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International Journal of Human–Computer Interaction

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hihc20

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To cite this article: Chris Creed, Maadh Al-Kalbani, Arthur Theil, Sayan Sarcar & Ian Williams (27 Aug 2023): Inclusive Augmented and Virtual Reality: A Research Agenda, International Journal of Human–Computer Interaction, DOI: 10.1080/10447318.2023.2247614

To link to this article: https://doi.org/10.1080/10447318.2023.2247614

Published online: 27 Aug 2023.

INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
https://doi.org/10.1080/10447318.2023.2247614

Inclusive Augmented and Virtual Reality: A Research Agenda

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ABSTRACT

Augmented and virtual reality experiences present significant barriers for disabled people, making it challenging to fully engage with immersive platforms. Whilst researchers have started to explore potential solutions addressing these accessibility issues, we currently lack a comprehensive understanding of research areas requiring further investigation to support the development of inclusive AR/VR systems. To address current gaps in knowledge, we led a series of multidisciplinary sandpits with relevant stakeholders (i.e., academic researchers, industry specialists, people with lived experience of disability, assistive technologists, and representatives from disability organisations, charities, and special needs educational institutions) to collaboratively explore research challenges, opportunities, and solutions. Based on insights shared by participants, we present a research agenda identifying key areas where further work is required in relation to specific forms of disability (i.e., across the spectrum of physical, visual, cognitive, and hearing impairments), including wider considerations associated with the development of more accessible immersive platforms.

KEYWORDS

Accessibility; virtual reality; augmented reality; inclusive design

1. Introduction

Augmented and virtual reality (AR/VR) present new transformative opportunities around how we work, communicate, collaborate, and engage with others. However, recent research has highlighted significant accessibility barriers associated with these technologies that can lead to the exclusion of disabled people (Boyd et al., 2018; Creed et al., 2023; D'Cunha et al., 2019; Gerling et al., 2020; Gerling & Spiel, 2021; Mott et al., 2020; Motti, 2019; Zhao et al., 2019; Zheng & Motti, 2018). For instance, work has identified how people with physical impairments can experience challenges around initialising a VR system (e.g., configuring associated peripherals and play boundaries), putting on and removing head mounted displays (HMDs), concerns around cords linked to a device (e.g., becoming trip hazards), and the requirement with some devices to use two (inaccessible) physical controllers simultaneously (Mott et al., 2020).

In terms of neurodiversity and cognitive impairment, research has highlighted a range of barriers across AR and VR experiences such as a lack of customisation, difficulties in interpreting interpersonal spaces, and issues in relation to confusion, anxiety, and misinterpretation of reality (Creed et al., 2023; D'Cunha et al., 2019; Motti, 2019; Rodríguez-Cano et al., 2022). Zhao et al. (2019) also highlight how current devices and applications do not support users who are blind or experience low vision. In particular, research has identified access barriers associated with voice activation, accessible menus, sensory overload, and usability challenges with haptic interactions (Creed et al., 2023). Similarly, barriers for people with hearing impairments include issues around the ergonomics of HMDs in relation to hearing aids, integration of other assistive tools, and a lack of synchronisation in group conversations (Creed et al., 2023).

These challenges are particularly pertinent in the context of the Metaverse where future growth and usage across the wider population will potentially lead to the exclusion of disabled people, thus further widening the digital divide (Macdonald & Clayton, 2013). However, there has been limited work undertaken to date around the design and development of more inclusive immersive experiences. This has led to calls within the field to urgently address these challenges with recommendations focused around ensuring key stakeholders (i.e., designers, developers, researchers, and users) are integrating disability as a core consideration across all elements of their work, increasing disability representation within research studies, and building stronger collaborative partnerships with disability and accessibility groups (Peck et al., 2021).

To address the lack of work in this area, we initially led two full-day multidisciplinary sandpits to thoroughly map out the barriers disabled people experience in relation to immersive experiences (Creed et al., 2023). Whilst this previous work highlighted key accessibility challenges with AR and VR experiences, additional research is required to identify where further work is necessary to tackle these barriers and to identify any important wider considerations (e.g., ethical issues). We address this research gap through the design of two subsequent full-day multidisciplinary sandpits (presented in this paper) that focused on identifying key research areas requiring further attention to support the

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development of more accessible AR and VR platforms. To ensure a diverse range of perspectives, the sandpits were comprised of academic researchers (specialising in Human Computer Interaction (HCI), immersive technologies, and accessibility), AR/VR industry specialists, people with lived experience of disability (including different forms of impairment), and representatives from national charities, special needs schools and colleges, and assistive technologists. Based on the insights shared by participants, we present a comprehensive research agenda for the field highlighting the core areas where additional research is urgently required to facilitate more inclusive AR and VR experiences. The agenda was collaboratively developed and validated in partnership with sandpit attendees and maps out key research challenges across a spectrum of impairments (i.e., physical, visual, hearing, and cognitive) that need to be addressed moving forward.

The paper is structured as follows: Section 2 presents a review of barriers experienced by disabled users when using immersive technologies and current assistive technology developments, Section 3 details the sandpit methodology adopted in this work, Section 4 presents key research areas and opportunities for addressing accessibility barriers across impairments (Physical – subsection 4.1, Visual – subsection 4.2, Neurodiverse/Cognitive – subsection 4.3, and Hearing – subsection 4.4), whilst Section 5 concludes with a discussion of important wider ethical considerations also raised by participants.

2. Related work

We initially summarise key barriers identified from our previous sandpits and position this alongside related work in the field. We then highlight previous research that has explored approaches and solutions to provide more inclusive experiences across a range of impairments.

2.1. AR/VR accessibility barriers

In previous work we led two multi-disciplinary sandpits to explore the key AR/VR barriers experienced by disabled people with physical, visual, auditory, and cognitive impairments (Creed et al., 2023). These collaborative online events were comprised of leading academics working around HCI, accessibility, and immersive technologies, representatives from national charities, industry specialists, assistive technologists from special needs schools/colleges, and people with impairments. The emphasis of these sandpits was primarily on commercial HMDs (e.g., Microsoft HoloLens, Meta Quest 2, etc.), as opposed to mobile AR/VR. Key themes to emerge from the sandpits were aligned with different forms of impairment and were categorised into barriers associated with software and hardware, as well as general ethical concerns with the technologies.

In terms of physical impairment, a range of software issues were highlighted such as challenges around involuntary movements, fatigue, real world physical awareness and proprioception, and a lack of personalisation and dynamic mapping of user reality. In terms of hardware usability, participants highlighted challenges around limited physical movement, lack of compatibility and integration with existing mobility aids, and issues around physical device ergonomics. Furthermore, challenges associated with hand, manual, bimanual, and limb interactions were highlighted as significant issues (e.g., the need to use controllers that require dexterous movements). These findings complement and build on other work in the field focused around interaction barriers for people with physical impairments (Baker et al., 2019, 2020; Gerling et al., 2020; Gerling & Spiel, 2021; Malu & Findlater, 2014; McNaney et al., 2014; Mott et al., 2020). For instance, Mott et al. (2021) identified accessibility barriers associated with VR HMDs for people with mobility impairments, whilst Gerling et al. (2020) identified a range of related barriers in relation to VR gaming for wheelchair users. Similarly, Gerling et al. (2021) identified how current commercial VR devices are typically designed for non-disabled bodies and highlighted the challenges this can present for people with physical impairments. Research has also explored accessibility issues associated with AR devices such as Google Glass (Malu & Findlater, 2014; McNaney et al., 2014) where a range of related barriers were highlighted (e.g., challenges in performing gestures on the device and in issuing voice commands).

In relation to neurodiversity and cognitive impairments, key software issues identified from the sandpits include detachment from the real environment, cybersickness and usage aftereffects, sudden unexpected changes in immersive experiences, and sensory and information overload. In terms of hardware, a range of barriers were highlighted such as discomfort of HMDs, physical or mental injuries or stress, and a lack of support and training. These findings again complement related work in the field (Boyd et al., 2018; D'Cunha et al., 2019; Motti, 2019; Rodríguez-Cano et al., 2022; Seifert & Schlomann, 2021) – for instance, Boyd et al. (2018) reviewed challenges faced by people with autism spectrum disorder (ASD) in relation to VR environments and identified barriers such as lack of customisation, hypersensitivity to sounds, visual processing deficits, difficulties interpreting interpersonal spaces, fear, anxiety, vestibular difficulties (i.e., balance) and elongated temporal processing. Mott et al. (2019) presented several barriers faced by neurodiverse users such as a lack of text customisation, workplace distractions, social interaction challenges, nausea and cybersickness. D'Cunha et al. (2019) highlighted AR and VR barriers for people living with mild cognitive impairment and dementia such as confusion, motion sickness, eye strain, anxiety, incompatibility of HMDs with physical accessibility aids (e.g., glasses), discomfort of VR headsets, agitation, unintentional damage of VR headsets, and misinterpretation of reality (i.e., users believing VR is real). Rodríguez-Cano et al. (2022) also highlight key barriers within a gamified VR system for students living with dyslexia such as challenges in decoding phonemes, concentration deficit, incorrect reading comprehension, visuospatial attention deficit, impaired motor development and difficulties with semantic and lexical development.

In relation to visual impairments, participants identified a range of software barriers during the sandpits such as a lack of binaural audio, issues around voice activation and accessible menus, lack of built-in accessibility features, sensory and information overload, and limited customisation features. In terms of hardware, barriers included a lack of standardisation of the headset system and usability challenges associated with haptics. Participants also highlighted challenges around limited environment and user awareness in immersive environments, as well as a range of entry-level barriers that occur prior to interaction (e.g., challenges with locating buttons for switching devices on). Whilst there has been significant research activity around accessible AR/VR solutions for people with visual impairments, there has been much less wider work around investigating the barriers experienced (Teófilo et al., 2018; Zhao et al., 2019).

In terms of hearing impairments, participants highlighted a range of software barriers including initial access friction, lack of clarity in sounds and instructions in audio format, lack of standardisation in text presentation, and difficulty in pinpointing locations and environment navigation. In relation to hardware, there were barriers around headset ergonomics not supporting the use of hearing aids, compatibility challenges with existing assistive devices and tools to support users, and limited customisation options within immersive experiences. There were also barriers highlighted around the inability to use sign language, lack of synchronisation in conversations with others, and poor rendering of avatars not facilitating lip reading. Similar to work on inclusive AR/VR experiences for people with visual impairments, there has been a range of research focused on exploring new accessible solutions for people who are d/Deaf or hard of hearing (DHH) (Izaguirre et al., 2020), although much less emphasis around the fundamental barriers and challenges they might experience when interacting with others in immersive environments.

2.2. Inclusive AR/VR developments

Whilst researchers have widely explored the potential of immersive experiences to support people with impairments, present literature has largely focused on proposing solutions which train, engage and support users in completing specific processes, with considerable emphasis given to activities such as rehabilitation, treatment, and education. Additionally, while work has started to explore solutions associated with usability barriers for people with physical impairments (when utilising immersive experiences), less research has sought to solve the fundamental usability issues these users face with devices (i.e., the headsets or software platforms), although some notable work has explored the potential of supplementary adaptive controllers (Wang et al., 2018), additional control mechanisms (Sanfilippo et al., 2022) and alternative interfaces (Spicer et al., 2017; Wang et al., 2019). Considering the availability of current consumer ready wearable immersive technology in relation to both AR headsets (e.g., Microsoft HoloLens 2, Magic Leap, etc.) and VR devices (e.g., Meta Quest 2, HTC Vive and Valve Index), the current literature focuses primarily on exploring potential accessible solutions for VR platforms. This can be attributed to the consumer proliferation of VR devices over AR headsets and the availability of entry level consumer VR devices to support recent advances in the VR gaming industry. Therefore, many current solutions presented in the literature focus heavily on the VR spectrum of devices with solutions being proposed for rehabilitation (Elor et al., 2019), training (Oates et al., 2008) and monitoring/assessment (Yeh et al., 2012), whilst fewer studies have been conducted in relation to AR experiences.

VR technologies have been proposed which present a potential pathway to solutions, notably for locomotion and walking with a virtual cane (Kim, 2020; Tatsumi et al., 2016), motion analysis and support via training (Draganov & Boumbarov, 2015), supporting alternative interfaces via eye gaze control (Wang et al., 2019), for navigation in complex environments (De Oliveira et al., 2017) and to support teleoperations of exterior devices/mechanisms (Sanfilippo et al., 2022; Y. Zhang et al., 2021). Whilst less mature in the depth of exploration, literature has begun to illustrate the value and potential of AR solutions to enrich users' lives. Previous work presents solutions associated with supportive technologies for improving motion in AR environments via haptics (Joseph et al., 2013), using contactless gesture-based interfaces to support wider communication (Huo et al., 2021), alternative input paradigms (e.g., tongue control) in controlling the AR environment (Chu et al., 2018), and for improving communication and intervention with third party supervision teams (Machado et al., 2019).

Whilst there has been initial work exploring AR/VR solutions for people with physical impairments, there has been much less research in terms of visual impairment due to the inability of current VR devices to support users who are blind or experience low vision (Zhao et al., 2019). While the inclusion of magnification, recolouring, and high contrast tools could potentially increase the accessibility of virtual reality interfaces for users with low vision (Teófilo et al., 2018), further research is required to address effective ways to make heavily vision-centric consumer-driven VR applications more accessible. However, complimentary to research for users with physical impairment, research has also focused on using VR headsets for developing novel interaction techniques to assist users with visual impairments in different tasks such as guidance via real-time object localisation and spatial audio (India et al., 2021; Katz et al., 2012), using echolocation to improve spatial interaction (Andrade et al., 2021), and in utilising haptic feedback as a supplementary interface via canes and gloves (Kim, 2020; Kreimeier et al., 2020; Zhao et al., 2018).

The literature has also explored the use of feedforward techniques to support users with visual impairments in virtual interactions, notably in the use of visual enhancements to improve touch-based interactions (Coughlan & Miele, 2017; Lang & Machulla, 2021; Zhao et al., 2019). Although results were generally promising in supporting users with low vision in performing interaction tasks, further research is needed for supporting blind users who require alternative interface adaptations and voice-based interaction. Similar to work on VR solutions, AR systems have also explored approaches to support improved environmental awareness via translating visual information into text and speech (Granquist et al., 2021). Furthermore, research has presented novel interaction methods for users who are blind or experience low vision for collision avoidance (Lee et al., 2021), presenting magnification and visual enhancements to the virtual environment (Coughlan & Miele, 2017), and voice-controlled interfaces (Lee et al., 2022).

Research providing solutions and pathways to support VR/AR for users with a hearing impairment is less mature. For instance, initial research has provided guidance and recommendations for frameworks supporting the development of accessible sound representations in immersive technology (Jain et al., 2021). Additionally, work has focused on subtitle recommendations for 360-degree video in immersive environments, considering solutions for subtitle placement, contrast, and speaker diarization or location (Agulló & Matamala, 2019). Research has also explored the extent to which haptics can be used to support people with hearing impairments, notably in sound to visual/haptic mappings (Jain et al., 2021) and wearable devices (i.e., smartwatches) to support an enriched level of environment awareness (Goodman et al., 2020). Furthermore, communication has been a focus of research to support users with hearing impairments, with research proposing solutions for implementing sign language interpretations (Quandt, 2020) or interpretation of sign gestures using novel sensors (Shao et al., 2020). Additionally, communication systems supporting paediatric care and enriched collaborations (including real-time and remote communications) within immersive environments have been explored (Garnica, 2014; Lee et al., 2021; Tenesaca et al., 2019).

Recent advancements in immersive technologies unlock numerous opportunities for neurodiverse users and those living with cognitive impairments. In particular, AR and VR hold potential to provide engaging and innovative solutions offering the ability to manipulate and specifically target cognitive, sensory, interpersonal, and motor processes that contribute to atypical developmental trajectories (Farroni et al., 2022). For learning disabilities researchers have developed supportive AR and VR tools for people with dyslexia (Gupta et al., 2019; Thelijjagoda et al., 2019), dysgraphia (Abid et al., 2019; Hutama et al., 2021), and dyscalculia (Avila-Pesantez et al., 2018). For cognitive impairments, AR and VR interventions have been explored for mild cognitive impairments, dementia and age-related disability (Thapa et al., 2020; Wolf et al., 2019). For intellectual and developmental disabilities, research has focused on developing assistive tools for people with ASD (De Luca et al., 2021; Zhao et al., 2021), attention-deficit hyperactivity disorder (ADHD) (Alqithami et al., 2019; Tosto et al., 2021), obsessive compulsive disorder (OCD) (Cullen et al., 2021; Francova et al., 2019) and dyspraxia (Dhanalakshmi et al., 2020).

In summary, previous work has identified AR/VR accessibility barriers in relation to different forms of impairment, alongside research that has investigated potential solutions to address these interaction challenges. However, whilst this research has made some important initial contributions towards developing more inclusive immersive experiences, there has been limited work investigating new approaches that address the broad range of accessibility challenges experienced by disabled people. We therefore currently lack a clear understanding of how the wide spectrum of accessibility barriers identified in previous work can be addressed and where future research activities should focus to support the development of more inclusive AR/VR platforms. To address this gap in knowledge, further work is required to map out the key areas where additional research is required and to identify any wider challenges associated with the development of accessible immersive systems (e.g., ethical considerations).

3. Methodology

To investigate further the key research areas where work is required to address AR/VR accessibility barriers, we led two full-day multidisciplinary sandpits comprised of academic researchers (specialising in HCI, immersive technologies, and accessibility), AR/VR industry specialists (from organisations such as Unity, UltraLeap, Sense Glove, and SynergyXR), people with lived experience of disability (including different forms of impairment), and representatives from national charities (e.g., Anne Sullivan Foundation, Leonard Cheshire, Shaw Trust Accessibility Services, Everyone Can), special needs schools and colleges (e.g., Treloar School and College), and assistive technologists. We followed the same Sandpit methodology adopted in our previous work (Creed et al., 2023) to facilitate a collaborative approach where individuals from different disciplines could share their knowledge and expertise. Our motivation in utilising this approach was to expose participants to a range of perspectives, thus supporting more inclusive discussions around potential solutions for addressing accessibility challenges associated with immersive experiences. Both sandpits were full-day online events held via Microsoft Teams for which Institutional Review Board approval was obtained. The first sandpit was held on 25th March 2022 and involved 38 participants (including eight academics from the organising research team) who all had experience around immersive technologies. Two British Sign Language (BSL) interpreters were also available for participants who required translation.

All participants were contacted by email prior to the event to send an information sheet detailing key activities and responsibilities during the sandpit. Participants were also asked to complete a consent form prior to the day of the event, as well as to request any access requirements. The event began with an introduction from the research team detailing the motivation for the project and main activities for the day. It was emphasised to participants that the project focus was around experiences with AR/VR HMDs, as opposed to immersive mobile applications. The key rationale for this approach was that the accessibility challenges associated with mobile devices have been thoroughly explored to date, although less work has investigated the barriers and inclusive opportunities associated with HMDs.

Participants were then divided into four groups focused around a specific form of impairment (i.e., physical, visual, hearing, and cognitive/neurodivergent). When selecting participants for different groups we aimed for a diversity of representation including academic researchers, industry specialists, charity representatives, people with lived experiences of disability, and assistive technologists to ensure a range of perspectives were presented and considered. Whilst the majority of external participants aligned directly with one of these perspectives, there were also 4 participants who identified with multiple roles (e.g., an academic with an impairment). In total, there were 9 participants who disclosed a disability, 11 academic experts (4 specialising in accessibility and 7 in AR/VR), and 14 additional stakeholders including industry AR/VR specialists, charity representatives, and assistive technologists. All groups were comprised of at least two disabled participants representing each impairment group (i.e., across the spectrum of physical, visual, auditory, and cognitive impairment). Each group also included two expert facilitators from the core research team. The main focus for the day was to present the barriers identified in Creed et al. (2023) to participants and to explore potential solutions and key research areas which require further attention in the short-medium term. In the morning, group facilitators introduced three high-level themes ("Usability Barriers – Software," "Usability Barriers – Hardware," and "Ethics") which were all comprised of multiple barriers. Each theme was discussed in turn and participants were invited to share their perspectives around potential solutions to address the barriers highlighted.

The afternoon also followed the same process with an additional two high-level themes ("Collaboration and Interaction" and "Lack of Inclusion/Integration") introduced and discussed by participants. After all activities had been completed, groups returned into the main meeting room where lead facilitators fed back on key discussion points covered during the day. All group activities were video recorded for later analysis with participants receiving a £250 gift voucher for their participation during the event. Following the sandpit, a thematic analysis was conducted by the research team to categorise the research areas, solutions, and wider considerations highlighted by participants. All insights were coded to identify initial themes and research opportunities - these themes were then iteratively refined through exploring the relationship between different research areas and solutions. This led to the development of a draft research agenda which was structured across similar themes to the categorisation of accessibility barriers – i.e., "Usability – Software," "Usability – Hardware," "Ethics," "Collaboration and Interaction," and "Inclusion and Integration."

After developing the draft agenda, our goal was to gain feedback from the community around whether it accurately captured key challenges and research opportunities. We therefore organised and led a second full-day sandpit held on 8th June 2022 which involved 30 participants (including eight members of the core research team), in addition to two BSL interpreters. External participants again spanned a range of disciplines including accessibility researchers and practitioners (5), AR/VR specialists (6), people with lived experienced of disability (9), and representation from organisations such as disability charities, specialist education providers, assistive technologists, and policymakers (9). Whilst the majority of participants again aligned directly with a single field, five participants also identified with multiple "roles" (e.g., an assistive technologist with an impairment). Similar to the first sandpit, we aimed for a diversity of perspectives in each group - this included a minimum of two disabled participants, at least one accessibility expert and AR/VR specialist, and individuals representing other stakeholders. We opted for a mix of participants who had attended one of the previous sandpits (to provide some continuity and ensure that key points from the first sandpit had been captured accurately), in addition to new participants who could offer a fresh perspective on the draft agenda.

The sandpit followed the same process with participants being divided into four groups focused around the same forms of impairment (i.e., physical, visual, hearing, and neurodivergent/cognitive). In the morning, facilitators (i.e., members of the core research team) introduced the areas associated with three high-level themes where participants were asked to consider whether anything needed to be added or refined within the agenda, as well as any barriers that might present challenges in exploring the research areas captured. The afternoon session followed the same process and involved covering the final two key research agenda themes. After all activities were completed, each group reconvened into the main meeting room for lead facilitators to again summarise the key themes discussed in their groups. All discussions were recorded for later analysis to help inform and shape the final version of the research agenda. Participants were also provided with a £250 gift voucher for their participation.

Following the sandpit, two experts with a background in immersive technology who have both designed and implemented novel accessible VR solutions independently transcribed and coded the dialogue from each video. Each expert then coded the transcriptions around the thematic topics of the sandpit discussions with a focus on the barriers identified in Creed et al. (2023) (i.e., hardware/software opportunities and ethical considerations). After completing this analysis, both coders met to discuss and iteratively refine the key themes captured to ensure they accurately reflected participants' views. This analysis then shaped the final version of the research agenda presented in Section 4.

4. Inclusive AR/VR research agenda

A research agenda based on the research areas and solutions raised by participants across both sandpits is presented below. Owing to the lack of current research into the opportunities associated with delivering inclusive AR/VR technology, we decided to approach the research agenda through covering a spectrum of impairments that can inform and foster a wider range of research activity. Additionally, this approach aligned with our earlier work (Creed et al., 2023) where we structured barriers according to forms of impairment (i.e., physical, visual, hearing, and cognitive) and thus creates a pathway from barriers to research opportunities. The insights provided by participants are categorised under two core themes – "Software" and "Hardware" – for each type of impairment, alongside "Ethical and Wider Considerations" highlighted in Section 5. All points are summarised in separate tables, alongside further discussion elaborating on the research areas and wider insights captured. The discussion sections are informed by the barriers highlighted in Creed et al. (2023) and focus on high-level themes such as usability challenges (during use), entry level barriers, and compatibility of existing accessibility aids. It is also important to note that we considered prioritising different research areas across each form of impairment. However, when asking participants to consider prioritisation of the themes captured during sandpit activities, this was widely rejected by both disabled and non-disabled participants due to ethical concerns around giving precedence to some ideas over others. It was therefore agreed that prioritisation of research areas should not be undertaken and that all research agenda items should be openly shared as important areas for the wider community to tackle moving forward.

4.1. Physical impairment

4.1.1. Software

For barriers linked with involuntary limb and/or eye movements, participants suggested providing users with multiple input options and control over them – for instance, options to opt out of certain input methods (e.g., eye tracking) and opt into any other input modality (e.g., voice control), as well as filtering out involuntary and less frequent movements (e.g., falling, lurching) via intelligent environments (e.g., filtering out subtle repetitive movements such as tremor). Sharing controls with other users to allow multi-user control of separate interactions or movements was also suggested to support users in collaborative settings and to promote experiences in playing, working, and socialising with others. For barriers associated with physical, mental, and temporal fatigue, as well as potential worsening of conditions due to use of AR/VR devices, participants proposed developing immersive environments that allow users to personalise (or block out) different stimuli in terms of visuals and interactions (e.g., slower speeds, black and white environments, lower sound, etc.) to mitigate fatigue. Exploring the use and potential benefits of AR in reducing full immersion barriers and presenting digital representations of physical environments was also proposed to enable users with impairments to experience physical spaces through immersive technologies (which can be particularly useful for users who are house bound). Proximity measures, safe areas, and spatial personalisation in adaptable immersive environments were other solutions proposed. This would enable users to mark out safe areas in the environment for interaction at the onboarding stage of an immersive experience and would also present benefits for users with involuntary movements.

In terms of barriers linked to real world physical awareness (i.e., balance) and losing proprioception (i.e., body awareness) during AR/VR use, participants suggested exploring accessible options to opt-out of immersive experiences and built-in help features that can be accessed at any given time during use of immersive experiences to counteract potential fatigue. For challenges associated with lack of personalisation to individual interaction requirements, participants shared that user centric design approaches and accurate user profiling should be the ground basics and first layer of inclusive interfaces in AR/VR systems to break the rule of "*one interface is good for everybody*," with one participant stating, "*if you design for everyone, you design for no one*" (i.e., everyone has different needs). Participants further added personalisation is currently only available from a technical perspective and users must follow specific technical steps to personalise experiences, and current systems assume that "*trying things out*" or "*changing system settings*" is accessible. It is therefore also important to consider how users will perform customisations to support the adaptation of more inclusive experiences.

Participants also recommended designing and developing immersive experiences that are tailored around the abilities of the user and to consider the "powers" of people with impairments (such as heightened senses, superior multi-tasking skills, higher attention to visual details). For instance, participants proposed developing immersive environments that dynamically map the reality/disability of the user and simplify movements by mapping physical abilities of users and certain movements to virtual spaces (e.g., if the AR/VR system can recognise that the user can only move a single finger, it would ideally map that finger as an arm during interactions). Participants further shared that audio and gaze mapping can also be effective as alternative methods for interaction in immersive environments for users that face challenges in limb movements.

4.1.2. Hardware

For hardware related barriers linked to limited movement, device ergonomics and lack of customisation in current AR/VR devices, participants suggested further exploring physical devices/headsets that are easy to configure and investigating non-conventional approaches to AR/VR headset design and development through starting from the viewpoint of disabled users in the design stage. Participants were also critical of the lack of attention given by manufacturers to customisation of AR/VR technologies to accommodate for differences in user abilities, in comparison to efforts made in allowing editing or reconfiguration of hair colour, clothes, and faces. Additionally, participants suggested exploring haptic interfaces in simulating sensations otherwise not possible with other wearable devices like headsets (e.g., heat, breeze, etc.), and further added that haptics can be helpful for proprioception as it simulates feedback normally used to help people with their body awareness (e.g., skin tension, changes in wind).

For barriers linked to hand control and limb interactions due to the lack of flexibility of current devices, participants proposed dynamic mapping of user reality and integration of current physical accessibility aids in immersive environments in a simple way where assistive devices can be "plugged into" current AR/VR systems. Mapping changes in physical AR/VR environments and user physiological states (during AR/VR use) to adapt immersive experiences accordingly was also suggested as a solution to address issues associated with limb interaction. In terms of cost and access barriers, participants proposed creating a distributed network of immersive technology devices and support to improve accessibility, affordability, and availability of AR/VR devices and technologies by providing disabled users and communities local resources to access devices, infrastructure, development, and data captured from user studies.

For barriers related to the lack of integration of existing mobility aids, participants suggested that further work is required to develop inclusive AR/VR hardware (i.e., devices) that is compatible with commonly used assistive technologies (e.g., switches, communication aids, etc.). This is an underexplored area and presents significant challenges for people with physical impairments to engage with immersive experiences.

4.2. Visual impairments

4.2.1. Software

For barriers associated with a lack of binaural audio and audio descriptions, participants shared that it is essential to explore how integrated surround sounds can further enrich AR/VR experiences and to investigate customisable methods where users can decide the level between foreground audio and audio designed to assist with navigation. Participants also suggested exploring approaches to support the detection and use of sounds to pinpoint locations, provide self-perception information, and embed customised information within certain parts of the environment. Furthermore, it was highlighted that there is currently a lack of research on which sounds users rely on most when navigating different types of immersive environments (e.g., surrounding sounds, short and targeted audio, sounds environment materials).

For barriers related to inaccessible menus and lack of built-in accessibility features for users with visual impairments, participants highlighted that it is crucial to investigate further how menus can be activated/accessed using a combination of touch and/or voice for interaction (or ideally based on user choice) and advised to consider the different subgroups and communication methods within the visual impairment community when developing accessible menus (e.g., screen readers, Apple's VoiceOver, colour blindness, deafblindness, etc.). Participants also recommended exploring customisable menus that allow users to choose where menus are placed in the immersive experience and to provide a "co-pilot mode" where external users (e.g., individuals supporting disabled users) can select different elements or interact on behalf of users to help improve access. However, it was noted that some users may not have a preference for external support during AR/VR use and that alternative methods will need to provide accessible support in this scenario. Participants also suggested investigating further the use of simple and accessible voice interaction commands to access menus for users that are fully blind (e.g., "menu," "menu sound higher") and highlighted the importance of enriching immersive experiences using binaural audio. Additionally, participants proposed including a specialised tutorial mode for menus to highlight how to interact them - this could be in the form of training for users to become familiar with new menus or central learning embedded within the software that could adapt to the user and guide them through menu use. It was also advised to consider different levels of ability within visual impairment communities when developing learning capabilities for menus to minimise the risk of isolating users from receiving the optimal experience.

To address barriers around lack of customisation in current AR/VR technologies due to accessibility challenges associated with adjusting immersive experiences, participants proposed exploring different accessibility approaches that provide continuous feedback informing users of changes in the environment and their own interactions (e.g., what they have selected on menus, interaction updates, confirmation/-success/failure feedback, etc.) to support users in staying connected to the immersive experience. Additionally, participants advised that continuous feedback methods are suitable for environments that are dynamically changing, although are not necessarily required for experiences that do not regularly change and highlighted it would be important to consider application context and user preferences when providing continuous updates (as not all users would be accepting of this approach).

For barriers related to awareness of surroundings and other users in immersive collaborative settings, participants suggested investigating time out or emergency options that are accessible for users with visual impairments when they are lost in the environment. It was also added that such options should provide auditory feedback that transcribes information around the location of the user, the environment, and other users (e.g., where they are, what other users are doing, if they are in the right space or not, etc.). Moreover, participants proposed considering further the potential of cross-modal associations and correspondences (e.g., colours associated with sounds, sounds associated with temperatures, etc.) that align with different sensory modalities that may be heightened or not impaired. Participants also suggested further research around the impact of realistic sounds or "echo-location" on environment awareness and whether sounds that are relevant to environment materials (e.g., walls of a church or subway) provide accurate associations with places, objects, and users. Participants shared that some users would need the system to assist them in building a visual picture (if they have visual references in the past), but that for others this may not be effective if they were born blind.

For entry point barriers that are faced by users with visual impairments (e.g., inaccessible menus, inability to locate the power button on headsets), participants suggested developing new immersive interaction modes for existing mainstream collaborative platforms currently used that are relevant for users with impairments (e.g., Teams, Zoom), and not solely focus on new technologies, platforms, and devices. Additionally, participants suggested developing immersive environments that enable users to share tasks and cognitive load with others in collaborative settings to make shared experiences more accessible for users with visual impairments.

4.2.2. Hardware

For hardware related barriers linked to lack of standardisation of headset systems and the diversity between current devices in terms of controls and ergonomics, participants highlighted that incompatibility of current devices with physical aids is a common problem for disabled users and recommended collecting user requirements of the design and standardisation of a headset system suitable for people with visual impairments. Participants questioned whether it would be more valuable to have one standard (i.e., one uniform) or multiple minimal standards (e.g., heavier headsets, lighter headsets, controllers that come in multiple sizes, etc.), and suggested that separate AR/VR headsets with different accessibility options could potentially be effective in accommodating varying user needs (e.g., headsets that include accessibility from the ground up, headsets designed specifically for accessibility, and accessibility add-ons for existing headsets that implement inclusive features).

For barriers related to the use of haptics in terms of challenges associated with setup requirements and usability, participants proposed exploring mid-air interactions without any instrumentation and ultrasound methods to provide haptic feedback for notifications or confirmation, although noted that mid-air haptics provides limited feedback in terms of space that does not cover the whole environment and surroundings. Additionally, participants highlighted the importance of keeping interactions natural and comfortable in terms of hardware when using haptic and mid-air interfaces. Providing proximity measures and environment information using haptics in collaborative settings was also suggested by participants to improve effectiveness of such interfaces for users with visual impairments. This approach would take advantage of wavelength and intensity customisations offered by haptics to provide environment, interaction, and proximity information depending on user and environment changes in the immersive environment (e.g., a certain vibration for notifications, higher haptic feedback for hazard notifications, etc.). Participants also proposed development of AR/VR systems that can transform visual information to tactile representations. Participants further noted it would be key to identify the most important features in the environment for the user in order for these approaches to work effectively (i.e., "*grab the essence of the visual information*" and transform those to a form that is usable for users with visual impairments).

Similarly, for barriers linked to **sensory and information overload**, participants proposed investigating multimodal AR/VR systems with well targeted audio feedback and haptics to better understand the optimal conditions for utilising these technologies and to mitigate some of the sensory overload experienced in collaborative immersive systems (i.e., examine the extent to which no extra surrounding audio or noisy surroundings can limit the feeling of haptic feedback). Participants also suggested exploring separate haptic interfaces on different body parts to convey information (i.e., navigation restricted to the right hand, a belt vibrating the direction to turn, etc.) and the use of haptics to define virtual spaces to support users with environment navigation. Using non-conventional interfaces (e.g., BCI, EEG, Galvanic Skin Responses) to mitigate sensory overload challenges was proposed by participants to monitor the status of the user during VR/AR use and accordingly moderate the sensory information and environment based on the reality and ability of the user (i.e., monitor and adapt the experience based on stress levels, sensory information load, cognitive load, physiological data, etc.). Participants also shared that it is essential to develop customisable immersive environments that allow users to "strip out" sensory information that is not required to mitigate sensory or information overload. It was also noted that a similar approach could work for audio, where users can choose between "all audio" and/or "essential audio."

Use of haptics as a "back channel" was also recommended – in particular, participants shared that the audio channel is normally fully used or occupied in collaborative settings for people with visual impairments (i.e., when communicating with other users, processing of audio environment descriptions, etc.) and utilising a different modality such as haptics in immersive environments can be effective to address problems of lack of awareness of surroundings, other users, and interactions in immersive environments. Participants also discussed exploring new methods where physical aids used by users are considered an extension of the user's body (e.g., a walking stick) and can be utilised to navigate immersive environments, interact with other users, and provide feedback. Examining the potential of different multisensory feedback to describe the immersive environment was also suggested to enhance user awareness (e.g., adding smells, sounds, temperature, humidity, breeze, etc.), and other sensory information that do not need to be processed using hearing (e.g., the smell of trees can suggest a user is located in a forest). Further research on how LiDAR technology can help users with visual impairments was also proposed to better understand how light can be transformed to meaningful audio descriptions.

4.3. Neurodiversity/cognitive impairments

4.3.1. Software

To mitigate key barriers associated with full immersion and feeling of detachment from the real environment, participants shared that exploring how AR can potentially mitigate stress through recreating real environments and familiar surroundings that users are comfortable with could be a fruitful area. Customisation of AR experiences and the ability to dimmish certain aspects of immersive environments was also proposed to mitigate full immersion barriers. Furthermore, participants highlighted the importance of multimodal material feedback systems that utilise tactile feedback and grounding methods (e.g., simulating feet pressing on the ground or holding onto surfaces) to improve navigation and awareness in immersive environments, particularly for users that experience visual mismatches and/or proprioception. While full immersion presents several barriers, participants noted that detachment and full immersion could also be useful in recreating experiences not feasible in real environments that can potentially lead to positive mental outcomes.

For barriers related to cybersickness, participants suggested investigating further the use of software design "tricks" (e.g., virtual frame of reference or horizon, using teleportation for environment navigation, etc.) and customisation of certain elements of the immersive environments (e.g., colour, speed, volume, brightness, etc.) to mitigate cybersickness and potential usage aftereffects. Participants emphasised the importance of framing expectations clearly around potential side effects during AR/VR exposure and providing support before, during and after experiences. Additionally, participants shared that cybersickness will be significantly mitigated or eliminated as AR/VR technologies advance with better hardware and software, while also acknowledging that cybersickness is not only a software design problem, but an inherit issue in HMDs due to the vergence-accommodation conflict (Kramida, 2016; Zhou et al., 2021) and can also be influenced by how different individuals experience AR and VR (i.e., different mental models, cognitive levels, etc.).

To address barriers related to sensory/information overload, uncertainty about generated environments and stress caused by sudden changes (e.g., changes in brightness, movements, avatars), participants proposed exploring methods for providing users with detailed walkthrough video previews of immersive experiences that clearly showcase all possible interactions, visualisations and scenarios that will be experienced by users. Such previews would ideally also provide information on the timings in which events or changes would occur in the immersive environment. Development of proximity measures and marking of safe areas for interaction and collaboration in immersive environments was also suggested as a design solution to limit sudden changes (or eliminate them completely). Participants shared that proximity measures could provide promising results as they have already been used effectively in previous research focusing on crowd simulation and modelling for collision avoidance (Dickinson et al., 2019; Grzeskowiak et al., 2021). Participants also highlighted challenges from previous research around complexity, running time, latency in multiuser AR experiences (Alzahrani, 2020; He et al., 2019), and recommended developing intelligent immersive platforms that can decide and handle task scheduling, and prioritise tasks based on user abilities to mitigate problems associated with cognitive load and coordination during multiuser interaction environments. Providing users of AR/VR technologies with accessible ways to leave immersive experiences when needed was also highlighted and would allow users to step away from immersive experiences if faced with any of the negative aspects of collaborative environments (e.g., cyberbullying, harassment, stalking, etc.).

4.3.2. Hardware

For hardware related barriers such as discomfort of HMDs and their incompatibility with physical assistive devices (e.g., eyeglasses, canes, etc.), participants proposed the development and exploration of non-immersive experiences for users who cannot use headsets. This future direction would consider large semi-immersive screens, 3D glasses, and holographic screens where users are not required to wear any devices and can still access interactive elements within the experience. Participants further added that providing options around immersion levels and the ability to opt out still remains essential for non-immersive experiences. Participants also stressed the need to consider broader aspects of HMD designs and not discomfort alone, and highlighted current devices are not readily designed to consider many physical differences (e.g., position of lenses and the range in which you can manipulate them (i.e., interpupillary distance) in current headsets are biased towards males). Development of bespoke headsets that are informed by neurodivergent users in terms of design and functionality was also suggested to improve accessibility and usability. Participants shared this is now a practical solution given the availability of open access circuits and electronics knowledge, and cautioned that such efforts should not aspire to compete with existing large manufacturers of AR/VR devices (e.g., Meta, HoloLens).

Regarding barriers of physical or mental injuries and stress due to full immersion and uncomfortable headsets, participants suggested monitoring the physical and physiological states of users during AR/VR exposure using non-conventional interfaces to mitigate physical and/or mental injuries (e.g., BCI, EEG, vestibular or galvanic responses). Participants shared that recent research is focusing on BCIs and/or EEG VR interfaces to monitor brain activity to give warnings and adapt immersive environments based on the user's brain, skin, and heart activity (Dey et al., 2022; Kico & Liarokapis, 2022; Sra et al., 2018; Ventura & Profini, 2021). Participants also proposed investigating the use of cheek swabs for stress and cortisol stress hormone levels for longer term monitoring. However, participants cautioned that these approaches are not "out of the box" solutions and need to be programmed to be adaptable based on user reality (e.g., if brain activity, galvanic response, or heart rate reaches a certain threshold, a particular action can be triggered, or the immersive environment can be modified or adapted). Additionally, most non-conventional sensors are not currently accessible, with setups that are usually bulky, uncomfortable, and heavy (typically utilising wearable devices). Participants recommended that monitoring should primarily focus on comfort of users to report on their experience rather than investing extensive amounts of time and resources dissecting physiological and mental activities that are costly and time consuming. Simple rating systems that are seamlessly built into experiences was recommended as a beneficial alternative that can monitor and support users in response to certain activities in immersive environments.

For barriers related to input and hand coordination challenges and multitasking, participants recommended exploring alternative and non-invasive input modalities to work around the limitations of current controllers (e.g., computer vision methods for interaction, hands free control, gaze input, non-invasive BCIs, heart rate-based interactions with ECG, sound interactions, etc.), and shared that multimodal approaches in particular would be useful to tailor interactions depending on the abilities of individual users. Participants were also critical of current consumer devices that do not provide this breadth of input by default, especially when viable means of interaction in immersive environments have been well researched with positive results "*… we are not exploiting this breadth of potential interactions and inputs, and why are these companies not exploiting these options? Do we have to legislate to ensure these capabilities are provided for different kinds of interactions and users?*." Additionally, participants shared that funding should be directed towards significant accessibility issues initially and then investigate applications for these technologies instead of solely focusing on the applications of current tools, though participants also acknowledged this proposition may not be attractive for potential funders.

For barriers related to controller usability and ergonomics, participants were critical of the lack of standardisation for controllers and limited synchronisation across AR/VR devices (in terms of interaction methods). Participants recommended development of different controller designs and types to improve interaction and collaboration for users with impairments, ideally with comfortable larger buttons and text, tactile feedback, and light colours. It was suggested that research on input methods should focus on the development of different controller types and designs suitable for a range of applications (e.g., painting, games, navigation etc.), controllers that can be placed around the neck if not in use (to mitigate fatigue), and the use of bespoke controllers using 3D printing methods as custom addons for individual users.

4.4. Hearing impairments

4.4.1. Software

For entry level barriers faced by users prior to interacting with AR/VR experiences (i.e., due to low literacy in AR/VR knowledge, lack of support and technology acceptance by the d/Deaf community, etc.), participants suggested investigating methods that integrate technical support and bespoke tutorial modes within immersive systems to ease the friction experienced during initial access to AR/VR technologies. Participants also urged for more standardisation in immersive technologies and called for mandates that force manufacturers to adopt unified and accessible tools, and shared the example of how Apple is now mandated to adopt USB C by 2025 as an ideal route to follow for AR/VR technologies (Sparkes, 2021). Participants also proposed investigating the development of assistive paths that are embedded in immersive ecosystems where AR/VR providers can provide remote support for users with hearing impairments and manage devices remotely. This would be similar to enterprise licenses used by large organisations to allow technology providers to manage their devices and software remotely.

For barriers relating to lack of clarity in sounds and instructions in audio format in immersive environments, participants reiterated that current captioning standards do not provide sufficient detail (e.g., "loud bang," "music plays") and recommended embedding realistic and detailed audio descriptions to better support understanding within immersive environment surroundings (e.g., detailed descriptions of a musician playing the violin would help understand the information and replicate it). Participants further added this will potentially mitigate challenges around users being excluded from interactions in collaborative settings. Providing real-time sign language interpretation embedded in immersive environments (i.e., using real people or realistic avatars) was proposed by participants to address barriers around lack of standards in text presentation, audio description and descriptions of external sounds as more emotion and details are typically conveyed (in comparison to live captioning). Participants advised considering the different layers within the Deaf community when exploring this research pathway (i.e., users born deaf, users who become deaf later in life, deaf and visually impaired), and further reiterated that current sign language automation attempts are limited and not as accurate as real interpreters, as well as being costly with extensive motion capture requirements.

For collaboration and interaction barriers related to inability to use sign language in immersive environments due to poor visual quality, sign language not being the first language of users, and/or inaccessible experiences, participants reiterated the need for real time interpreters using humans or avatars that can transcribe built in audio detection back to users in formats usable for users with hearing impairments to provide an enhanced experience. Participants also suggested considering users' perceptions of immersive environments when developing accessible systems for people with hearing impairments, and further added that providing binaural audio in immersive environments can improve interaction and collaboration by giving users a sense of where other users are in the environment.

For barriers linked to lack of synchronisation in conversation during collaboration in shared virtual spaces due to slow audio transcription/captioning, using different (and incompatible) assistive methods, or/and not being able to lip read, participants proposed the development of less immersive and desktop-based experiences where users with impairments would not need to actively process full immersion while communicating and collaborating with others. Participants also recommended developing immersive and non-immersive experiences that present information in the field of view of users to mitigate high cognitive load and distractions caused by processing different sources of information simultaneously (i.e., having to read, lip read and process visual information, use different devices, etc.), and added that interaction or information should ideally be integrated in a unified immersive experience rather than presenting it as an add-on or extra steps that users need to take to interact with or navigate environments.

For barriers related to inability to lip read in immersive environments due to poor rendering of avatars, participants recommended research contributing towards common facial data sets that can be shared between platforms, especially with the current absence of a common standard to define facial mapping/expressions and harmonise the precision of facial expression detection and mapping across platforms and devices. This will be useful for users with hearing impairments that need to render more precise facial capture information, where avatars could have the capability to access facial capture datasets and render more precise facial expressions. Participants further shared that Unity and Unreal are making a push towards hyper realistic virtual humans that run in real time, where users of Unity and Unreal will be able to access those realistic humans for free to create avatars that relay much more precise facial expressions that would be useful for users with hearing impairments (Sunny et al., 2022; Van Der Boon et al., 2022). Additionally, participants suggested further research to test the usability and accuracy of lip reading on avatars and shared they would be interested to try lip reading on avatars given the importance for deaf users in social and collaborative settings, especially if they are not users of sign language. Participants also suggested that reducing the cost and complexity of advanced motion capture techniques (e.g., for avatar rendering) would reduce entry barriers and improve adoption.

4.4.2. Hardware

For hardware related barriers such as full immersion, bulky devices with limited space for hearing aids, audio feedback caused by device microphones on top of hearing aids, participants proposed the use of see-through AR devices (e.g., HoloLens 2) or modes (e.g., passthrough mode in Meta Quest) as potential solutions for users with hearing impairments to avoid blocking the main means of interaction with their surroundings and the environment (i.e., sight) and highlighted the importance of understanding disorientation and usability barriers of pass through AR/VR headsets. Participants also suggested further research on the feasibility and effectiveness of using current devices as hearing aids, and development of bespoke adapters that can adjust headset width, size, cloth materials to accommodate for different user preferences and assistive aids. Development of customisable headset facial interfaces that are integrated in the design process of AR/VR devices was also suggested to ensure devices are useful for users with different needs and assistive aids (i.e., people using glasses or hearing aids). Participants also proposed development of semi-immersive experiences (e.g., 360-degree domes, 180-degree domes, WebXR) that can be used as a desktop model. Participants shared this setup and level of immersion would be more suitable for users that cannot tolerate headsets. This can also mitigate problems around compatibility and comfort, thus leading to lower cognitive load associated with processing different information simultaneously.

For barriers around lack of compatibility of current AR/VR devices with existing devices and accessibility aids, participants shared a number of good practices (e.g., Meta Quest, HoloLens) and stressed the importance of developing devices and platforms that are extendable to be compatible with other assistive devices to ensure they are useful for users with different needs, with one participant stating, "*as platforms, we need to be conscious of this and make sure this is integrated in the design and commercialisation process*." Participants also suggested developing AI assisted solutions capable of capturing and transcribing user/environment audio in non-auditory formats. Exploring headless trackers that can be placed on physical aids (e.g., glasses, walking canes) in desktop or semi-immersive settings/domes to mitigate hardware related barriers was also suggested.

For barriers relating to the challenges associated with the use of haptics in terms of setup requirements and usability, as well as challenges around pinpointing locations and environment navigation, participants suggested the use of haptics and subtle haptic variations for confirming changes in location, detection of singular actions, describing what sounds are and where they are coming from in immersive environments. Multimodal feedback approaches using a combination of haptics, detailed text descriptions and live interpretation to convey spatial cues more accurately was also proposed to help users with hearing impairments better navigate immersive environments. Participants shared that similar live captioning methods using a real person zooming into calls is a current solution where emotions are conveyed by visually showing who is speaking/playing which helps in environment navigation, and highlighted that it is essential for developers and researchers to understand the differences between sign language and live captioning in terms of syntax to develop similar accessibility tools that are useful for users with hearing impairments (i.e., sign language is a visual language with different and faster syntax). Participants also shared that the use of haptics could be counterintuitive as touch is another means of primary communication that should ideally be accessed without additional devices. Participants further added haptics may interfere with hearing equipment and/or hearing concentration, and suggested mid-air haptics without instrumentation as an alternative approach.

For barriers linked to the lack of customisation in current AR/VR devices, participants stressed the importance of including inclusive design and development guidelines to open standards that are focused on agnostic AR and VR to improve accessibility and compatibility with other assistive devices, with one participant stating, *"the key problem is that solutions go down a path of limiting to only one solution rather than having an open system where different types of solutions can use the same system. if you have a feature that only works on a VR headset but not anywhere else then you're excluding people*." Such standards would also include development for immersive screens or interfaces that do not use screens. Participants shared that there is a positive shift in industry towards supporting OpenXR (the official software layer adopted by Meta and HoloLens) using open standards that aim to enable users to create custom made extensions and tools that can be integrated with custom hardware and software layers in the future. Additionally, participants shared that part of the customisation effort should rely on having a network of professionals that provide users with access to customisable features (i.e., in terms of content, hardware, software) and help users onboard as AR/VR platforms become more ubiquitous and advised that customisation can introduce complexity during the onboarding journey of the user.

5. Discussion

This paper maps out future research pathways (Tables 1–4) for improving the accessibility of immersive technologies for users with a range of impairments (i.e., physical, visual, hearing, and cognitive), informed through a user-centric and participatory study design that included collaboration with disabled participants and relevant key stakeholders (i.e., national charities, community representatives, assistive technologists, academic and industry experts). These new insights develop our previous work in this area where accessibility challenges and barriers across the same spectrum of impairments were captured from disabled people and other stakeholders (Creed et al., 2023). Furthermore, alongside the research areas identified, a range of ethical and wider considerations were also highlighted by participants that will be crucial in ensuring that accessible and inclusive immersive systems are developed moving forward.

For instance, the development of national and international networks, centres of excellence and public communities to provide training, access to devices and user centric experiences was a common theme across all groups to improve access to AR/VR technologies, AR/VR adoption and technology acceptance within disabled communities. Similarly, developing and promoting sustainable lending schemes of XR devices and technologies that directly benefit users with impairments, charities, and other stakeholders was also proposed to improve accessibility of AR/VR devices and technologies, with one participant stating, "*that's something that will probably win a lot of hearts and minds as well, it looks sustainable, it looks ecological, it looks as if it's improving social justice, things like that can gain a tremendous amount of good will, let's be honest this stuff will be way beyond the reach of most people at a consumer level for long time, so I think there could be a lot of good will by recycling and sharing*." Participants cautioned that commercial gains for large AR/VR companies may break such recycling and sustainable approaches (i.e., older versions of devices and software becoming obsolete to motivate consumers to move to the next model), but remained positive of a change in this approach with enough vocal criticism around sustainability and environmental impact with one participant stating, "*the younger generation are loud and angry about these issues, and not getting the buy in from this generation will potentially be a strong pressure point for change*."

Additionally, empowering disabled users to develop inclusive solutions for their communities through extendable platforms, accessible training, and support in developing the necessary technical skills to work with large manufacturers of AR/VR technologies was also a common proposition across groups (to improve accessibility and user adoption of AR/VR technologies). Open APIs, public access to the source code of systems, development of an accessible design and development platform (similar to Unity) were some of the solutions proposed by participants to make the process of creating custom solutions using intelligent and assisted creation methods approachable and accessible for users with impairments. Participants noted that extendable and open-source approaches would empower users with impairments (or their representatives) to create custom interfaces that work for them across different platforms and devices. Furthermore, they noted that content and tools created by users with impairments would provide useful representations of what these communities are seeking and would accordingly help non-disabled developers draw inspiration around developing more useful and inclusive tools. This would also mitigate reliance on commercial resources from one or several companies, with one participant stating, "*building accessibility into all the products is key*." Participants also highlighted the importance of pushing for clauses and laws that mandate manufacturers of headsets and AR/VR products to comply with certain accessibility standards and regulations to ensure that accessibility becomes a requirement and part of future AR/VR systems and devices. Recent research investigating the ethical implications of AR/VR technologies (Ro et al., 2018; Simon-Liedtke & Baraas, 2022; Spiegel, 2018) reaffirms the need for the development of guidelines, standards and best practices into regulations and laws to improve accessibility and usability of AR/VR technologies.

To improve support and training and mitigate challenges often faced by users with disabilities in setting up of AR/VR hardware and learning of AR/VR technologies, participants proposed several practical routes forward. For instance, they highlighted the importance of building awareness of complex AR/VR issues for all stakeholders, with measures being put in place to protect disabled users especially when there is an obligation for healthcare and education (or the workplace) to use AR/VR technologies. Participants also recommended evangelising of immersive technologies by stakeholders to raise awareness around their benefits and risks, and provision of appropriate disability awareness training for organisations using AR/VR tools. Lobbying professional and accrediting bodies to embed training on AR/VR technologies and inclusive design into the development of professionals working in these domains (e.g., social worker, nursing, occupational therapy) was also a common recommendation across groups. Participants proposed the development of short AR/VR courses focused on upskilling professionals working in this area and highlighted the importance of exposing professionals to immersive

Table 1. Research agenda items to improve accessibility of AR/VR technologies for users with physical impairments.

Software
Alternative input methods: explore alternative control input options specifically for people with physical impairments (e.g., using eye gaze tracking and voice control).
Movement filtering: investigate methods for filtering out involuntary and less frequent movements (e.g., falling, lurching, subtle repetitive movements such as tremor).
Interaction/control sharing: investigate multi-user control approaches to support people with physical impairments in participating within collaborative and wider immersive experiences.
Customisable experiences: examine new customisable methods that allow users to personalise (or block) stimuli in environments (e.g., lower interaction speeds to reduce fatigue).
Simulation of physical worlds: investigate the impact of AR/VR enabling disabled people to experience physical spaces via immersive environments (e.g., for those who are house bound).
Proximity measures, safe areas, and spatial personalisation: explore adaptable environments enabling users to mark safe areas for interaction (e.g., to reduce risk of physical injury).
Opting in/out: investigate accessible approaches for opting in/out of immersive experiences to counteract potential physical and mental fatigue.
Built-in help options: research the optimal way to provide inclusive built-in help and support features within immersive experiences that can assist users at any point during an interaction.
Personalisation and dynamic mapping: investigate methods for dynamically mapping user physical abilities and simplify movements to virtual spaces via accurate user profiling.
Hardware
AR/VR headset design: investigate alternative approaches to headset design that are easy to configure for people with physical impairments and align with disabled users' requirements.
Customisable devices: conduct further research on customisable device interfaces for people with varying physical abilities prior to engagement with immersive experiences.
Integration of physical accessibility aids: explore the development of hardware systems that can integrate and support common physical accessibility aids.
Physical and physiological environment: investigate methods for monitoring physical environment and user physiological changes and adapt immersive systems accordingly.
Haptic feedback: examine new haptic experiences for simulating sensations that can support body awareness for people with physical impairments (e.g., skin tension and changes in wind).

Table 2. Research agenda items to improve accessibility of AR/VR technologies for users with visual impairments.

Software
Binaural audio: investigate immersive environments with integrated surround sounds to enrich AR/VR experiences for people with visual impairments.
Audio-based navigation: explore further the detection and use of sounds to pinpoint locations or embed customised information within certain parts of the environment.
Accessible menus: develop inclusive menus controlled using touch and/or voice, as well as integration of a "co-pilot mode" where external users can perform selections on behalf of users.
Continuous feedback: explore methods for continuously informing users about menu status, interaction events/environments, and during avatar customisation.
Timeouts: investigate time out or emergency buttons in immersive environments that are accessible for users with visual impairments if they become "lost" within the environment.
Sensory modalities: examine potential of utilising cross-modal associations (e.g., colours associated with sounds) and sensory modalities that may be heightened if others are impaired.
Realistic sounds and awareness: investigate the impact of realistic sounds on environment awareness and whether they provide accurate associations with places, objects, and users.
Collaborative tools: consider new immersive interactions for existing mainstream collaborative platforms (e.g., Teams and Zoom) used by people with visual impairments.
Cognitive load and task sharing: explore approaches enabling sharing of tasks with others to reduce cognitive load within collaborative settings.
Hardware
Device design: understand further the specific requirements for people with visual impairments in terms of the design and standardisation of inclusive headset systems.
Mid-air haptic interaction: investigate mid-air haptic interactions for improved feedback (e.g., ultrasound providing haptic feedback for notifications or confirmation).
Multimodal audio and haptic feedback: research multimodal AR/VR systems combining audio feedback and haptics to address sensory overload in collaborative environments.
Intelligent sensory adaptation: monitor user sensory information during AR/VR use and adapt experiences accordingly (i.e., in terms of stress levels, cognitive load, physiological data).
Customisable sensory experiences: investigate customisable approaches allowing users to "strip out" sensory information not required within immersive experiences (e.g., choosing audio levels).
Tactile information: explore AR/VR systems capable of transforming visual information to tactile representations that are useful for users with visual impairments.
Tool extensions: explore potential of physical aids that are considered an extension of the user's body (e.g., walking stick) to navigate environments, interact with others, and provide feedback.
LiDAR as an assistive tool: further research how LiDAR technology can support users with visual impairments and how light can be transformed to meaningful audio descriptions.

technologies early in their academic journey to ensure they advocate for these technologies once on the job, and shared experiences of how the process of integrating existing practitioners with these tools can be less effective if undertaken later. Additionally, participants urged for more focus on visibility awareness in AR/VR conferences (i.e., through keynotes and workshops) and disability justice training for all stakeholders that focuses on autonomy and empowerment for disabled users when using immersive environments (to push for more inclusive AR/VR technologies and practices).

For ethical barriers linked to protection of users with impairments from potential negative aspects of virtual collaborative spaces (e.g., cyberbullying, exclusion of users, harassment, etc.), participants recommended that relevant

Table 3. Research agenda items to improve accessibility of AR/VR technologies for users with cognitive impairments.

Software
Reality Perceptions: explore solutions to manage users' perception of reality and offer customisation options to alter reality and/or diminish unwanted aspects.
Feedback methods for self-awareness: investigate approaches associated with tactile feedback and grounding methods to inform users where they are in immersive environments.
Cybersickness: develop solutions to mitigate cybersickness for neurodivergent users who may be sensitive to immersive experiences.
Walkthrough previews: explore potential of introductory walkthrough previews of immersive experiences showcasing all possible interactions that will be experienced during use.
Sudden changes: investigate new methods for supporting proximity measures and safe area marking that limit the potential for sudden changes within an immersive environment.
Intelligent task management: develop intelligent systems that can handle task scheduling and prioritisation in multiuser interaction environments to reduce cognitive load and coordination.
Accessible exit controls: explore accessible methods for providing choice around leaving immersive experiences (e.g., if neurodivergent users face cyberbullying, harassment, or stalking).
Hardware
Alternative non-immersive experiences: examine non-immersive experiences for users that face challenges in using headsets (e.g., large semi-immersive screens, holographic screens, etc.).
Exclusive devices for disabled users: researchers and small companies should consider developing specialised headsets for neurodivergent users with different forms of impairment.
User state monitoring: investigate monitoring of physical and physiological states using non-conventional devices to mitigate physical/mental injuries and support adaptable environments.
Accessible input modalities: examine different input modalities (e.g., haptics, gaze, speech) tailored specifically for users with cognitive impairments as alternatives to current controllers.
Bespoke controllers: explore the design of custom and tailored physical controllers that can accommodate neurodivergent users.

Table 4. Key research agenda items to improve accessibility of AR/VR technologies for users with hearing impairments.

Software
Onboarding guidance and technical support: explore methods for providing technical support (especially during onboarding) to ease friction for d/Deaf users during initial access to AR/VR.
Assistive paths: investigate the integration of assistive paths within immersive systems that allow AR/VR providers to manage and support devices remotely for users with hearing impairments.
Real time "detailed" audio descriptions: explore approaches to present detailed audio descriptions to support understanding of surroundings in immersive environments.
Real time interpretation: investigate and develop methods that provide real time interpretation in immersive environments (i.e., using real people or realistic avatars).
Positional perception in shared environments: explore further the use of binaural audio for giving users a sense of where other users are located within shared immersive environments.
Information presentation within field of vision: explore presentation of information in a user's field of view and impact on cognitive load and distractions from other sources.
Facial mapping data sets: contribute towards facial data sets that can be shared across platforms and investigate opportunities for enhanced rendering of avatar expressions and movements.
Avatar lip-reading: investigate opportunities for further improving avatar fidelity to facilitate accurate lip-reading interpretation for d/Deaf users in social and collaborative settings.
Hardware
See-through modes: investigate the extent to which pass through devices or models can provide potential solutions to avoid full immersion for users with hearing impairments.
Headsets as hearing aids: further research the feasibility and effectiveness of using current devices as hearing aids for users with auditory impairments.
Specialised headset adapters: explore development of tailored adapters that support adjustment of headset width, size, and cloth materials, as well as integration with existing accessibility aids.
Customisable facial interfaces: investigate the potential of customisable headset facial interfaces to ensure AR/VR devices work for everyone (e.g., people using hearing aids).
Non-immersive experiences: investigate potential of 180°/360° domes and WebXR to mitigate comfort and cognitive load issues associated with processing different sources simultaneously.
Translate captured audio to non-auditory formats: create intelligent assistive solutions capable of capturing user/environment audio and transforming into non-auditory formats.
Headless trackers and physical assistive aids: investigate headless trackers that can be placed on physical aids in desktop or semi-immersive settings to mitigate compatibility related barriers.
Haptic feedback: examine subtle haptic variations for confirming changes in location, detection of singular actions, and describing sounds and their locations within immersive environments.
Multimodal navigation: investigate a combination of haptics, detailed text descriptions, and live interpretation to facilitate enhanced environment navigation.

stakeholders should join global initiatives focused on ethics for immersive environments (e.g., XR standards, Global Initiative, XR Access for XR Ethics) to further strengthen the push towards accessible immersive environments with measures to protect disabled users. Participants added that shared outputs from these initiatives can influence legislation and initiate change. Participants also suggested public campaigns to raise awareness around negative humanity traits in social immersive environments and stressed the need for legislation and clear policies in immersive environments to protect users with impairments and further added that manufacturers should ideally be held accountable and mandated to produce guidelines, instructions, and support for disabled users. Raising awareness on social and historical issues is critical for impairment communities that may appear closed such as Deaf communities to help developers and researchers understand why users with hearing impairments may appear closed off or unsure to try new technologies (even if developed by a person living with a hearing impairment).

Additionally, participants suggested considering the ethical implications of simulating real life impairments to promote empathy and raise awareness among non-disabled users in shared virtual spaces. Participants argued that simulation of disabilities to promote empathy presents a good starting point in the research to raise awareness, however a more useful effort would be to provide disabled users with the tools to create the layer of information required for their community. Participants shared simulations could also be uncomfortable experiences and raised concerns around the value and effectiveness of simulating different disabilities, with one participant stating, "*a simulation would never recreate the experience and it is problematic as you cannot swap the lived experience with a simulation*." For Deaf communities in particular, simulations would not be useful for users who were born deaf with no information around what sound is and would not pick up on senses that may have become heightened or stronger with impairments to compensate for lost senses (e.g., lip reading comes naturally with hearing impairments, more attention to detail with neurodiversity). Participants also shared past experiences in using simulations of hearing impairments and indicated that such efforts are normally not long enough and do not provide an accurate representation of the impairment. Participants also stressed the need for further research on the implications and complexities that can arise from content and experiences created by users (not just developers) in current immersive technologies and platforms on accessibility, especially when there is a big push and attraction for users creating content for immersive environments, and reiterated the need for standardisation to ensure that content created by users is also following the same guidelines, and is not damaging to certain communities.

Several recommendations were shared by participants for barriers around the unknown impact of hyper realistic immersive experiences on physical and mental health and disassociation with reality following AR/VR exposure. Participants suggested further research on physical and mental disassociations with the physical world experienced by users with impairments after leaving AR/VR environments and further added that carers and clinicians have a duty of care where they would not be able to facilitate use of technologies that can harm users - it will therefore be critical that they can understand the full impact of immersive technologies on their patients. Participants provided a range of suggestions to limit AR/VR exposure time and mitigate hyperrealism challenges such as incentivising users to take breaks and built-in usage limits (e.g., similar to Minecraft games where players receive better bonuses if they take longer breaks), using robust controls that go beyond using generic "18+" or "16+" labels normally used for other media formats (e.g., movies or games) to minimise potential abuse, use of cartoonish depictions (e.g., exaggerated characters and features with cartoonish characters), built-in prompts for moderating use (e.g., "are you sure you want to continue?," hyper realistic experiences switch off after a certain period of time), safety videos prior to experience/device usage, and screen time summaries for AR/VR devices. However, participants cautioned that enforced usage limits may not be suitable or convenient for all users and noted that disassociation from reality is sometimes an aspiration for some users. It will therefore be key to strike a balance that ensures people are not excluded from the escapism benefits that immersive environments can present for users. Attendees also shared that realism should not be the sole aspiration of AR/VR systems (in terms of interactions and visuals) and the assumption that more realism leads to higher accessibility should be revised in research and development. Moreover, participants were critical of current systems that strive to mimic real world realism and interactions, rather than tailor AR/VR experiences around the reality of users or explore the "limitless" capabilities of AR/VR in terms of physics, gravity, movements, and "superpowers" for users with impairments.

Users across impairment groups also highlighted the importance of embedding disabled users across all stages of AR/VR product development (i.e., concept, design, and development) to fully understand the complex needs associated within different forms of disability and to create tools that resonate with users living with impairments. Additionally, participants recommended direct user consultation across all stages of research and development to ensure users get the maximum benefit from AR/VR in a way that is usable and valuable for them. Direct contact and collaboration with impaired individuals and communities is key to improve acceptance of AR/VR by closed communities (e.g., Deaf communities), with one participant stating, "*you have to work with someone who's within the Deaf community, I don't think there is any getting away or round that*." Additionally, participants in this particular group highlighted that it is essential for developers of immersive experiences to consider subgroups and different methods of communication when developing accessible tools (i.e., people born deaf who are BSL users, people who become deaf later in life, etc.). Existing literature has highlighted that considering the accessibility of interactive experiences, standards and guidelines in the early stages of research and development of AR/VR technologies can lead to wider adoption and more usable solutions (Montagud et al., 2020), as well as enhancing the reach and impact of AR/VR technologies for users with disabilities (Mott et al., 2019).

Recent research also underlines the importance of user centred approaches that considers different aspects of user reality (e.g., personal space, mental state, environment, habits and behaviours) to address the diverse needs of disabled users (Miesenberger et al., 2022). In particular, participants highlighted that inclusion and integration should be a two-way process where developers and researchers should integrate more with disabled communities. Participants stressed the importance of training developers and software engineers early in their educational and professional journeys to develop inclusive tools and devices using an iterative process that has inclusion and integration of disabled users at the heart of all stages of development. Participants were particularly critical of how integration is considered in current research practices where technologies are often developed to embed disabled people within non-disabled communities, as opposed to manufacturers and researchers first integrating with the disabled communities who they wish to utilise their products and experiences. Additionally, participants proposed pushing for new legislation and rules that mandate manufacturers of AR/VR technologies and other stakeholders to include, integrate, and employ people with disabilities with one participant stating, "*we just need to make sure that everybody (industry, academia etc.) is mandated to include and to employ disabled people who are able to represent their needs rather than having these silos*" (i.e., segregated AR/VR experiences and prototypes that are not usable or accessible to the disabled community).

For barriers related to representation, avatar choice and protection of identities, participants recommended that users should ideally have the option and freedom to declare and represent their disability through avatars in immersive environments in a flexible and customisable manner and highlighted that personalisation needs to be varied, not generic or forced and should still mediate a choice (e.g., an option for a powered wheelchair as opposed to a generic manual one, a wide range of prosthetics instead of a wooden one, etc.). Participants criticised the lack of inclusive customisation options for current avatars (e.g., wheelchairs, canes, guide dogs, amputees, etc.), especially given that other customisation options are available (e.g., gender, skin colour, etc.). Developing environments that enable users to input their physical information prior to using the experience to support appropriate adaptation of the environment (e.g., user height, eye level, etc.) was recommended as a potential solution and participants stressed the need to ensure that all user disability data is highly protected, even to the level of biometrics with recorded metrics within a virtual environment. Furthermore, it should also be noted that while personalisation and interaction were raised as key areas for research of AR/VR systems, consideration should be given to data-privacy in future research. This is particularly important when considering the disclosure of personal information or the use of innovative sensor systems to control an immersive experience. Consideration should therefore be given to the development of an ethical AR/VR framework which has data privacy at its core.

Participants stressed the need for equality in regulation of accessibility features in AR/VR technologies and recommended developing measures to ensure AR/VR platforms are affordable and sustainable to support continual improvements in terms of usability and accessibility. Participants across all groups also shared concerns around how other aspects of technologies are easily regulated (e.g., accessibility features on mobile phones and the web) whilst accessibility requirements for disabled users are constantly questioned. Attendees therefore highlighted the need for equality in regulations and changing the narrative that accessibility features only cater for the minority of users (i.e., disabled users). This concern is reported in the recent "IEEE Global Initiative on Ethics of Extended Reality (XR) Report on Extended Reality (XR) Ethics in Medicine" (Evans, 2022) that discusses how accessibility and usability concerns are often perceived as features for the minorities in the population (e.g., disabled users) at the end of research and development cycles, and recommend treating accessibility as a core part of the design process that is valuable for all users.

Finally, to address the lack of inclusivity in current academic research practices and resulting outputs that do not generally move into production or reach end users with impairments, participants emphasised that a synchronised effort is required to address accessibility issues in a more efficient manner. In particular, they recommended revising review guidelines of academic research to address biases in current research to enforce more inclusion and integration within AR/VR research practice (i.e., research that proposes solutions for disabled users, but does not include people with impairments for testing or validation of outputs). Furthermore, participants across groups suggested that academic research teams should directly collaborate with disability communities and representatives of users with impairments to better understand the context and processes associated with developing inclusive systems. Recent

Table 5. Ethical and wider considerations related to future work associated with research on developing inclusive immersive experiences.

Centres of excellence and international networks: provide AR/VR training, education, and access to devices for practitioners through national centres of excellence and networks.
Lend/donate XR devices: develop and promote sustainable lending schemes of XR devices and technologies in educational institutions, research centres, and centres of excellence.
Accessible development platforms: build accessible design platforms and Open APIs that empower disabled developers to build relevant tools for their communities.
Mandate manufacturers: push for clauses and laws that mandate manufacturers of headsets and AR/VR products to comply with certain accessibility standards and regulations.
Disability awareness: ensure representation in key AR/VR events to accelerate awareness and provide disability training focusing on autonomy and empowerment for disabled people.
Lobby professional bodies and accrediting bodies: embed accessibility training into the professional development of people who are certified to work in these areas.
Global XR ethics initiatives: wider participation in global initiatives that focus on ethics for XR to push for more inclusive AR/VR technologies and practices.
Awareness campaigns: support public campaigns to raise awareness around negative humanity traits in social immersive environments to mitigate negative aspects of online collaboration.
Disability simulation: explore the effectiveness and ethical implications of promoting empathy among non-disabled users through simulations of disabilities in AR/VR.
Hyper realistic immersive experiences: investigate unknown impact of hyper realistic immersive experiences on physical and mental health and disassociation with reality.
Direct consultation with disabled users: user consultation across all stages of research and design is essential to ensure usable and valuable AR/VR systems are developed.
Make all representation options available: users should have the option and freedom to declare and represent their disability in immersive environments.

research demonstrates a promising shift towards more inclusive reviewing guidelines and study designs when developing AR/VR for users with impairments (Bauer et al., 2022; Bosse et al., 2022; Masneri et al., 2020; Teófilo et al., 2018). Additionally, several frameworks now provide clear guidelines for designers and developers to establish participatory methods and inclusive experiences to ensure development of tools that address user needs and capitalise on user strengths (Dombrowski et al., 2019; Evans, 2022; Gerling & Spiel, 2021; Iqbal et al., 2022) (Table 5).

6. Conclusion

The research agenda presented contributes a deeper and more comprehensive understanding of essential research areas requiring further investigation to support the development of more inclusive immersive experiences across a spectrum of impairments. It is crucial now that research groups and the wider community urgently address the technical challenges highlighted, as well as the wider ethical, societal, and economic issues identified. In particular, it is essential that a multidisciplinary and collaborative approach is adopted moving forward to ensure the research pathways identified can be addressed in an inclusive fashion and that people with impairments are not excluded from the future proliferation of AR/VR technologies.

Disclosure statement

The authors report there are no competing interests to declare.

Funding

This work was funded through a "Consider Everyone" grant from Facebook/Meta Reality Labs.

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