methodically testing all possible combinations of states that could produce a flickering effect is feasible with simple interactive webpages or data visualizations [64], but would require a prohibitive amount of computing power for more complex VR applications. Crowdsourcing information about flashing lights in individual VR games, applications, or worlds could be an alternative approach for identifying flashing lights in VR worlds that are too complex to automatically test for seizure-inducing sequences given the current efficiency of testing algorithms. Crowdsourced warnings about flashing lights are occasionally found in social VR worlds through both formal and informal methods (Figure 1). VR systems can encourage users to flag content that contains flashing lights to create crowdsourced warnings that people with PSE can use to safely navigate virtual environments.

Warnings about flashing lights: Several participants commented on the need for prominent warnings on VR applications that could be triggering for users with photosensitivity. P5 explained her concern about the need for warnings to prevent younger users from accidentally being triggered by flashing lights: *"And warnings, really, for kids and for younger people because they're just going to go for it, aren't they? They're just going to try. I imagine probably that a younger brain will not operate like mine. I imagine they may well be absolutely fine and then somehow find themselves triggered later on."* P4 describes her vision for VR warnings by making comparisons to how warnings are presented on televisions: *"I think it would just be very similar to flashing lights that you get on TV, you get essentially a warning sign come up saying viewers with photosensitive epilepsy, you need to be careful. The fact that I think it turns off the whole screen and it's just simply that warning. It's a big sign and whoever's paying attention will be like 'ok yeah yeah' and if that severely affects them they can turn it off. And I think it should be a warning if someone's to book a VR event online, it should come up as a similar warning."* These warnings could be generated automatically through an algorithm or could be produced by crowdsourcing information about flashing lights in VR content from other players.

Customization for visual displays: P5 described her process of customizing social media apps to better suit her needs in terms of color, contrast, and movement: *"And the ability to have complete*

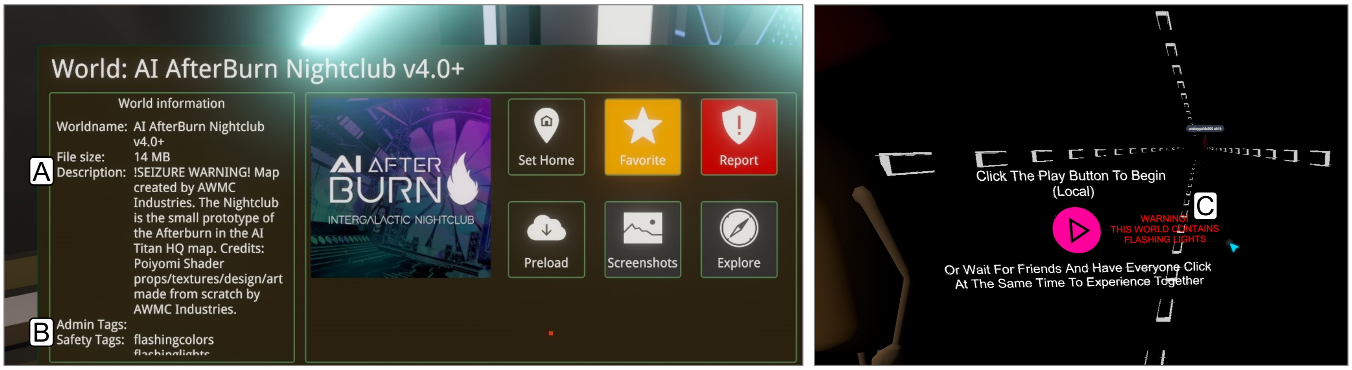

Figure 1: Two examples of crowdsourced warnings about flashing lights in virtual worlds created in Chillout VR (left) and VRChat (right). Warnings appear in the description (A) and safety tags (B) on the world summary page and on the physical surfaces of the world (C).

control as well, because you do things like say Twitter [...] if I hadn't turned off the autoplay, I wouldn't have been able to tolerate it. So just being able to control the autoplay is a big difference. It makes it much more accessible and I'll think about the color scheme, If I don't like the color scheme, I'll go and change it. I will. Sometimes I'll dull things down. Sometimes I brighten things up. It's about having a lot of control over the environment." P5 expressed her desire to have similar control over the visual appearance of interfaces in VR, saying *"If you were to do that in VR, it'd be a similar thing. Like try to turn it turn things down so it's not as stimulating, to be able to pull the colors down."* Customization features in VR could allow users to lower brightness and contrast on a VR headset, limit motion or animation effects from avatars around them in VR, or limit the vividness of bright colors in virtual worlds.

Interdependence: When asked about their procedures for seeking out accessible content, participants described their practices of relying on trusted family members or friends to help them stay safe while watching films or television (i.e., *interdependence* [9]). P4 trusts her partner or friends to tell her when it is safe to look back at the screen while watching films: *"I know that there have been certain films where I've been sat in bed waiting for the scene to change and it doesn't. I'm like 'Okay, yeah, that's not for me' then I can shut my eyes or turn away until my partner or my friends say 'Yeah that's over now, you're fine'."* P3 described how interdependence among VR players made her feel safer and more secure when playing a VR game that involved multiple users in the same physical room: *"Yeah it didn't cross my mind at that moment but it did later on. Mostly because at the time I had five people in the room and it was quite a small room. So I thought if anything happened I'm safe. But if I was on my own obviously that could – you know you could hit your head, cause quite a bit of damage, couldn't it? So it was something that I thought about more after. I thought 'Oh, this isn't really a good idea'."* While some VR games, such as the one P3 played, might incorporate aspects of interdependence among users by default, intentionally designing VR experiences with interdependence in mind could lead to systems that are safer and less stressful for people with photosensitive epilepsy. For example, VR systems could allow players to designate other players as trusted individuals with the ability to turn off shaders, particle effects, or other animations that might be hazardous to a person with photosensitivity.

5 DISCUSSION

Our interviews and thematic analysis generated four categories of barriers to accessibility in VR encountered by individuals with photosensitivity: physical VR equipment, content and interfaces in VR, specific applications of VR, and individual differences in sensitivity. Participants felt that automated testing and increased usage of warnings would improve the safety of VR environments. VR systems can be designed with photosensitive accessibility in mind by incorporating additional customization features that allow users to lower the brightness or contrast of the visual display, limit unexpected motion or animations by disabling visual effects, and control the vividness of certain colors within the VR headset. Finally, our findings suggest that VR systems should work to mirror current practices of interdependence that people with photosensitive epilepsy use in the real world.

5.1 Malicious behavior in VR

People with photosensitive epilepsy are frequently the targets of malicious attacks on social media in which an individual intentionally sends strobing content to specific people with the goal of causing a seizure. Recent attacks have targeted the Epilepsy Society [67], the Epilepsy Foundation [2], and individual accounts known for posting about their experience with epilepsy [39]. Only one participant (P2) mentioned the potential for malicious behavior in VR in our interviews, acknowledging that *"[t]here's always the possibility of malicious actors, like people specifically coming in with avatars or photos that are strobing or whatever, but you can't really account for those."* Prior work has demonstrated the potential for malicious cyberattacks in VR through frame rate manipulations [52], overlay and disorientation attacks [18], and perceptual manipulations [70]. Given that several aspects of a stereotypical physical VR setup are likely to increase an individual with photosensitivity's propensity for seizures (e.g., screen size, continuous immersion), malicious attacks in VR against people with photosensitivity have the potential to be devastating. Seizures are highly traumatic events that can lead to permanent damage or even death [29], and individuals may experience issues with motor control and neurological function for days or weeks after experiencing a seizure [39, 74]. Social VR platforms need to take action to prevent malicious attacks involving flashing lights from taking place in environments where individuals with photosensitivity might be impacted.

5.2 Similarities among different accessibility needs in VR

Several recent works have examined accessibility in VR from the perspective of different populations with varying levels of ability. It is useful to consider where there may be overlaps in the accessibility needs of different groups as research artifacts or prototypes created for one group of users might end up solving a problem for another group of users inadvertently. Boyd et al. created reduced sensory environments in immersive VR to support neurodiverse users with sensory differences [12]. Reduced sensory environments with basic visuals showing only objects that are needed for a given task could also be useful for individuals with photosensitive epilepsy who are trying to avoid being triggered by unnecessary visual stimuli and aiming to limit unpredictability in VR environments. Concerns about the effect of complete immersion for extended periods of time for neurodiverse VR users, as described by Creed et al. [20], share similarities with our participants' concerns about not being able to quickly break immersion, as well as concerns about being expected to use VR for long periods of time in workplace, training, or medical scenarios. Developing VR systems that allow users to easily leave immersion and take screen breaks could benefit both communities.

Interdependence and customization have been highlighted as valuable design elements for improving VR accessibility for users with limited mobility [48]. Customization has also been pointed out as a key way to improve accessibility in VR for people who are deaf or hard of hearing [20, 37]. Our findings showed that systems that encourage interdependence and customization are valuable for people with photosensitivity in non-immersive situations, like using social media or watching films. These design elements would likely also be useful for people with photosensitivity in immersive VR environments. For example, VR systems designed with interdependence in mind could allow people with photosensitivity to designate trusted individuals, such as family members or friends, with the ability to turn off a headset or remove the player from a virtual world. Similarly, customization in VR could enable users who have light sensitivity to lower the contrast on their screens or limit the colors present in a virtual environment. Several of the customizations implemented in *SeeingVR*, a set of accessibility tools to support people with low vision in VR, could be useful for helping people with photosensitivity customize their VR experience [77]. For example, *SeeingVR* lets users adjust brightness and contrast, as well as recolor objects in virtual environments. While people with low vision often want to increase brightness and contrast, the same tools could be repurposed to help people with photosensitivity lower brightness and contrast or make changes to color intensity as needed.

5.3 Limitations & future work

Our study includes interviews with five people who have photosensitivity. The low number of participants has the potential to limit the generalizability of our results, although it is important to note that a statistical-probabilistic interpretation of generalizability is not applicable for qualitative research [61]. We instead focus on interpretations of generalizability that are more appropriate to the qualitative nature of our work, such as transferability and analytical generalizability. We discuss potential areas of transferability and analytical generalizability within the broader VR and accessibility fields in Section 5.4 and 5.2. The sample size in our interviews was limited due to several factors. First, the population of people with PSE is relatively small compared to other disabilities, with studies suggesting a prevalence rate of approximately 1 in 4000 among the general population [25]. Second, people with PSE are often reluctant to interact with unknown people online due to concerns about harassment or abuse [2, 39, 56]. Finally, many people with PSE are either unfamiliar with VR or, for those who have used VR before, not confident in labelling themselves as familiar with the technology due to accessibility concerns. Our initial study protocol called for recruiting participants who had PSE and were regular users of VR. Two months of active recruiting efforts using this protocol failed to produce any prospective leads for participants. Instead, our recruiting efforts generated feedback from both PSE and VR communities that our recruitment criteria were not feasible given current levels of accessibility in VR.

In response to this feedback, we adjusted our recruitment criteria to no longer require that participants use VR regularly. We created four videos introducing VR concepts to participants who were not familiar with VR (Section 3), inspired by the procedure used by Mott et al. to be inclusive of participants who had not been able to use VR previously due to accessibility limitations [48]. This adjustment led to significantly more responses from people with PSE and ultimately facilitated the five interviews described in this paper. While our small sample size could limit the generalizability of our results, we believe the experiences relayed by our participants are valuable as an initial characterization of VR accessibility needs for a population that has not represented in prior work. This work will enable future research directions in further investigating the barriers to access identified in this paper, such as physical VR equipment and specific VR applications with particular concerns for photosensitive accessibility.

The iterative coding process in our thematic analysis was done by a single coder, which could introduce limitations for the generalizability of the work due to subjectivity. While we acknowledge the potential for subjectivity in our results, the nature of this work and our analysis is appropriate for a single coder. The reflexive thematic analysis process embraces subjectivity and is well-suited to a single researcher [15]. Bowman et al. discuss pitfalls that can be introduced when reflexive thematic analysis is done collaboratively [11], particularly when additional coders do not have the time or resources to fully participate in the crucial familiarization process, and argue that multiple coders are not always necessary or feasible for reflexive thematic analysis. Given that the aim of this work is experiential, with an emphasis on analyzing the lived experiences recounted by our participants, we felt that the lead author, who conducted the interviews and had direct interaction with participants, was most qualified to conduct the thematic analysis. The aim of this work is not to produce broadly applicable design guidelines or recommendations, but rather to report patterns of shared meaning generated through a reflexive thematic analysis procedure regarding current experiences of photosensitive accessibility in VR. We look forward to continuing our work in this research direction and conducting future studies to produce generalizable design guidelines for improving photosensitive accessibility.

5.4 Designing for photosensitive accessibility in VR

Our findings in Section 4.5 suggest that people with photosensitivity are curious and excited about the potential benefits of VR, but barriers to accessibility and safety prevent them from actively using VR systems on a regular basis. It is therefore necessary to develop practices to overcome the barriers to accessibility identified in this paper so that people with photosensitive epilepsy can enjoy using VR for recreation, therapy, job opportunities, and more. Failure to develop accessible VR systems could leave people with photosensitive epilepsy excluded from modern technology, particularly as VR continues to transition from primarily recreational activities to the necessary activities of daily life. When VR is used for activities that are difficult or impossible to opt out of without facing negative consequences, people with photosensitive epilepsy may be forced to choose between physical safety and their livelihood, social connections, or education. We can look to the themes generated from our interviews for initial ideas about what designing for photosensitive accessibility might look like (Figure 2). In this section we expand on the ideas suggested by participants in the **Improving VR accessibility** theme (Section 4.6) and situate these ideas in the broader context of accessibility research.

Lighter headsets built to break immersion: VR headsets are considered a significant barrier to accessibility for people with photosensitive epilepsy in their current design. Participants described feeling uncomfortable about the constant immersion required by a traditional VR headset and wanted a headset that made it easier to quickly return to the real world when needed, much in the same way that someone with epilepsy can close a laptop lid or turn a phone upside down to quickly remove themselves from seizure-inducing light sequences [65]. Participants felt that VR interfaces were unfamiliar and foreign, lacking the affordances for quickly removing dangerous content that they were used to managing when interacting with 2D interfaces. Incorporating a simple and quick interaction, such as a gesture or a button, to remove the user from a virtual world could produce a more accessible VR hardware design and allow people with photosensitivity more control over when to exit an uncomfortable situation by mirroring real-world behaviors. Lighter headsets designed to be easier to remove could be another approach to more accessible headset design, such as VR glasses [57]. See-through HMDs, which allow the user to see their surroundings through the virtual headset using cameras (e.g., [6, 55]), could be used to help ease the user between states of immersion and non-immersion and enable easier screen breaks.

Interdependence among trusted people: People with photosensitive epilepsy frequently rely on trusted family members or friends to help them safely navigate the real world and online spaces like social media [65]. Similar structures could be replicated in VR design to allow users with photosensitive epilepsy to designate a trusted individual with the ability to adjust the visual appearance of the world or to remove the individual from the virtual world if the situation becomes dangerous. Additionally, VR platforms can encourage crowdsourced warnings about flashing lights in user-generated content (e.g., Figure 1). These warnings should include details about the visual appearance of the flashes (e.g., color, size) to allow users with photosensitivity to determine if they will be triggered by the lights.

Customization for visual displays: Our participants frequently customize their devices (e.g., laptops, tablets, phones) and social media accounts to limit their exposure to triggering flashing lights. Some participants turn off autoplay to avoid sudden, unexpected video clips on social media feeds, while others adjust the contrast, brightness, and color settings on devices to accommodate their differing levels of light sensitivity. Users should be able to customize visual displays in VR at a hardware level (e.g., lowering contrast or lowering color intensity on a VR headset) and a software level (e.g., turning off animated effects in a social VR world) to improve photosensitive accessibility.

Warnings for flashing lights: Our participants felt that warnings are necessary on VR platforms, particularly those that are likely to contain flashing lights. In the same way that films and television episodes that contain flashing lights are shown with a warning, participants liked the idea of prominent, impossible-to-miss warnings in VR to help users navigate away from virtual spaces that will be triggering for them. Crowdsourced warnings about flashing lights are occasionally used in social VR platforms, such as the examples shown in Figure 1, but these efforts are non-standardized and largely user-driven as platform-driven systems for collecting and disseminating crowdsourced warnings have not yet been formed. Future research might investigate alternative methods for delivering warnings about flashing lights using affordances unique to immersive environments or more formalized systems for collecting crowdsourced warnings in VR environments.

6 CONCLUSION

VR is rapidly growing as an immersive way to explore new worlds, communicate with other people, and access new opportunities. However, this technology remains largely inaccessible to people with photosensitive epilepsy who experience seizures and other adverse symptoms in response to flashing or strobing lights. We conducted interviews with five people who have photosensitive epilepsy to learn about the barriers to accessibility that they face when it comes to participating in VR. Using a thematic analysis, we identified four categories of barriers to photosensitive accessibility: physical VR equipment, VR interfaces and content, specific VR applications, and individual differences in sensitivity. Our findings indicate that there are several ways that VR systems could be made safer for users with photosensitivity, ranging from high-tech solutions such as lighter headsets with functionality for quickly breaking immersion to let users escape triggering content to encouraging efforts to produce crowdsourced or automated warnings for content with flashing lights in VR spaces. Given the severe

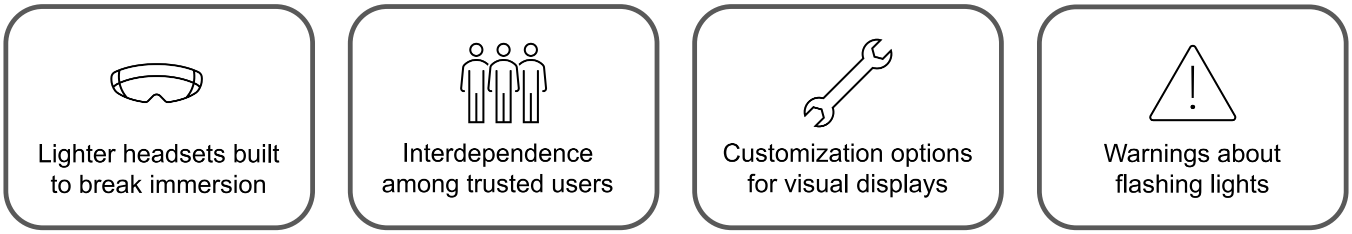

Figure 2: Our results indicate that designing for photosensitive accessibility in VR will involve lighter headsets that make it simple for the user to quickly remove themselves from immersion, systems to encourage people with photosensitivity to get help from trusted individuals (i.e., interdependence), methods for customizing the visual display of VR systems to account for individual sensitivities and preferences, and warnings about flashing lights to help users safely navigate virtual environments.

consequences that people with photosensitive epilepsy face when exposed to hazardous flashing lights, it is vital to understand the specific aspects of VR that make it a particularly dangerous medium for this population. This work is a first step towards identifying and dissolving the barriers to access that prevent people with photosensitive epilepsy from engaging with and benefiting from immersive VR technology.

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