# Inclusive Immersion: Barriers to Enjoyment and Emerging Design Principles for More Accessible Virtual and Augmented Reality

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**Abstract**

Given the nascent stage of virtual and augmented reality content design, there has been limited consideration of the unique requirements of users with disabilities. We present the results of an online survey ($n = 101$) that allow us to understand the obstacles and expectations of users with some form of impairment, disability or long-term health condition as they relate to the consumption of virtual and augmented reality content. The results indicate that among those who have experienced some form of immersive content, almost three quarters encountered obstacles to their enjoyment. We report the full results of this survey, which cover the types of barriers encountered by users with disabilities and opportunities for improving accessibility. The key findings of this survey are then distilled into a set of emerging design principles aimed at developers of immersive content. Finally, we present a vision for the design of immersive content that seamlessly removes barriers to enjoyment for users with disabilities. We call this vision *Inclusive Immersion*.

**Keywords:** Accessibility, Disability, Virtual Reality, Augmented Reality

## 1 Introduction

The social model of disability [1] stresses the role the physical environment plays in restricting one's access and capabilities. Immersive content can remove the barriers present in the physical world, as highlighted by one participant of our survey, "As my disability limits my mobility and changes the way and distance I can travel, using immersive content is a God send. And helps broaden my restricted world." By removing these barriers, users with a disability have access to new experiences and opportunities. An awareness among designers of the basic principles of accessibility for immersive content is therefore paramount in avoiding the needless erection of new access barriers within virtual environments.

This paper reports on a survey that examined the experience and expectations of users with disabilities regarding virtual reality (VR) and augmented reality (AR). This online survey was completed by 101 individuals and specifically targeted users with some form of impairment, disability or long-term health condition. The survey chiefly explored the barriers encountered by users as well as their expectations for how accessibility should be improved.

A detailed overview of the survey results is presented within the body of this paper, however, we highlight one key finding at this stage to illustrate the status quo of the accessibility of VR and AR. Among survey respondents with previous experience of VR or AR, 73% indicated that they had encountered barriers that affected how much they could enjoy immersive content. This observation highlights that there is substantial scope for improving the VR and AR experience of users with disabilities. There is a moral imperative to making this technology more inclusive but also likely usability and commercial benefits. It is generally accepted that improved usability considerations leads to better usability for all given the occurrence of situational impairments and varying levels of familiarity. There are clear commercial advantages to reaching a wider user base. As one of the respondents in our survey commented, "I have debated investing in gaming vr but often have not because of fear of the games etc not being accessible."

This paper aims to address an identified gap in the availability of guidance on improving the inclusivity of VR and AR technology and immersive content. This goal fits within a broader vision for improving the inclusivity of immersive technologies: a vision we refer to as *Inclusive Immersion*. This vision is founded on the principles of *inclusive design*, which seek to ensure products and services are usable by as broad a population as possible through a better understanding of user diversity [2]. Now is the time to increase awareness of accessibility needs in AR and VR to avoid potentially exclusionary design practices from taking root in the emerging realisations of the metaverse. This gap in guidance on how to deliver accessible VR and AR experiences is slowly being addressed thanks, in part, to industry associations and organisation like XR Access [3] and XR Association (XRA) [4]. Improved developer guidance from device manufacturers is also emerging [5]. An informative survey of VR accessibility issues conducted by Wong et al. [6] echoes many of the same issues revealed in our investigation. Garaj et al. [7] also gathered the attitudes and perspectives of users with disabilities towards VR and AR. Our survey complements and extends these various efforts thanks to its inclusion of users representing a broad range of encountered access barriers as well as a spectrum of prior familiarity with AR and VR.

The survey was scoped to examine user experience and expectations regarding the physical device and interface, the digital interface (i.e. device menus) and the VR/AR content consumed. We structure our analysis of the survey results by first examining the demographics and variety of access difficulties faced among the participant group. We then examine the responses of the subset of respondents with prior experience of VR/AR. Using this prior experience as a reference, participants were asked to comment on barriers they encountered during this experience, if/how these barriers were overcome and their requirements for additional accessibility features. Our survey and analysis also examines the interests and expectations of a subset of respondents who have no prior experience of VR/AR. The inclusion of this subgroup is critical to understanding what factors may have lead to some users failing to try this new technology and/or what might be critical to attracting potentially sceptical users to experience VR/AR.

Our key findings offer some preliminary guidance on effective design principles for more accessible immersive experiences. In Section 5, we contextualise these insights with supporting observations from the related literature.

The two key contributions of this paper are:

- A synthesis of the prevailing accessibility barriers and expectations facing users of AR and VR who have some form of disability, impairment of long-term health condition.
- A set of emerging design principles, derived from the survey insights, that offer guidance to developers for improving the accessibility of VR and AR.

## 2 Related Work

The gathering pace of AR and VR technology uptake has triggered wider consideration of the accessibility needs of a broader user base. A workshop focusing on accessibility in VR was held at ISMAR in 2019 [8]. Another workshop on VR and AR assistive technologies was also held at IEEE VR between 2013 and 2015. There has been a corresponding growth in technical work specifically addressing accessibility needs in VR and AR, primarily focused on particular forms of impairment. The most widely addressed forms of capability loss are visual impairments [9–15], hearing impairments [16–20], mobility impairments [21–23] and cognitive impairments [24–26].

SeeingVR [11] is a comprehensive toolkit aimed at supporting users with low vision, and Canetroller [9] is another tool that assists people with sight impairment to navigate and learn virtual environments. EarVR [16] uses vibrations helping users with hearing problems to detect 3D sounds. Li et al. [23] created a pen-shape controller to replace conventional VR controllers, allowing users to rely on wrist movement instead of fine motor movement for interaction. Hherskovitz et al. [27] conducted a study with 10 blind participants to evaluate alternative interactions designed to make mobile AR more accessible. Mott et al. [28] conducted interviews with users with limited mobility to understand their perspectives on the accessibility of VR. They identify the main issues encountered by those with limited mobility and propose several strategies for mitigating these effects. Gerling et al. [29] surveyed 25 wheelchair users to understand why they to do or do not engage with VR and derived several design implications subsequently validated with three different game prototypes.

Organisations like XR Access [3] and industry associations like XR Association (XRA) [4] have recently emerged as significant proponents of accessibility needs for VR and AR. The W3C Accessible Platform Architectures Working Group has also recently reviewed the accessibility issues exposed by VR on the web [30]. One of the major device manufacturers has also recently provided developer guidance on accessible design of VR content [5]. Some VR games, such as *Cystal Rift*, *Persistence*, *Moss*, *Arca's Path VR*, *Island 359*, *Beat Saber* and *Clash of Chefs VR*, have incorporated accessible settings to simplify the immersive experience for players with different difficulties and requirements. Broadcasters, such as the BBC [31] and Sky [32], have recognised that the demand for immersive video content is likely to increase and there has been some early research work seeking to examine preferred methods for subtitle placement in 360-degree videos [33, 34].

The Disability Visibility Project in partnership with ILMxLAB [6] conducted an online survey to investigate accessibility issues faced with VR. Garaj et al. [7] also conducted an online survey eliciting perspectives of VR and AR from people with disabilities and impairments. Both of these surveys provide excellent insight into the various issues relevant to supporting this community. A common factor that emerges from the findings of both of these studies is the frequency of co-occurrence of disability, Wong et al. [6] found that 29% of respondents reported having two or more disabilities while this proportion in the participant group of the study by Garaj et al. [7] was higher still at 58%. As observed by Waller et al. [35], an appreciation of the co-occurrence of disability is critical to understanding whether mitigating one form of capability loss is rendered ineffective by a second co-occurring capability loss.

The vision of inclusive immersion draws significant inspiration from the concept of inclusive design [2]. Inclusive design is a design process which seeks to make a product, service, experience or system usable by as many people as possible. These principles are well suited to the design and evaluation of digital products [36, 37]. There are other closely related design philosophies that also emphasise the concept of inclusion. For example, Dombrowski et al. [38] adapted the seven principles of universal design [39] to VR technology.

There are many examples within the field of human-computer interaction seeking to improve the accessibility of computing technologies more generally that also inform this work. Sears and Young [40] provide a comprehensive examination of how various physical impairments introduce different barriers to interacting with conventional computing technologies. Brulé et al. [41] are more narrow in their scope, but they provide a review of quantitative evaluations of technologies targeted at visually impaired users.

The literature landscape indicates that improving the accessibility of VR and AR is a recognised problem demanding research attention. Gerling and Spiel [42] observe that VR is an "inherently ableist technology" and suggest a paradigm shift from a reactive to a proactive approach to designing for accessibility. There remains, however, limited evidence-based generalisable guidance that is easily absorbed and utilised by developers. Indeed, Ashtari et al. [43] list the lack of concrete design guidelines as one of eight key barriers in developing AR/VR applications more generally. This paper seeks to address this limitation by accurately capturing the voice of users with a disability and identifying their concerns and preferred solutions for making immersive content and technologies more inclusive.

We see our paper as being complementary to previous efforts [6, 7] in refining the broader picture of accessibility for VR/AR, unconstrained by a particular form of access barrier. The survey performed by Wong et al. [6] employed a recruitment strategy that chiefly gathered responses from users with an already established interest in VR. A risk exposed by this methodology is the potential exclusion of users who have experimented with the technology but then encountered too many barriers to enjoyment to warrant continuation, resulting in them losing interest in future use. Garaj et al. [7] collected expectations and attitudes regarding AR and VR from participants who had mostly (75.3 %) never before tried using an immersive headset. By contrast, 73.2 % of respondents to our survey have at least some prior exposure to AR and VR and also represent varied levels of interest and engagement: from users who engage with immersive content every month (14.9 %) to users who have only ever experienced immersive content once or twice in their life (48.6 %). The broader higher-level perspective brought by our survey is particularly important given the prevalence of co-occurring capability loss. In addition, for guidelines to gain traction among designers and developers, they should be unified and complete rather than disparate and partial in their coverage. This pursuit of breadth is consistent with a core tenet of inclusive design: capturing and learning from diverse perspectives [2].

# 3 Survey Design

Due to the lack of primary user research in the area of inclusive immersive experiences, we sought to design an exploratory survey and recruit a sufficient number of respondents to reveal dominant preferences and emerging trends. The questions took inspiration form a related survey developed by Garaj et al. [7] as well as taking influence from a custom capability loss matrix produced to categorise the difficulties that disabled people might experience.

The survey was divided into six sections: 1) demographics, 2) access barriers, 3) familiarity with immersive content, 4) barriers encountered in immersive experiences and solutions to them, 5) expectations for the accessibility of immersive experiences, and 6) perspectives on personalisation. The survey contained mostly close-ended questions, however, we used a smaller set of open-ended questions to encourage participants to share in-depth perspectives, and to complement and extend their answers to the close-ended questions. Given the influence of Covid-19, we carried out the survey online to avoid close contact with our participants, many of whom are in a vulnerable group.

We aimed to collect 100 responses and sought to ensure recruitment was as inclusive and representative as possible in terms of age, gender, access needs and familiarity with technology. Survey participants were recruited through a panel managed by a commercial agency specialising in disability and inclusivity research. Most of these panel members are based in the United Kingdom and have diverse attributes in terms of gender, age, medical condition, education, digital literacy and socio-economic levels in addition to their varying access needs and adaption strategies. A secondary recruitment objective for the 100 participants was that at least two thirds of participants must have tried immersive reality using a headset at least once, and up to a quarter of participants should have never tried any immersive content. This targeted recruitment strategy was facilitated by the custodians of the user panel who maintain records on the past exposure of participants to various technologies.

The primary method of communication for this study was by email and via shared links to an online version of the survey. Additional steps were taken to include participants who required alternative forms of communication, such as distributing a fully accessible offline digital version of the survey as required. Participants in the survey received a payment of £15 as compensation for their time. The study was approved by our institution's ethics committee.

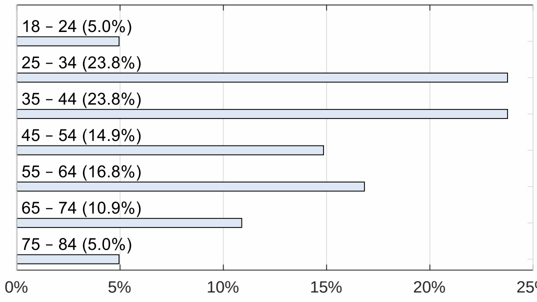


**Fig. 1** Distribution of survey respondents across age groups.

# 4 Results

In total, 101 participants completed the survey. We report on the collected responses organised as follows: demographics, access barriers, familiarity with immersive content, barriers encountered, desired accessibility features, attitudes and expectations of participants with no prior experience, and desired content types. Due to space constraints, we focus on the survey questions (included as supplementary material) delivering unique insights.

The answers to the open-ended questions are analysed using qualitative content analysis methods [44]. This involved identifying the similarities and differences in the meaning of the written comments, coding and categorising the data according to themes, and exploring the relevance among the categories. These thematic codes help us to better understand the answers to the close-ended questions.

## 4.1 Demographics

Of the 101 respondents, 61 were female, 38 were male and one person indicated they prefer to self-describe (the one remaining participant provided no response to this question). The age distributions of the sample are summarised in Figure 1. From Figure 1, we can see that 25 - 34 and 35 - 44 were the most sampled age groups, together accounting for just less than half (47.6 %) of all respondents. 98 of 101 respondents answered yes to the question, "Do you consider yourself to have an impairment, disability or long-term health condition?" The main forms of access barriers encountered by participants are examined later in Section 4.2.

The majority of survey participants identified as being of White ethnicity (78.2 %). The proportion of other ethnicities sampled, in descending order, were Asian/Asian British (7.9 %), other not listed (5.9 %), Black/African/Caribbean/Black British (3.0 %), Arab (2.0 %) and Mixed/Multiple (2.0 %). This sampling shows good consistency with the general population statistics of England and Wales (White (86.0 %), Asian ethnic groups (7.5%) and Black ethnic groups (3.3 %)) [45].

Given this investigation's focus on the relatively novel technology of VR and AR, we saw value in contextualising later responses by capturing participants' general level of comfort with technology. Participants were asked to respond to the question, "How comfortable are you with personal technology such as smartphones, tablets or computers?" on the range from "I struggle using even basic technology and often need help" to "Very comfortable. I find technology easy to use and often help others." We found that 83.1 % of respondents were either comfortable or very comfortable with technology, suggesting that the vast majority of participants are likely to have generally positive attitudes towards new technology.

It is common for users with a disability or impairment to use some form of assistive technology to reduce or remove barriers to interaction with a computer or smartphone. The survey asked participants to indicate what form of assistive technology they use. These responses are summarised in Figure 2. The results indicate that the majority of respondents do use some form of assistive technology, although there is a large proportion of participants who do not (40.6 %). The most widely used assistive technologies among respondents were display adjustments at 32.7 % (e.g. Dark Mode, inverted colours, larger font size), voice for input and/or navigation at 24.8 % (e.g. Dragon NaturallySpeaking, iOS Voice Control, Google Voice Assistant) and screenreaders at 19.8 % (e.g. VoiceOver, Talkback, JAWS).

## 4.2 Access Barriers

Within the United Kingdom, the social model of disability [1] is the preferred perspective for viewing the consequence of living with some form of disability, impairment or long term health condition. The social model seeks to highlight how

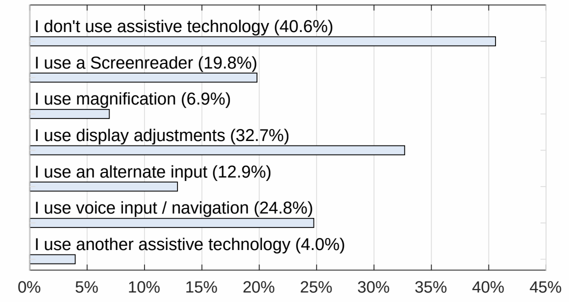


**Fig. 2** Categorical responses to question, "Do you use assistive technology to make digital experiences easier for you?"

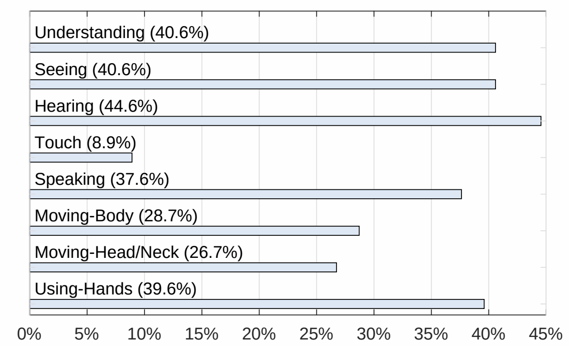


**Fig. 3** Percentage of respondents who encounter different forms of access barriers in their daily life.

society and the physical environment impose barriers to accessibility. This contrasts with the medical model of disability which highlights how the loss of access is a consequence of a physiological or psychological impairment. The value of the social model is that it stresses how a redesign or reconfiguration of the environment, that is, factors external to the individual, can improve accessibility. In line with the social model of disability, we asked survey participants to reflect on what forms of access barriers they face in daily life. Specific questions were presented covering the following eight forms of access barrier: i) understanding and problem solving; ii) perceiving or understanding visual content; iii) perceiving or understanding sound; iv) perceiving touch sensations; v) communicating with your voice; vi) moving your torso, arms or legs; vii) moving your head or neck; and viii) using your hands. Figure 3 summarises the percentage of respondents who encounter the different forms of access barriers in their daily lives.

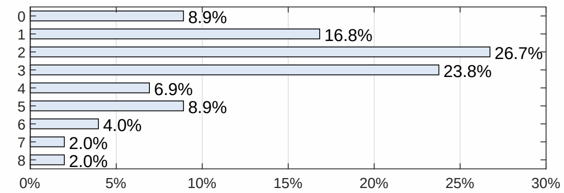


**Fig. 4** Co-occurrence of access barriers for the eight forms of access barrier queried in the survey.

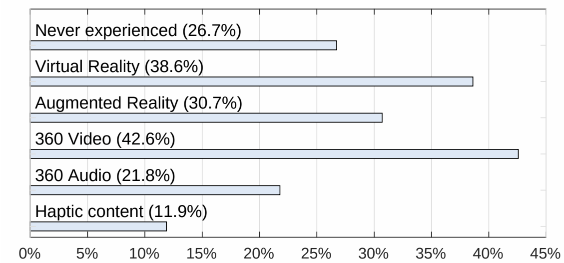


**Fig. 5** Categorical responses to question, "What immersive content do you have experience with?"

Barriers to understanding, seeing, hearing, speaking and dexterity were encountered by more than one third of respondents. Barriers to moving the body and head or neck were less common but still encountered by more than 25 % of respondents.

Figure 4 plots the percentage of participants grouped according to how many different forms of access barriers they indicated, i.e. co-occurrence of access barriers. An important observation from this plot is the fact that it is common for users with a disability to encounter multiple forms of barriers in their daily life. 74.3 % of participants indicated that they encounter two or more different forms of access barrier and 47.5 % encounter three or more.

## 4.3 Familiarity with Immersive Content

In this portion of the survey we sought to examine the familiarity of the participant group with immersive content. Figure 5 summarises the forms of immersive content that respondents had previously experienced. Note that one of the objectives of the survey was to capture attitudes and expectations of users without prior experience. Figure 5 shows that 26.7% of respondents fall into this category. Those without prior experience were transitioned to a dedicated portion of the survey, which is examined later in Section 4.6. The

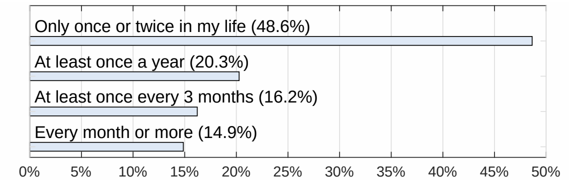


**Fig. 6** Categorical responses to question, "How often do you experience or use immersive content?"

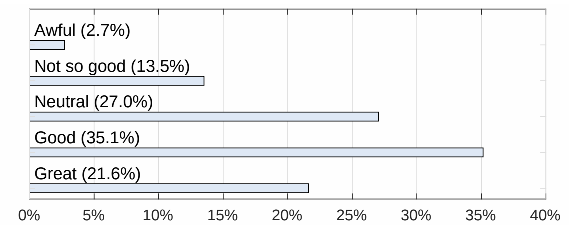


**Fig. 7** Responses to the question, "In general, when you experience immersive content, how do you feel?"

remaining results in this section and the following Section 4.4 report on just the subset of respondents *with* prior experience ($n$=74) of immersive content.

Those with prior experience were asked to comment on how frequently they used VR or AR. The distribution of responses is summarised in Figure 6. The majority (48.6 %) of respondents with prior experience had tried immersive content only once or twice before. 31.1 % indicated that they used VR or AR at least once every three months or more regularly. The remainder (20.3 %) experienced immersive content at least once a year. The subset of participants who indicated that they had tried immersive content only once before, or only used it once a year, were asked a follow up question to gauge their interest in trying it again in the future. 64.7% of participants indicated they would like to experience immersive content again in the future. A further 25.5% indicated that they would maybe like to try it again. Only four participants indicated that they would not be interested in trying VR or AR again.

Participants were asked to reflect on their prior experience and rate how it made them feel on a five-point Likert scale from *Great!* to *Awful!*. The distribution of responses to this question is summarised in Figure 7. From Figure 7 we observe that although the experience of most respondents was positive, there is still a relatively large group of users (16.2 %) whose experience was less than neutral.

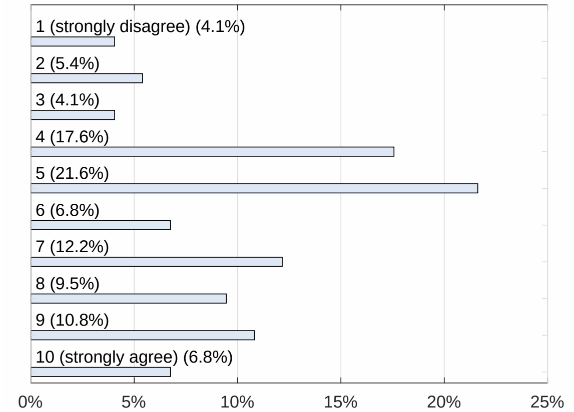


**Fig. 8** Response on a scale from 1 (strongly disagree) to 10 (strongly agree) to the statement, "In general, when I experience immersive content I feel safe."

Certain access barriers can manifest as anxiety or concern about one's personal safety. The use of VR and AR has the potential to exacerbate some of these concerns due to the risks introduced by the potential for disorientation, vertigo-like sensations and nausea. Indeed, research indicates that older adults and people with neurological disorders who have difficulty with balance may struggle to enjoy many forms of immersive content as per the design intent [46, 47]. We therefore asked respondents with prior experience to respond to the statement, "In general, when I experience immersive content I feel safe." on a ten-point Likert scale from one (strongly disagree) to ten (strongly agree). Figure 8 summarises the responses to this survey question. A key point to observe in Figure 8 is that there are, very approximately, two modes to this distribution with some respondents indicating general agreement with the statement (rating 7–9) and another subset indicating neutral or slight disagreement (rating 4–5). More generally we can observe that 31.2 % indicated some degree of disagreement with the statement (rating 1–4). This suggests that VR and AR technology and content could do more to address user concerns around safety.

## 4.4 Barriers Encountered by Users with Prior Experience of Immersive Content

The subset of respondents ($n$=74) with prior experience of immersive content were probed as to

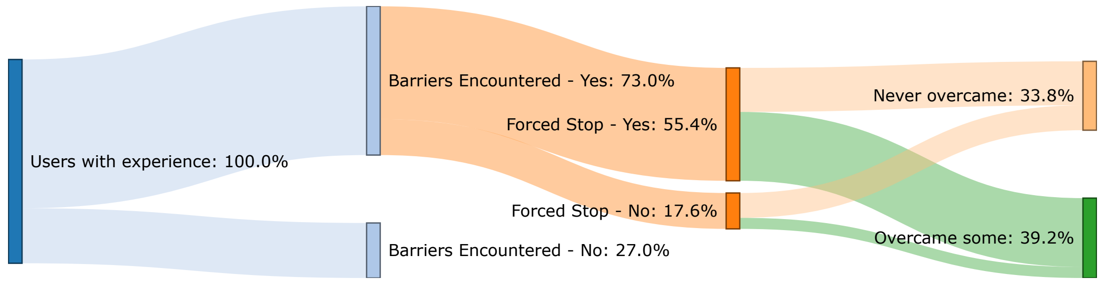


**Fig. 9** Sankey diagram illustrating the survey responses to the sequence of questions: 1) "Thinking back to the times you experienced immersive content, did you ever encounter barriers that affected how much you could enjoy that content?"; 2) "Did the barriers force you to stop experiencing the immersive content at any point?"; 3) "Did you overcome at least some of the barriers?"

**Table 1** Barriers to enjoyment encountered by respondents with prior experience of AR/VR, categorised by the primary form of access difficulty responsible for erecting this barrier. This table captures Cognition and Perception barriers and is continued in Table 2. Also listed are solutions or workarounds found by participants as well as desired accessibility features.

| **Access Difficulty** | **Barriers to Enjoyment** | **Solutions/Workarounds Found** | **Features Desired** |
|---|---|---|---|
| Cognition<br>⇒*Understanding* | • Sensory overload<br>• Disorientation<br>• Fear of unexpected | • Self-managing exposure<br>• Slow/careful movements | • Control over content 'busyness'<br>• Control over sudden sounds<br>• Control over colour and contrast<br>• Video passthrough overlay<br>• Remote assistance<br>• Wider availability of 'easy' mode<br>• Calmer, more realistic content<br>• Simplified menus |
| Perception<br>⇒*Seeing* | • Can't perceive 3D<br>• Miss some content in scene<br>• Disorientation<br>• Light sensitivity<br>• Can't use screen reader | • Stream to PC/TV and enlarge<br>• Adjust font and text size<br>• Enable 'easy' mode<br>• Assistance from someone<br>• Familiarisation<br>• Remain seated<br>• Reduce audio level<br>• Use white cane | • Audio descriptions<br>• Magnification tool<br>• Screen reader integration<br>• Support voice control<br>• Support voice-to-text input<br>• Warn of/disable jump scares |
| ⇒*Hearing* | • Can't perceive content audio<br>• Can't perceive 3D sound<br>• Disorientation | • Enable subtitles/captions<br>• Enable 'easy' mode<br>• Adjust sound levels<br>• Visual indication of audio source | • Speed adjustable audio<br>• Hearing aid connectivity<br>• Sign language interpreter<br>• Realistic character mouth movements to permit lip-reading<br>• Incorporate haptic feedback<br>• Warn of/disable jump scares |

whether they had encountered any barriers that affected their enjoyment levels. If barriers were encountered, follow-up questions were posed asking about what these barriers were, whether they forced a cessation of the experience and whether some of these barriers were overcome. Figure 9 shows a Sankey diagram illustrating the proportion of participants who had encountered barriers and whether these led to a cessation and/or were partially overcome. 73 % of respondents had encountered barriers to their enjoyment of immersive content. These barriers forced the cessation of the experience for 55.4 % of participants and 33.8 % of barriers were never overcome, whether they forced a cessation or not. The subset of

**Table 2** Barriers to enjoyment encountered by respondents with prior experience of AR/VR, categorised by the primary form of access difficulty responsible for erecting this barrier. This table captures Movement barriers and is a continuation of Table 1. Also listed are solutions or workarounds found by participants as well as desired accessibility features.

| **Access Difficulty** | **Barriers to Enjoyment** | **Solutions/Workarounds Found** | **Features Desired** |
|---|---|---|---|
| Movement | | | |
| ⇒*Body* | • Fear of collision/fall<br>• Hardware restricts movement<br>• Interactions highly fatiguing<br>• Difficulty putting on headset | • Familiarisation | • Alternative control schemes<br>• Adjustable control-display mapping<br>• Wheelchair friendly content<br>• Lighter hardware |
| ⇒*Head/Neck* | • Discomfort wearing headset<br>• Can't freely look around | • Assistance from someone | • Lighter hardware<br>• HMD shoulder support |
| ⇒*Hands* | • Can't use controllers<br>• Can't hold controllers | • Enable 'easy' mode<br>• Utilise other body parts<br>• Pain medication | • Alternative controller designs<br>• Simplified menus reducing interaction requirements |

participants who were forced to stop their experience covered the full spectrum of access barriers encountered in daily life described in Section 4.2. In other words, there was no single form of access barrier faced by individuals that correlated with the need to halt their experience. These results indicate that there is significant scope for improvement in the accessibility of VR and AR to help reduce and eliminate these barriers to enjoyment.

Tables 1 and 2 summarise the written explanations provided by participants about the types of barriers they had encountered and their corresponding solutions, where found. Tables 1 and 2 categorise the barriers encountered based on the primary access difficulty responsible for erecting that barrier. Note that the listed solutions/workarounds found by participants were not necessarily effective.

Interestingly, we see 'Disorientation' raised as a common barrier to enjoyment for those facing cognitive and perception difficulties. The written responses from participants highlight, however, that this feeling of disorientation manifests in different ways and has different implications for use of AR and VR. For users who have difficulty with understanding and problem solving (*Understanding*) this disorientation arises, in part, as a consequence of the overwhelming sensory experience. For those who have difficulty with perceiving visual content (*Seeing*) this disorientation arises from the audio presented in immersive experiences obstructing the primary sense normally used to maintain an awareness of what is happening nearby in the real world. Similarly, for those who have difficulty with perceiving audio content (*Hearing*) the primary sense normally used to attend the physical environment (vision) is obstructed by the HMD. This observation suggests the barriers to enjoyment may be more keenly felt in VR than AR for users who have difficulty hearing given that AR better preserves visibility of the physical world.

Regarding solutions or workarounds found by users, one widely mentioned solution was switching to the 'easy' mode of a game or experience. Several respondents expressed how they usually required more time or effort than non-disabled users to complete certain tasks, and 'easy' modes offer a way to reduce temporal and physical demands.

Multiple participants referred to a reliance on others as a way to mitigate the barriers to enjoyment they encountered. This third-party assistance came in various forms. One user who had difficulty seeing the visual content relied on another person to describe the virtual scene and what they were required to do. Several participants who experience difficulty with moving their head or neck relied on assistance from someone else to put on and take off the HMD. These observations clearly have different implications for the design of accessibility features. It may be possible to offer audio descriptions to users who have difficult seeing, however, there is no obvious digital intervention for addressing difficulties in putting on or taking off the HMD.

## 4.5 Desired Accessibility Features

Participants with prior experience of immersive content were asked to describe what accessibility features they would have liked to use, but which were not available to them, as well as any other factors developers should consider when developing accessible immersive experiences. The open-ended responses to these questions are summarised in the final column of Tables 1 and 2.

A common high-level theme present in Tables 1 and 2 across different forms of access difficulty is the desire for compatibility with established assistive technologies (e.g. screen readers, hearing aids, wheelchairs). This observation reflects the fact that users with a disability typically have an established way of mitigating the effects of their access difficulty by leveraging assistive technologies.

Another recurring high-level theme reflected in Tables 1 and 2 is the desire for greater configurability of both the content as well as the interactions. Several participants who experience difficult with seeing or hearing specifically mentioned a wish to be able to warn of or disable jump scares present in content. This is also echoed by participants facing access difficulties in understanding who mention a desire for exercising control over sudden sounds. With comments focused more on the hardware/software interface, several participants who experience difficulty moving their body expressed a desire for greater configurability of control schemes and control-display mappings. These themes of greater configurability were further explored under the topic of personalisation, as reported in the following subsection.

### 4.5.1 Personalisation Options

Our prior experience in the development of accessible solutions lead us to hypothesise that personalisation would be an effective approach to enhance the inclusivity of immersive experiences. Therefore, in the survey we explored participants' perspectives regarding personalisation of settings for immersive content. Both participants with and without prior immersive experiences shared their thoughts on this topic. More than 85% of respondents were interested in personalisation. Reasons given for this interest included the potential for removing barriers in immersive experiences as well as making content more inclusive for both people with capability loss and able-bodied people with different requirements. Participants stated that they believed personalisation could enhance enjoyment, attention, independence, and some participants felt that it would empower them with more control and freedom in immersive experiences.

**Table 3** Common themes in participants' responses regarding personalised accessibility features in immersive experiences.

| **Personalisation of Immersive Experiences** |
|---|
| • Simplify the menu, settings and instructions |
| • Focus on variation of each user's preferences and disability over time |
| • Allow for features to be easily toggled |
| • Ensure smooth transitions between personalised and non-personalised modes |
| • Prevent the assistance from interfering with the experience |
| • Design personalisation features with people who experience difficulties |

Participants were asked to consider how they would expect to utilise such personalistion features and were presented with the question, "How would you expect to select such options? Choose all that apply." The presented alternatives were: internal – i.e. from inside the immersive experience; external – i.e. externally using buttons during the immersive experience; voice – i.e. using voice commands during the immersive experience; before – i.e. before starting the immersive experience; and other. More than 60% of the participants would like to access personalisation inside the immersive experience through the menu, and around half of the participants expected to configure settings before starting an immersive experience or during the experience using controllers, other tools (e.g. keyboard) or voice. Those who selected Other ($n$=4) were asked to explain their reasoning. Two suggested personalisation settings applied by a secondary device, such as a smartphone. Another suggestion was to apply personalisation settings from a 'profile' configured by the user. The remaining explanation was just a comment indicating that the respondent did not feel they had sufficient experience to say.

We sought the participants' perspectives on personalisation and categorised their written responses into themes as shown in Table 3. Participants suggested that developers simplify the navigation, settings, and instructions for personalisation features. These settings should also be adjustable based on each user's preferences, disability and ability, and update over time as the user's condition changes. Some participants suggested developers provide a method for easily toggling personalisation features or offer an auto-on mode, and that the transition between the "On" and "Off" mode should be smooth. Participants also wished to flag that personalisation settings must not cause the user to miss other types of information or distract them during interactions. Finally, several participants suggested developers design personalisation features by collecting feedback from users who are disabled rather than assuming what users with disabilities would need.

## 4.6 Attitudes and Expectations of Users without Prior Experience of Immersive Content

In this section we examine the attitudes and expectations of the subset of survey respondents ($n$=27) who had no prior exposure to immersive content. As described in Section 3, we specifically sought to recruit a portion of participants without prior experience as a way to examine interest levels and to explore any reasons why users with a disability or impairment may be hesitant to try VR or AR.

In response to the question, "What interests you the most about immersive content?" participants mentioned the novelty, the reality and immersion of immersive content and 360-degree videos. Participants expressed particular interest in experiences that were impossible for them in the real world. For example, two respondents wanted to try extreme sports, such as white-water rafting and skydiving. Other participants were interested in sharing immersive experiences with other people.

The survey asked participants without prior experience to indicate, "What type of immersive content in the home interest you the most?" as well as the same question relating to experiences outside the home. More than half of the respondents in this group were interested in trying cultural, shopping, entertainment and educational experiences, as well as social activities and remote physical treatment from home in the future. One participant expressed interest in virtual training for daily tasks, such as writing, buttoning, carrying a tray and holding a mug. When outside the home, approximately 50% of respondents believed immersive cultural and retail experiences would be most appealing. The general interest in gaming content was by comparison relatively low, no matter whether in or outside the home.

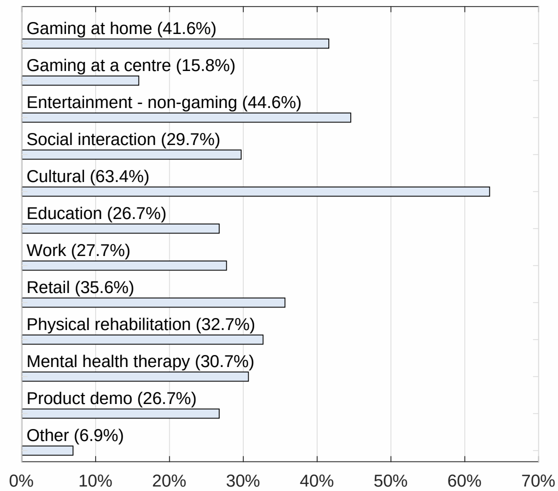


**Fig. 10** Selected alternatives in response to the question, "Would you like more/other experiences to be immersive? What areas interest you the most?"

## 4.7 Desired Content Types

Finally, survey participants were asked to respond to a question seeking to understand what types of immersive experiences they would like to enjoy if made available. Figure 10 summarises the content types of interest to respondents (both those with and without prior experience). Over 60 % of participants indicated an interest in more cultural immersive experiences, for example, travel, museum tours, galleries and concerts. One written comment highlights the value AR and VR may have for users with disabilities in terms of providing access to experiences that would otherwise be impossible, "Because augmented or virtual reality is the only way I will be able to experience world travel or some exhibitions due to physical limitations." High levels of interest were also expressed for gaming and other forms of non-gaming entertainment, such as video.

# 5 Emerging Design Principles

In this section we distil the main findings collected from the survey into a set of emerging design principles for improving the accessibility of VR and AR technology and content. These principles may offer some guidance for developers seeking to make their immersive experiences more inclusive. We also contextualise these design principles by linking them to related findings in the literature.

## 5.1 Provide Redundancy in Information Streams

Our findings indicate that participants who face some form of access barrier are keen to exploit other capabilities that they do have available, and which are not obstructed. For example, one participant with a visual impairment indicated that they would love to see more accessible VR, "even if it was just accessible through sound and haptic feedback." Another participant expressed frustration due to their visual field deficit which meant that, "you genuinely have no way of knowing whether you've missed seeing something as you just have no visual feedback in that portion of your field of vision - this can be confusing as you try to 'keep up' with a process or narrative not knowing if you've taken everything on board." Providing redundancy in the communication of information to the user is a well-recognised strategy for improving the accessibility of content. Subtitles are an obvious means for communicating audio information to those facing barriers to hearing but are challenging to deliver in a 3D setting [33] and may be disruptive to immersion. SeeingVR [11] exercised this principle of redundancy in their development of 14 alternative support tools for low vision users. Similarly, EarVR [16] demonstrates how more traditional accessibility features aimed at users with hearing impairments might be complemented by thoughtfully integrated haptic feedback.

Redundancy without careful thought, however, can result in other issues such as cognitive overload and over-stimulation. The principle of ability-based design [48] stresses a focus on ability rather than disability. Focusing on what users *can do* rather than what they *cannot do* provides a useful perspective that may help avoid redundancy for redundancy's sake alone. Mott et al. [28] also highlight the potential of ability-based design as a framework for addressing VR accessibility barriers encountered by users with limited mobility.

## 5.2 Support Redundancy in Input Modalities

In Section 4.2 we found that 74.3 % of participants face two or more different forms of access barrier and 47.5 % face three or more. As the complement to the previous principle around redundancy in information streams (i.e. from the content to the user), this principle addresses the need to support interaction (i.e. from the user to the content). In the context of wheelchair-accessible VR, Gerling et al. [29] identify the related design implication of offering "flexible control schemes". Our findings indicate that the range of barriers encountered by users are unlikely to be foreseen by developers. For example, one survey participant recalled, "I was engaging in a VR video game that required 2 controllers; one for the right hand and one for the left hand. I'm missing my left hand, so this made attempting to play these games frustrating." Mott et al. [28] similarly observed that users with limited mobility may need to use two hands to operate a single controller, thus preventing the use of two controllers simultaneously. If developers can provide a degree of redundancy in the modes of input available to the user, users may themselves be able to identify an arrangement that works for them. For this to be truly effective, developers should seek redundancy by supporting input modes that are non-overlapping in terms of the capabilities required, that is, a controller and a keyboard are distinct input devices but may not mitigate the needs of a user facing barriers to dexterity. As one participant noted, "It would be useful if consideration could be given for increasing the amount of voice control options so the immersive reality experience could be enjoyed without the need for complex dexterity and movement."

### 5.3 Enable Integration of Assistive Technologies

We found that 59.4 % of respondents used some form of assistive technology (see Figure 2). One respondent expressed an interest in, "Wheelchair friendly content" while another wished for, "Audio description and compatibility with voiceover screen reader." Developers should be aware of the fact that users with a disability have often evolved finely tuned strategies leveraging various tools for interacting with technology. Herskovitz et al. [27] describe relatively simple strategies for including meta data in virtual objects to enable screen readers to function in mobile AR. Canetroller [9] and a similar system demonstrated by Siu et al. [15] are excellent examples of the inclusion of assistive technologies in a way that is core to the experience of immersive content. Gerling et al. [29, 49, 50] also provide examples of compelling games that not only include the user's wheelchair but leverage it as a core game mechanic. These examples from the literature highlight that integration of assistive technologies can not only deliver accessibility benefits but open new opportunities for delivering compelling immersive experiences.

Related to the principle of allowing users to integrate their assistive technology is the concept of *inclusive representations* [8], referring to the idea that some users wish to reflect their personal attributes in the virtual content. Gerling et al. [29] caution, however, that not all users wish to reflect their disability in a virtual avatar and so inclusive representations should be optional.

### 5.4 Provide Tutorials and Familiarisation Content

A common theme that emerged in the open-ended responses from participants was the desire for a smoother transition into immersive experiences and more control over the pace. As one participant commented, "I need a process that'd give me gradual buildup to immersive content." Another expressed a desire for more explanation on, "what is going to happen when you put the VR goggle's on and what movements would be needed." For some users, the uncertainty about what was happening or was about to happen in the immersive experience was a cause for anxiety. This finding is consistent with Wong et al. [6] who made similar observations regarding the lack of control over potentially overwhelming stimuli. One participant mentioned that it, "Would be really useful to prewarn of content, scares etc either in the experience or beforehand so the user knows what's coming and can prepare." Several respondents also wished for more support in familiarising themselves with complex input control schemes that are unlabelled during the experience and for which the resulting button-press actions may not be visible to the user ("It is difficult to know what button performs what action" and "Label all the buttons on apps, unlabelled ones can be difficult to use due to not knowing what's going on on screen").

### 5.5 Provide Physical-Virtual Reference Points

Among the survey participants with experience of VR or AR, 31.2 % indicated some degree of disagreement with the statement (ratings 1–4 on a ten-point Likert scale), "I feel safe". Balance-related concerns were also prominent in the survey responses captured by Garaj et al. [7] and Wong et al. [6]. This suggests that VR and AR technology and content could do more to address user concerns around safety. A common theme observed in written comments was anxiety regarding the loss of perception of and orientation within the real world. Certain forms of disability may particularly exacerbate issues related to balance and disorientation ("Depth perception issues are already an issue for me, but this becomes greatly exacerbated with these types of experiences to the extent that some may consider it unsafe due to risk of falling, injury or distress"). Most developers are unlikely to appreciate the fact that, "For people with visual loss, disorientation can take a long time to recover from in terms of orientating yourself back into time and place." Guo et al. [51] observed that users with mobility impairments will transfer their behaviour of walking close to walls (offering a potential support aid if needed) into a VR setting. A potential solution to these issues around safety and disorientation may be the provision of persistent reference points that connect the physical and virtual world. A simple example of this may be placing a virtual couch in the same location as one's real couch. As one participant suggested, "I would like some way to easily be able to let in the outside world during the experience, for example by quickly lowering the sound level [...]. This is very important to me for safety reasons as audio is my primary means of taking in information." Modern VR headsets, such as the Oculus Quest 2, provide 'pass-through' modes that activate a camera feed of the real world. The Oculus Quest 2 also currently offers experimental features that allow users to 'add' virtual representations of a physical table and/or sofa into one's 'home' VR environment.

### 5.6 Provide Customisable Accessibility Settings

Many survey participants stressed that the requirements of each individual varies due to different impaired conditions, preferences and changes over time. As one participant explained, "people have very differing access requirements even for the same type of barrier." Another participants added that, "each one of us is unique – need tailor made technology to 'fill in gaps' on par with able-bodied people." These statements echo a key theme that emerged from the survey conducted by Wong et al. [6] regarding the need to, "Provide maximum flexibility and customization in any software/hardware and have this as the standard default."

One participant observed that, "The more options the better. One size does not fit all and I think choice is hugely important." As Franz et al. [52] observed in the context of mobile devices, accessibility settings may be ineffective if they cannot accommodate combinations of disabilities, for example, a user with limited dexterity may struggle to operate a magnification tool. Further, accessibility features cannot achieve the best effect if users are confused about what options they need. As another participant noted, "Unless i have an opportunity, I am unable to identify the kind of assistance I may require." There is clearly a tension between customisability and overly complicated settings interfaces ("As long as the choices were not too complicated") that must also be carefully navigated. To make customisations more accessible and easier to utilise, options must be clearly explained. There may also be value in intelligent accessibility feature recommendations [53] to improve discoverability.

### 5.7 Adapt to Ability

One advanced solution to managing the accessibility needs of users is to embed a degree of intelligence that can dynamically adapt to the user's requirements. As one participant observed, "With a disability, your needs can vary from day to day. Or even moment to moment." Burying accessibility settings deep within a system menu is unlikely to support users experiencing such variability in their capabilities. One participant actually suggested an adaptive approach, "Make the most of your experience according to you[r] needs at the time. So flexibility which adapts seamlessly." Another participant highlighted how certain health conditions (many of which co-occur) frustrate efforts to apply a set-and-forget strategy to the configuration of accessibility settings, "Must provide optimised solutions for need at the time. For example, people living with MH [(Mental Health)] challenges may have variable responses depending on mood, meds etc. Those with ms [(multiple sclerosis)] have varying capacity etc. ie, don't assume only one set of variable parameters works. Device should have capacity to ask/check in each session to ask." The participants' comments are in line with the principles of ability-based design [48] that interactive systems should trace, simulate and foresee user performance and adapt to user abilities through the analysis of performance and/or context. Embedding this adaptation functionality into applications in a way that is robust yet simple is clearly challenging in practice. There have been several recent efforts that demonstrate the potential for dynamic adaptation of immersive content to accommodate objectives, such as legibility [54], physical effort and comfort [55, 56], and cognitive load [57]. We highlight this design principle as an aspirational goal that is likely to require the provision of support tools to the developer community.

## 6 Discussion

The survey reported in this paper delivers numerous insights into the challenges around delivering more accessible VR and AR. Many insightful comments from participants also offer helpful suggestions on potential solutions to these challenges.

Our goal in this research is to address an identified gap in the availability of guidance for developers in building more inclusive immersive experiences. Various comments from participants highlight the potential benefits that VR and AR offer to users with a disability. By eliminating physical environment barriers, VR and AR offers a form of liberation to users. Developers should therefore consider how the liberating experiences they are building could be more inclusive of those who might benefit most from the content.

We observed in written responses that users facing access barriers are willing to expend significant effort in trying to use content that was designed without thought for their needs. Consider the experience reported by one participant, "I was trying to use augmented reality apps on my iPhone SE 2 to play games and also for home decoration but as I'm blind and use voiceover screen-reading software on my iPhone SE 2020, I couldn't use the apps as they were completely inaccessible with voiceover, the developers hadn't made them compatible. I tried turning off voiceover and tapping around but didn't know what I was doing." This experience highlights the fact that many users with a disability are interested and willing to engage with AR and VR but face many obstacles, some of which may be easily addressed by design if given sufficient attention.

The vision of inclusive immersion, founded on the principles of Inclusive Design, seeks to promote an understanding of the diversity of users of immersive content. At the most basic level, simply being aware of the various forms of access barriers encountered by users with a disability may encourage developers to make alternative design decisions. Similarly, a basic appreciation of the co-occurrence of capability loss readily highlights the benefits of supporting alternative forms of input and feedback. In this paper we have also sought to capture and represent the voice of users with a disability or impairment to document their unique expectations and interests. Presented in this easily digestible format, we hope that the findings of our survey contribute to the emerging collection of guidance for improving the inclusivity of immersive content.

## 6.1 Limitations and Future Work

A key limitation of this study stems from the fact that it is difficult to reach a large group of users with a disability who have substantial experience in VR or AR. Only 31.1 % of participants in our survey who had some exposure to VR or AR used the technology once every three months or more frequently. Nevertheless, 74 of the 101 total respondents had at least some experience of engaging with immersive content and were therefore able to directly reflect on their prior personal experience. The respondent demographics described in Section 4.1 suggest that there is under-sampling of males and some age groups. In particular, there are fewer respondents in the 18–24 age group than the broader over-18 UK population, despite this age group likely representing a key target audience for immersive content. We acknowledge that these sampling effects may have influenced the results obtained but we suggest that our survey still captures the typical experience of a broad population of users with a disability or impairment.

We utilised an online survey as our primary research method in order to maximise coverage of the spectrum of access barriers encountered by disabled users. We recognise, however, that this choice means that we must rely on self-reported data and potentially inaccurate interpretations of questions. Without the ability to ask clarifying follow up questions, it is difficult to assess the direct relationship between capability loss and user experience of immersive content. We attempted to address this limitation by incorporating open-ended questions seeking further explanation. Nevertheless, some findings require further in-depth exploration.

As immediate future work, we plan to conduct a series of focus groups involving a representative population of users with disabilities to gain more detailed insights and expand on the observations obtained in this survey. This work will serve to confirm our key findings and also allow for greater resolution in the investigation of how accessibility needs may vary for different types of AR or VR devices and content. For example, our survey was designed to capture accessibility issues and expectations common to AR and VR. Regrettably this limits the identification of distinct issues particular to each of these technologies beyond specific comments made by participants. In recognition of the gap in guidance for developers, we are also planning to conduct focus groups with companies and developers to understand where and how consideration of accessibility needs could be embedded into the design process for VR and AR content. One tool which we anticipate being of potential benefit to developers and companies is a simulator that can be used to experience content as though limited by a particular access barrier or a combined set of barriers.

## 7 Conclusions

In this paper we report on the findings of a survey examining the barriers faced by users with some form of impairment, disability or long-term health condition in their access and enjoyment of VR and AR. We found that there is significant scope for improving the experience of users in this group given that 73 % of those participating in our survey with some prior experience of VR or AR had encountered a barrier to their enjoyment. We asked respondents to reflect on if, and how, they were able to overcome some of these barriers in order to assemble a set of potential solutions and workarounds. Extending this line of inquiry further, we also collected participants' expectations and desires regarding features that could be added or improved to make VR and AR more accessible. Tables 1 and 2 concisely summarise these identified barriers, solutions and desired features categorized by access difficulty.

Finally, we have distilled the common themes and solutions emerging from the survey into a set of seven design principles. Each of these design principles is reinforced and contextualized by related work offering similar findings. Critically, our overall approach differs from most prior work in that our response group represents a board range of access difficulties rather than focusing on a single form of disability or impairment. This approach better reflects the frequent co-occurrence of disability and helps to surface the commonality in required accessibility solutions and features. We hope that the design principles identified will offer initial guidance to developers at this critical point in time, given the nascent stage of VR and AR content design.

## Declarations

**Data Availability.** All data generated or analysed during this study are included in this published article and its supplementary information files.

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**Competing Interests.** The authors declare that they have no conflict of interest.

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