Exclusion Rates among Disabled and Older Users of Virtual and Augmented Reality

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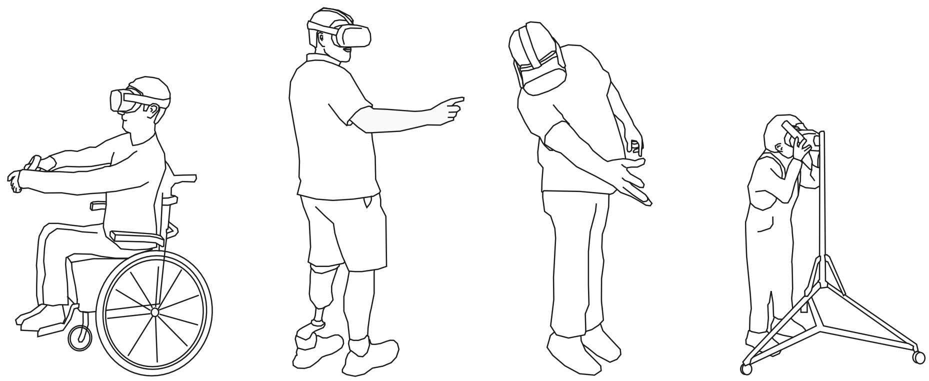

Figure 1: Four participants in our usability study perform scheduled tasks in VR. The participants have been accompanied by a researcher and, if required, their carer and a sign language interpreter.

Abstract

This paper examines the levels of exclusion encountered by disabled and older users of consumer-level VR and AR technology and identifies methods formed by people with diverse access needs to circumvent encountered barriers to use. First, we estimate exclusion rates for a selection of nine immersive experiences of VR and AR, computed using population statistics data for the United Kingdom (UK). We then present an empirical lab-based study evaluating the usability of the same VR and AR experiences. The study involved 60 UK-based participants with varying access needs and the study results were used to calculate the empirical exclusion rates. Both the estimated and empirical exclusion rates display high levels of exclusion, which for the more complex experiences in the study reached 100 %. However, multiple participants overcame usability barriers and completed experiences through provided assistance and self-initiated adaptations, suggesting that future VR and AR can become more inclusive if designed to counter these barriers.

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CCS Concepts

• **Human-centered computing → Empirical studies in accessibility**; **Virtual reality**; **Mixed / augmented reality**; • **Social and professional topics → People with disabilities**; **Seniors**.

Keywords

Accessibility, Virtual Reality, Augmented Reality, Disabilities, Ageing

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1 Introduction

Virtual and Augmented Reality (VR and AR) have the potential to improve the quality of life for people with disabilities and older adults by providing unprecedented access to immersive experiences across work, education, healthcare, entertainment and other domains [12, 14]. These novel experiences establish digital parallels to the physical world minus its prevailing barriers, which can create various opportunities for individuals who lack access in their daily lives due to a reduction in mobility as a consequence of disability and/or the aging process. However, the immersive experiences are not yet fully accessible with respect to different forms of access needs. It is therefore important to continue investigating the levels of exclusion in VR and AR and existing accessibility barriers to improve the inclusiveness of the experiences that these technologies enable.

People with disabilities and older adults can face a range of barriers when it comes to digital inclusion and meaningful use of different digital systems. This problem arises from technoableist perspectives, lack of access to technological applications or poor technology literacy [25, 47]. In the UK alone, 16 million people have some form of disability, with mobility, fatigue and mental health being the most frequently reported [23], and 11 million people are aged 65 years or older [5]. These figures are set to rise due to people living longer but not necessarily better, with a higher incidence of disease [28] and, therefore, increased access needs.

Products in the market usually target younger and non-disabled users [22], disregarding the fundamental user requirements of people with specific access needs. These user groups are usually less inclined or entirely unable to engage with such products [41], which in turn leaves them with fewer opportunities to participate in society and enjoy life. By determining how many people cannot use VR and AR technology and the specific accessibility barriers that obstruct their experience, it is possible to highlight which areas of immersive technology require improvement while integrating their needs into the design process [8].

This research is highly important in terms of raising awareness of the current state of exclusion in VR and AR across the immersive technology community and thus ultimately achieving a higher level of accessibility and, accordingly, a significant increase in the number of VR and AR users. Recent work has framed disabled and older users as experts in adapting devices and experiences to shape them around their access needs [1, 6, 7, 21, 26, 38], but there is still limited research on such adaptations in the VR and AR context (see Section 2). We address this gap by estimating the current levels of exclusion encountered by disabled and older users of consumer-level VR and AR technology and then by identifying strategies in a representative user sample to circumvent encountered barriers to use.

The work in this paper offers two complementary methodologies. First, we analytically estimated exclusion rates using a task-based Exclusion Calculator[1] [49]. This process provides an approximate measure of the UK population currently excluded by VR, AR and other forms of immersive content. The precise methodology and results of this analytical evaluation are presented in Section 4. Second, we conducted a lab-based usability study with 60 participants from the UK, representing a broad spectrum of access needs. Each participant engaged in a series of structured headset-based VR and tablet-based AR tasks. Results provide a more precise account of how specific tasks and content can exclude different individuals. The protocol for this usability study and associated results are presented later in Section 5. We also describe the related assistance and adaptation solutions leveraged to address these barriers. We report on these observations in Section 6.

[1]https://calc.inclusivedesigntoolkit.com/

Our investigation was guided by the *social model of disability* [42], which suggests people are disabled by barriers imposed by society and not due to their impairment or different capability levels, and the principles of *inclusive design* [8], a design methodology drawing from user diversity. This approach considers the human diversity-related access needs and requirements to remove design aspects that exclude underrepresented users, delivering technologies that are more usable for everyone. As a result, we examine diverse access needs related to functional differences across the disability and older age spectrum. To our knowledge, our usability study is the most detailed and broad-spectrum study of VR and AR usability for users with disabilities and older users publicly reported to date. Therefore, our work provides empirical evidence and a consequent understanding of the extent and reasons for the exclusion of disabled and older users from the VR and AR environments. To date, there have been only a few attempts to estimate the rates of exclusion by design (see Section 2.1) and none analysing the exclusion for VR and AR.

In summary, this paper offers the following key contributions: (1) we report the estimated exclusion of the UK population due to representative tasks encountered in VR and AR; (2) we report on a comprehensive user study, highlighting the levels of exclusion encountered by different groups of UK-based users with varying forms of access needs; and (3) we present an outline of key observed strategies users employ to circumvent the barriers they encounter when using VR and AR.

2 Related Work

Our research draws on previous work on the accessibility of VR and AR environments for users with diverse access needs related to disability or older age. This section positions our work within this context by outlining the fundamentals of countering design exclusion, highlighting previous research efforts around technology-based design exclusion and general accessibility research work within the domain.

2.1 Assessing Usability and Exclusion

Design exclusion pertains to users who cannot use a product or service because their access needs are greater than what is supported by said product or service. This approach assesses user demands irrespective of specific impairments or health conditions. Instead, it explores how each feature places particular demands on the user based on the goals and required tasks to achieve them, determining the inclusivity level of a design solution [8]. A tablet device, for instance, will require a certain level of vision and dexterity abilities to be operated. Exclusion here could be detected in users who cannot see the screen or cannot press the buttons, and some users could even present a combination of access needs in both areas [48]. Focusing on the number of people excluded, instead of the number of people who can use a product, facilitates exploration of how many and which demands are posed. By lessening the demand, a wider range of users can potentially access the product, expanding inclusion and accessibility without the need for special aids or external adaptations.

Few approaches to auditing exclusion have been proposed [35, 36, 54]. The work presented here is based on the exclusion analysis tool [49], an audit tool that takes functional access need scales as a baseline. It is based on the 1996/1997 Great Britain Disability Follow-up Survey (DFS) [17]. The tool estimates the number of people excluded from the disabled UK population according to quality of life levels. Quantitative assessment of the inclusive merit of specific design solutions facilitates the detection of areas of improvement to expand their user base. Additionally, it is advised to complement exclusion auditing with other tools such as user studies, disability simulators or expert opinion [48]. We follow this recommendation by combining an exclusion audit with a usability study involving a representative sample.

2.2 Accessibility in Virtual and Augmented Reality

Addressing accessibility needs is an evolving HCI research area, with work mainly focusing on specific impairments such as visual or hearing loss, cognitive issues or age-related decline [9, 39]. Significant work in assistive technologies tends to focus on a specific disability. For instance, tools, toolkits and wearable devices have been developed to assist users with some form of sight impairment (i.e., low vision, colour blindness and blindness) in navigating real-life activities through AR support or immersing into VR for social engagement [43, 45, 52, 53]. VR and AR tools have been combined with automated sound recognition and haptic stimulation to support users with hearing impairment by transforming speech into text or detecting 3D sounds [29, 30, 30]. In terms of motor and cognitive impairments, systems have been created to support physiotherapy and neurorehabilitation through exergames and immersive platforms [4, 31, 33, 37]. Beyond assisting users with specific accessibility needs, these technologies have fostered novel interaction forms within the VR and AR ecosystem [18, 24].

Placing users with specific impairments at the centre of the research has been a fundamental part of advancing accessibilty studies in the HCI context. Our usability study approach is informed and builds upon existing empirical research exploring this scope. Salient usability studies in this area include research on the design of alternative interactions for accessible AR involving 10 blind participants [19], exploration of key issues encountered by users with limited mobility and a proposal of strategies to mitigate these within VR through participant interviews [32] and analysis of VR consumption by wheelchair users with subsequent design implications and game prototypes through surveying 25 wheelchair users [16].

A different research strand has focused on multiple and co-occurring disabilities. In this area, Wong et al. [50] conducted online surveys with 79 participants to explore accessibility issues within VR; Creed et al. [10] and Garaj et al. [15] expanded this analysis to both VR and AR by carrying out sandpits with 38 to start with and then 30 additional critical stakeholders and surveying 100 people with different disabilities, respectively. Su et al. [44] formed a small panel of 18 participants from five access needs-related communities (wheelchair users, blind or low vision users, older adults, families with children and occupational therapists), to develop an AR prototype to mitigate safety and access issues (e.g., unsafe loose rug). These studies leverage the understanding of existing issues, such as design strategies rendered ineffective by co-occurring conditions, hinting at the need to design for users with multiple access needs.

In recent years, we have also seen the emergence of affordable consumer VR and AR devices, plus the expansion of immersive technologies from the gaming and entertainment industries to other domains, reaching broader populations. However, there is a perceived gap within the research field due to the low level of evidence-based generalisable guidance for accessible VR and AR development [2]. Dudley et al. [13] suggest that enhancing the accessibility of such platforms can contribute to the quality of life for a broader user base that includes people currently excluded. Furthermore, Creed et al. [11] highlight the need for a holistic approach addressing technical, ethical, societal and economic issues from a multidisciplinary practice.

Informed by this body of work, we propose an approach that involves people with diverse levels and co-occurrences of disability, directly engaging with representative VR and AR technologies in the current commercial landscape. We draw from the results of existing surveys and expert forums [10, 11, 15, 50] in combination with empirical work [16, 19, 32], to examine, through user exploration and direct observation, the assistance and adaptation strategies that a diverse spectrum of disabled and older users implement when using these immersive technologies.

3 Usability Demands in VR and AR

To perform the analytical (Section 4) and empirical (Section 5) evaluations presented in this paper, we must first define a set of tasks encountered by users of VR and AR. For the analytical estimation of exclusion rates, this selection provides the basis for concretely assessing the use demands of each task. For the empirical usability study, these will be the actual tasks that we ask participants to complete. The key factors used to scrutinise and select existing VR and AR experiences available on application marketplaces at the time of the study were: (i) that they should together require the use of the whole range of human faculties, including vision, hearing, cognition, voice communication, mobility and dexterity; and (ii) that they should be approximately ordered in increasing interactivity, which we hypothesise is correlated with difficulty. We specifically sought to include a representative coverage of existing consumer-level, single-user VR and AR content, while also ensuring a variety of experience to promote participant engagement. For VR, we aimed to assess both passive and interactive experiences, as well as both embodied (i.e. where the user *is* the main character) and third-person (i.e. where the user is remotely controlling the main character) experiences. We also specifically attempted to cover the aforementioned range of human faculties and interaction modes, such as assessing the usability of the hand-tracking functionality available on modern VR devices. We then aimed to assess popular use cases of through-the-screen AR, which at the time of study design, included applications in online shopping and edutainment.

For VR, we also consider the basic task of putting on the headset and picking up and using the controllers. It is worth noting that the order of increasing interactivity/difficulty for the empirical study provides a more pleasant experience for participants, as they are gradually introduced to more interactively complex and difficult experiences, allowing them to adapt to the demands of the study along the way. We describe the selected experiences for VR and AR separately in the following subsections.

3.1 VR Experiences

The five interactive experiences (*VR1-5*) selected for VR are summarised in Table 1, alongside the basic tasks of putting on the headset (*VRH*) and holding and operating the controllers (*VRC*). We briefly review each of these tasks and experiences below.

VRH: Headset. This task focuses on the act of putting on and adjusting the VR headset. For the analytical and empirical evaluations of VR, we assessed use of the Meta Quest 2 headset. This headset is light, standalone, powered by its own operating system and currently relatively affordable to a wide user base. Its design includes an adjustable three-point elastic strap to fit the headset on each user's head. Small speakers integrated into the strap remove the need for headphones. This task allowed us to analyse and observe potential friction when wearing and fitting the headset.

VRC: Controllers. This task focuses on picking up, holding and operating the controllers. In the usability study, we provided participants with a set of two Meta Quest 2 controllers (right and left) with an ergonomic button layout and responsive haptic feedback. This task allowed us to analyse and observe potential friction when handling controllers.

VR1: Menu. This task focuses on user interaction with the device's operating system and settings menu, specifically on adjusting accessibility settings within the related sub-menu. This task allowed us to analyse potential friction points encountered by users when customising settings according to their personal needs.

VR2: "As it is" 360° video[2]. This primarily passive experience involves viewing a 360° video documentary about the Grand Canyon. There are no enforced interactive elements and only a small set of video controls. The particular section of the video used in the study allowed the user to experience a river rafting trip. We also considered the sub-task of manipulating the video playback settings within the immersive environment. This task allowed us to analyse potential friction in experiencing immersive video content with low-level interactivity.

VR3: Job Simulator[3]. This experience is an immersive educational game that requires players to carry out everyday tasks (like cooking) within the virtual environment. The user's hands are mapped to virtual hands to pick up and manipulate specific objects through embodied interactions. The experience allowed us to observe friction regarding interactables and environment exploration in VR.

VR4: Moss[4]. This experience, also an immersive game, combines interaction styles. The user controls the main character (a mouse called *Quill*) using a conventional style of interaction similar to console-based gaming, i.e. directing the character with the controller's thumb stick and pressing a button to perform various actions. At the same time, the immersed user is a secondary character within the game and can interact with objects around *Quill*. The experience allowed us to analyse and observe friction encountered by users when performing more precise controller-based interactions within an immersive VR setting.

VR5: Elixir[5]. This experience includes hand-tracking. The user interacts with and navigates the virtual environment using their hands rather than standard VR controllers; they must follow in-game instructions to reach the game goals. The experience allowed us to analyse friction encountered when interacting in VR using hand-tracking features.

While *VR3, VR4* and *VR5* are arguably not entirely representative of the most popular VR experiences available at present, they were chosen to fulfill the above-mentioned selection criteria of the progressive interactivity/difficulty of tasks. For example, these three VR experiences progressively increase the demand on dexterity and the use of hands, from using the virtual hands to manoeuvre objects in a micro-environment in *VR3*, navigating and actioning the character within a wider experience environment in *VR4*, to the hand tracking-based control, which represents the highest level of demand on hands, in *VR5* (Table 1).

3.2 AR Experiences

The two interactive experiences (*AR1*, *AR2*) chosen for AR are summarised in Table 2 and briefly reviewed in the text below. For the analytical and empirical evaluations of AR, we assessed a through-the-screen AR experience using the Galaxy Tab Active Pro. Thus, in this section we decided not to consider basic hardware and menu/operating system usability issues as these are indistinguishable from conventional phone/tablet use and so are not within the study's main purview. While more advanced head-worn AR devices exist (e.g., Microsoft HoloLens), we opted for technology that could be more realistically afforded by the study's target population.

AR1: Amazon Shopping App[6]. This experience allows the user to view virtual objects such as furniture, in a real-world room through the tablet screen, using the *'View in Your Room'* feature. Users can manipulate the size and orientation of the virtual object within the physical environment by interacting with the tablet's touchscreen. In the usability study, the experience allowed us to observe friction when engaging with AR content involving limited interactivity and requiring limited mobility. For the analytical and empirical evaluations, we took into account the human faculties required to hold a tablet along with the specific demands of the sub-tasks.

AR2: Van Gogh Room[7]. This experience provides a virtual door to an immersive reproduction of Van Gogh's painting, *'Bedroom in Arles'*. By moving through the physical space along with the tablet, users can step into the room to inspect the elements that compose

[2]Produced by 360 Labs: https://www.youtube.com/watch?v=BE-irHmbQOY
[3]Produced by Owlchemy Labs: https://jobsimulatorgame.com/
[4]Produced by Polyarc: https://www.polyarcgames.com/games/moss
[5]Produced by Magnopus: https://www.magnopus.com/projects/elixir
[6]Amazon's 'View in Your Room' button, see for example: https://amzn.eu/d/cZK7jlT
[7]Produced by ruslans3d in the ARLOOPA app: https://www.arloopa.com/experiences/6079

Table 1: VR usability tasks.

Experience	Task	Faculties Exercised
VRH: Headset	Put on, adjust and take off the headset.	Vision; mobility and dexterity: upper limb, both hands or one hand, head; vision.
VRC: Controllers	Hold and operate the controllers.	Vision; mobility and dexterity: upper limb, both hands.
VR1: Menu	Find and navigate the menu. Explore and adjust the accessibility settings.	Vision; cognition: spatial recognition; mobility and dexterity: upper limb, both hands.
VR2: "As it is" 360° Video	View and listen to 360° video content. Detect specific elements within content and operate playback settings.	Vision; hearing; cognition: spatial recognition; mobility: head, upper limbs and hand movement.
VR3: Job Simulator	Understand written and verbal instructions. Interact with the environment and control digital elements. Move within the virtual space.	Vision; hearing; cognition: information processing and spatial cognition; mobility and dexterity: hands, upper and lower limbs.
VR4: Moss	Read and learn instructions, move the characters within the virtual environment and control specific digital elements.	Vision; hearing; cognition: information processing and spatial cognition; mobility and dexterity.
VR5: Elixir	Follow verbal instructions and use hands (instead of controller) to interact with digital elements and to move around the environment.	Vision; hearing; cognition: information processing; mobility and dexterity: both hands.

the painting, now transformed into a 3D virtual space. The interaction is limited to the placement of the door in the real-world space and requires the user to move around (i.e. walking around the physical room) to view the room from different perspectives. More demanding than *AR1*, *AR2* allowed us to analyse friction encountered when engaging with AR content that requires mobility and low-level interaction.

4 Estimated Exclusion Rates

Population exclusion rates describe the percentage of the population that is unable to successfully complete a given task. Exclusion rates are determined with respect to the ability/inability to complete a given task rather than the underlying impairment or disability characteristics of individuals. To estimate the population exclusion rates associated with current forms of VR and AR technologies and experiences, we leverage an established methodology developed by Waller et al. [49]. The Exclusion Calculator provides a simple tool for estimating the percentage of the population that will be unable to successfully use a given product or service. The data underlying the Exclusion Calculator is taken from the Disability Follow-Up to the 1996/97 Family Resources Survey [17]. This survey queried the ability of individuals to perform various tasks relevant to daily life, such as their ability to read text in a newspaper, concentrate well enough to make toast, or whether they can reach up to put on a hat. Waller et al. [49] outline how this survey data can then be extrapolated to reflect the access needs of the broader population. The 'Pro' version of the Exclusion Calculator can also estimate the expected exclusion based on future projected age and gender profiles.

We use the Exclusion Calculator to assess the distinct tasks and experiences introduced in Section 3. This assessment requires mapping the sub-tasks performed within the main tasks described in Section 3 to the distinct tasks used for relative assessment in the Exclusion Calculator. For example, under the category of *Dominant hand*, the Exclusion Calculator requires a rating for the demand of the task in terms of *Lifting strength*. One point on this subscale is *'Pick up and hold a mug of coffee by the handle'* which we take as an approximate mapping to the lifting strength required to pick up a standard VR controller. The complete mapping between task demands and Exclusion Calculator subscale points is provided in the Supplementary Material for this paper.

4.1 Results

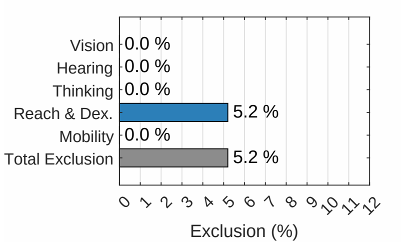
The reported exclusion rates are with respect to the 16 and over population of the UK as per the projected age and gender profile in 2025. The estimated exclusion rates for the VR tasks are presented in Figure 2. These plots are consistent with the output of the Exclusion Calculator Pro v3.0 and break the exclusion rates down into five faculty categories. The interpretation here is that, for example, in the case of Figure 2e, 4.3 % of the UK population are excluded due to the task demands on the reach and dexterity. When considering the task demands in terms of other input and output options, the total exclusion of the UK population is 8.0 %. From the exclusion rates presented in Figure 2, we can observe that exclusion generally increases with the interactivity/difficulty level of the experience. However, even the requirement to put on the headset (*VRH*) and use the controllers (*VRC*) excludes approximately 5 % of the population. The excluded population percentage is highest for *VR3* and *VR5*, which are the two experiences assessed requiring embodied interaction with the virtual environment.

The estimated exclusion rates for the two AR tasks are presented in Figures 2h and 2i. The exclusion rates are elevated compared to those observed for the VR tasks. This change is largely a consequence of the added demand on mobility as the user is required to view the virtual content from different perspectives in the physical environment. The total exclusion exceeds 8 % in both content types.

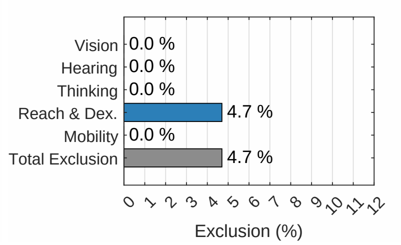
These estimated exclusion rates provide an appreciation of the degree to which current VR and AR technology and content are

Table 2: AR usability tasks.

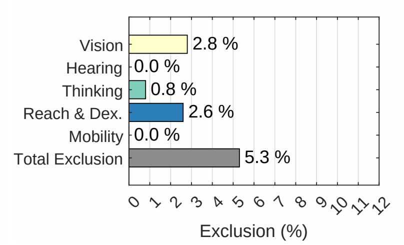
Experience	Task	Faculties Exercised
AR1: Amazon Shopping	Hold device to scan the real world. Control digital elements and change their location and position.	Vision; cognition: spatial cognition; mobility and dexterity: hands and upper limbs.
AR2: Van Gogh Room	Hold device to scan real world. Move across the space to explore and control digital elements.	Vision; cognition: spatial cognition; mobility and dexterity: hands, upper and lower limbs.



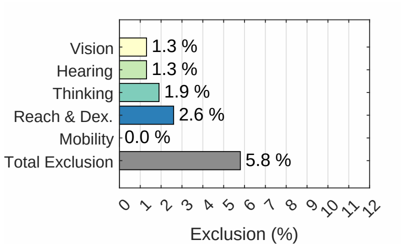
(a) Estimated exclusion on VRH.



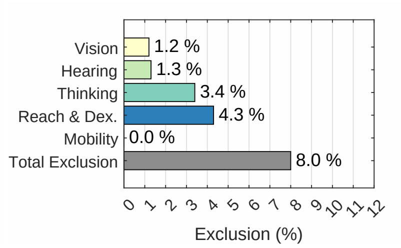
(b) Estimated exclusion on VRC.



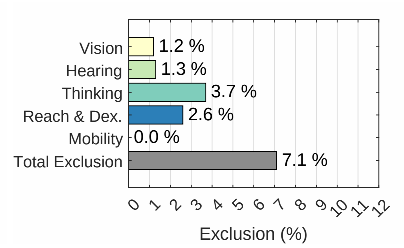
(c) Estimated exclusion on VR1.



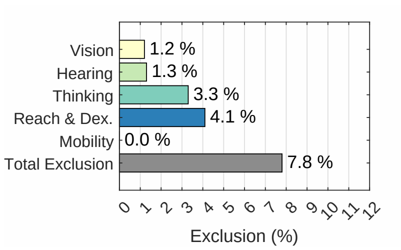
(d) Estimated exclusion on VR2.



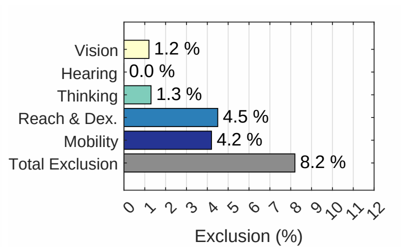
(e) Estimated exclusion on VR3.



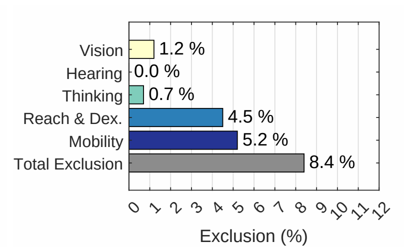
(f) Estimated exclusion on VR4.



(g) Estimated exclusion on VR5.



(h) Estimated exclusion on AR1.



(i) Estimated exclusion on AR2.

Figure 2: Estimated exclusion of the UK population for the VR and AR technology use and content consumption tasks.

inaccessible to proportions of the population. In the following section, we present a targeted assessment of usability with a stratified sample of users representing a spectrum of access needs. This evaluation provides concrete visibility of the excluded minority and serves to highlight where accessibility efforts should focus.

5 Usability Study

The usability study was designed to involve 60 research participants in 3 groups: (1) Disabled Group: 40 people who are registered or self-declare as having a single or co-occurring disability; (2) Over 65 Group: 10 people over the age of 65 years, with typical age-related access needs, but no particular disability; and (3) Control Group: 10 people in their 20's, without any specific access needs.

All participants were asked to complete the seven VR tasks and experiences and two AR experiences introduced in Section 3 and listed in Tables 1 and 2. Each task/experience was broken into subtasks as illustrated by Table 5. In total, there were 46 sub-tasks across the nine tasks and experiences. As described in Section 3, the VR tasks covered the whole user journey from putting the VR headset on and setting up the controllers, to navigating the headset's operating system and then engaging with the VR experiences, while for the AR tasks, the focus was on engaging with the experiences. The selection of the Meta Quest 2 and Galaxy Tab Active Pro as the devices used in this study was motivated by their general market availability and affordability. In particular, they were considered more affordable by our target population than more advanced AR and VR devices.

The study sessions were managed by an experienced user researcher guiding the session, observing and assisting the participants and scoring the performance of the tasks and a technician

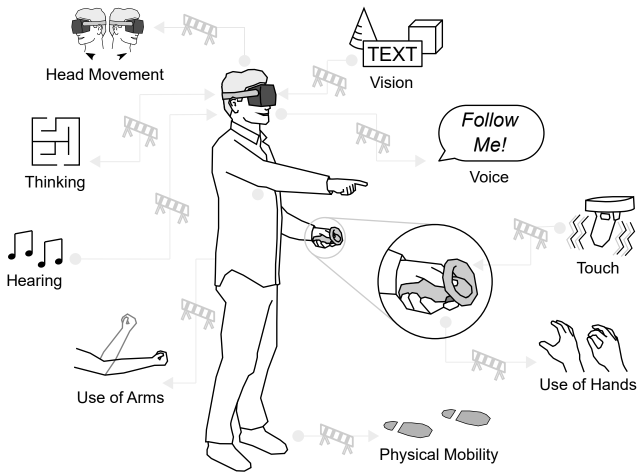


Figure 3: User faculties exercised in immersive technology use and content consumption. The degree to which these faculties can be fully exercised may vary for people with disabilities (A.1. to D.4.), older adults (E.1.) and people without disabilities (F.). The arrows pointing towards the user indicate input to the user and the arrows pointing away indicate output from the user.

overseeing the technological aspects of the study. The study was approved by the College of Engineering, Design and Physical Science Research Committee at Brunel University of London.

5.1 Participant Sampling and Recruitment

To ensure a representative participant sample for the empirical usability study, we developed a dedicated Disability and Ageing User Matrix as a basis for a stratified sampling process. This matrix was built upon previous frameworks (for instance [17, 51]) but expanded to incorporate the particular demands that VR and AR technology place upon users (see Figure 3). The matrix captures variations in four main domains of human faculties: Perception, Cognition, Communication and Mobility, relating to congenital or acquired disability, and Ageing, denoting a mild age-related faculty decline. Each domain is divided into categories pertaining to access needs clusters and the specific types of access needs within the categories. The particular demands regarding the use of VR and AR relate to, for example, the use of arms and hands, and head movement (see below), which are required to fully engage with VR experiences using a headset and hand controllers and which are usually not captured in the previous user frameworks.

The following is a short description of the domains and relevant user faculty–use demand relationships. Table 3 presents the access needs categories, and in the Supplementary Material, we provide a full breakdown of the matrix, including the domains, categories, and type of access needs.

- **Perception:** The design of immersive experiences should account for an adequate intake of environmental information. This domain includes three access needs categories related to *A.1. Vision, A.2. Hearing* and *A.3. Touch*; it addresses sensory functions that enable users to capture the external stimuli required to interpret and interact within VR and AR environments.
- **Cognition:** Learnability and understandability are essential aspects of engaging with immersive experiences, which must require a minimal cognitive load and aid the user in reaching their goals. This domain only includes the *B.1. Thinking* category and addresses neurodiversity, learning difficulties and mental health.
- **Communication:** Immersive experiences facilitated through VR and AR include embodied interactions grounded in real-life communication. Design for individual immersive experiences should support the continuous exchange of information between two or more agents, one being the user and the other(s) the digitally created elements (e.g., a navigation menu and an avatar). This domain includes the *C.1. Voice* category.
- **Mobility:** VR and AR experiences require motor abilities such as moving in physical space, grasping, reaching, and pressing to operate the access devices (controllers and headsets), and moving the head in different directions to interact. Numerous disability conditions lead to different types of motion and mobility reduction, limited strength, or lower fatigue thresholds. This domain includes four categories: *D.1. Physical Mobility, D.2. Use of Arms, D.3. Use of Hands* and *D.4. Head Movement*; it addresses the use of legs, arms, and hands, including dexterity and head required to immerse oneself in VR and AR experiences.
- **Ageing:** Older age is not a direct indication of disability. However, all human faculties deteriorate with age. This domain therefore considers the access needs resulting from the age-related deterioration that does not lead to a specific impairment or disability. With this purpose, participants in this category are aged over 65 years old and the domain thus includes the *E.1. Over 65* category.

50 UK-based participants with multiple access needs were recruited with the support of an inclusive research user panel managed by Open Inclusion (see A.1 to E.1 in Table 3). 40 of these participants were recruited into the Disabled Group (15 women and 25 men, mean age=42.6 years, *SD*=14.8) and classed into the access needs categories as follows: participants reported all their access needs and severity levels, the research team designated each participant's need of the highest severity as their *primary access need* and logged the rest of their access needs to consider in the analysis stage. Disabled participants satisfied the following criteria: (i) registered as disabled or self-declared a disability; (ii) able to communicate with others and perform tasks with or without the support of another person; and (iii) interested in consuming immersive content in VR or AR platforms, even if they have not experienced them before. Table 3 presents the participant demographics.

Our Disability and Ageing User Matrix proposes a different number of types of access needs per category. For instance, *A.2. Hearing* includes three types (*A.2.1. Hearing Acuity, Binaural Hearing; A.2.2. Hearing Field; A.2.3. Deaf*), while *B.1. Thinking* includes seven (*B.1.1. Comprehension; B.1.2. Concentration and Attention; B.1.3. Decoding*

Table 3: Participant demographics.

Category	Participants	Mean Age (sd)	Male	Female
A.1. Vision	9	43.11 (13.82)	6	3
A.2. Hearing	3	48.67 (7.51)	2	1
A.3. Touch	3	47.00 (23.43)	3	0
B.1. Thinking	7	34.29 (14.19)	3	4
C.1. Voice	4	35.75 (6.40)	4	0
D.1. Physical Mobility	4	61.50 (16.22)	2	2
D.2. Use of Arms	3	47.00 (17.44)	1	2
D.3. Use of Hands	4	40.50 (12.79)	2	2
D.4. Head Movement	3	35.67 (7.51)	2	1
E.1. Over 65	10	73.90 (4.72)	5	5
F. Non-disabled	10	24.40 (2.50)	5	5
TOTAL	**60**		**35**	**25**

Table 4: Scoring system implemented to assess task success.

Score	Description
0	The participant could not start or complete the sub-task, even with assistance or adaptations.
1	The participant could start the task with assistance or adaptations, but could not complete it, even with assistance or adaptations.
2	The participant could both start and complete a task with assistance or adaptations.
3	The participant could start and complete the task with the out-of-the-box configuration, without assistance or adaptations.

Language, Numbers and Emotional Meaning; B.1.4. Spatial Understanding and Navigation; B.1.5. Reaction and Response; B.1.6. Sensory Processing; B.1.7. Mental Health). Overall, the aim was to recruit at least one participant for each type. This aim was largely achieved except for the following due to recruitment challenges: *A.2.1 Hearing Acuity, Binaural Hearing*, *C.1.3 Stutter, Stammer*, *D.3.5 Missing Fingers* and *D.4.3 Dizziness and Vertigo*. Concurrently, two extra participants were recruited for *A.1.7 Blind* and one extra participant was recruited for *A.2.3. Deaf*.

The further 10 participants in the *E.1. Over 65 Group* (5 women and 5 men, mean age=73.9 years, *SD*=4.7) reported only mild age-related faculty decline but no chronic health conditions or long-term disabilities. In addition, 10 participants in the *F. Non-disabled* were recruited from Brunel Design School at Brunel University of London (5 women and 5 men, mean age=24.4 years, *SD*=2.5). This group was set up as a benchmark, with all participants being undergraduate or postgraduate students in the field of design and all self-described as not living with a disability. All 60 participants reported at least a basic level of experience with VR, AR and gaming platforms.

5.2 Protocol

The study tasks were performed by participants and scored in real-time by the researcher on a 0–3 scale, ranging from *unsuccessful* to *successful performance without assistance and/or adaptations* (Table 4 presents the scoring system in detail). This scoring system was designed to highlight the barriers encountered by participants during the session as well as any strategies employed by participants to circumvent these barriers. In considering these strategies employed by participants, we make a distinction between *Assistance* and *Adaptations*.

In this context, *Assistance* refers to any kind of support required from another person (i.e. the facilitator) to mimic the presence of a design feature that is non-existent in the interface. For instance, if a screen reader was needed for a blind participant to read menus, the facilitator performed an ad-hoc imitation of a screen reader. *Adaptations*, on the other hand, refer to behaviour changes or other adjustments that participants themselves implemented to interact with the VR or AR experience. For example, a participant might put down one controller and play with both hands on a single controller. When the study was being designed, following several pilot sessions, it was decided that the assistance provision was a necessary condition for the study to function, as many of the disabled participants would otherwise find the performance of a number of tasks impossible due to their access needs and the sessions would result in an overwhelming scoring of 0. The assistance was therefore embedded into the study as a *Wizard of Oz* simulation of the technology-driven accessibility and inclusion affordances that could potentially form part of the experiences in the future. This approach permitted finer granularity in the sub-task scoring.

Before the sessions, we supported participants in making their involvement as smooth as possible. Days before, they received text descriptions and images of the study location, including the parking lot, lab and accessible toilets nearby. A taxi was provided for those participants and their carers, where applicable, who did not have the personal means of transportation and did not wish to use public transport. The sessions were conducted under strictly controlled conditions in indoor lab spaces, as shown in Figures 1 and 4. The dedicated space provided a quiet environment where only the participant and two researchers (one of them facilitating the session and the other managing technical aspects) were present, plus a companion or carer and or sign language interpreter in several cases.

A *play area* free of trip hazards was designated for participants to move comfortably around the space when wearing the VR headset or using the AR tablet. Participants could decide, according to their ability, whether they would perform the prescribed tasks while seated or standing (Figure 4). Boundaries were created within the VR headset using the *Guardian* settings. The area was 2×2 m in size. We decided with each participant if the room settings needed further adjustments (e.g., dimming the lights). The researchers observed the participant's digital interactions in real time. The Meta Quest 2 was cast into a remote laptop, screen recorded and projected onto a 32 inch monitor for the VR section. The Galaxy Tab was screen recorded and one researcher accompanied the participant when moving across the space for the AR section.

During each session, participants were asked to think aloud by narrating their actions and thoughts as they performed the tasks or noting where they encountered any friction with the technology. The goal was to understand their motivations, goals, behaviours and thoughts and how/if they solved barriers encountered. Task instructions were delivered verbally whenever possible, but communication requirements were considered for people with specific

Figure 4: Usability study participant and researcher exploring one of the VR experiences.

Table 5: Sub-tasks within experience *VR2*.

Key	Sub-task
VR2-1	Find 'Skybox' in the menu, point at the 'Skybox' with the controller and press the Trigger to open it.
VR2-2	Pointing at the video "As it is – a Grand Canyon VR documentary" with the controller and press the Trigger to play the video. Use the Stick to scroll the menu if necessary.
VR2-3	View the content in 360°.
VR2-4	Listen to the narration.
VR2-5	Spot different visitors, from those close by to those at a distance.
VR2-6	Point at anywhere of the screen with the controller and press the Trigger to pop up the video menu.
VR2-7	Pause and resume playing the video in the menu with the Trigger.

needs (e.g., prompts provided in BSL for participants with hearing impairment). Each session lasted 180 minutes and was structured around three mandatory breaks. Extra breaks were provided as needed by each participant. At the end of the session, the researcher accompanied each participant to their preferred transport option. Each session was filmed, and screen recordings of the VR casting and AR tablet screen were collected for analysis. The facilitator kept detailed notes on participant observation and scored each sub-task for each participant.

5.3 Results

We report exclusion in our participant sample based on a coarse distinction between whether or not any assistance or adaptation was required to enable the participant to complete a specific subtask. This approach reflects the distinction between a score of 2 and a score of 3 under the scoring system outlined in Table 4.

The percentage of the participants per access need category that were unable to complete the task or experience *without* some form of assistance or adaptation are summarised in Table 6. These exclusion rates are computed by determining whether the minimum score obtained by the participant within the task was less than 3 (0, 1 or 2). For example, *VR2* contains several sub-tasks as listed in Table 5. If any one of these sub-tasks was scored to be less than 3, then this score was taken to reflect the fact that the overall task could not be completed without some assistance and/or adaptation.

Considering that some forms of assistance and adaptations may be relatively easy to provide or implement, Table 7 summarises the percentage of the participants that **could** complete the task or experience **with** some form of assistance or adaptation. These rates are computed by determining whether the minimum score obtained by the participant within the task was less than 2 (0 or 1). We can observe in Table 6 that the base exclusion of the sample is relatively high, particularly as the VR experiences increase in interactivity (*VR3–VR5*). This is consistent with the results presented in Section 4. 47 out of the 60 participants were unable to complete *VR5* without some assistance or adaptation and 100% exclusion was experienced by the *A.3. Touch*, *D.1. Physical Mobility*, *D.2. Use of Arms*, *D.3. Use of Hands*, *D.4. Head Movement* and *E.1. Over 65* category groups. While the increasing complexity of *VR3–VR5* also progressively excluded some of the non-disabled participants (*VR3*: 10 %, *VR4*: 20 % and *VR5*: 30 %), the 100 % rate and other high exclusion rates for the groups with specific access needs are compelling indication of the highly disabling nature of these three experiences.

Table 6 suggests that the two AR experiences evaluated were generally less exclusionary than the interactive VR experiences. Nevertheless, high exclusion was seen for the *D.2. Use of Arms* group in *AR1* and for the *A.3. Touch* group in *AR2*. Table 7 highlights the fact that assistance and adaptations were generally successful in allowing participants to be able to complete the task. This result is promising in instances where the delivered assistance or self-initiated adaptations can be embedded within the technology or experience. We expand on this point later in Section 6.

The persisting exclusion rates in Table 7 are particularly noticeable for *VR2* and *VR5*. One likely explanation for this result is that both *VR2* and *VR5* required the participants to look around the virtual environment to take in the content, in contrast to *VR1*, *VR3* and *VR4* where the experience was largely concentrated in the participant's default field of view. Table 7 indicates that exclusion after considering adaptations remains notably elevated across the tasks for the *A.1. Vision* and *D.4. Head Movement* groups. This finding suggests that accessibility research may be required to better accommodate both of these user groups since simple assistance and adaptions were ineffective.

6 Assistance and Adaptations

Participants were provided with a broad range of assistance and presented various adaptations to complete the VR and AR experiences. Tables 8 and 9 present an outline of the key barriers encountered by participants when interacting with the VR experiences and the corresponding assistance and adaptions implemented. Table 10 reports on the AR experiences' key barriers, assistance and adaptions.

Most adaptations directly performed by the participants were found in tasks related to the hardware (e.g., *pressing multiple buttons simultaneously until achieving the interaction's aim*, also known as *button mashing*) and physical aspects (e.g., *tilting head to expand vision field*). Tasks related to the immersive content or interface, on the other hand, required more consistent assistance. Such assistance was often provided as a way to *mimic* potential new accessibility features in specific experiences and through additional instructions.

Table 6: Sample exclusion for participant groups without provided assistance and/or self-adaptation. The number in brackets after each participant group is the number of participants in that group.

	VRH	VRC	VR1	VR2	VR3	VR4	VR5	AR1	AR2
A.1. Vision (9)	22.2 %	11.1 %	55.6 %	66.7 %	88.9 %	88.9 %	77.8 %	44.4 %	66.7 %
A.2. Hearing (3)	0.0 %	0.0 %	33.3 %	66.7 %	66.7 %	100.0 %	66.7 %	0.0 %	0.0 %
A.3. Touch (3)	33.3 %	66.7 %	33.3 %	0.0 %	100.0 %	100.0 %	100.0 %	33.3 %	100.0 %
B.1. Thinking (7)	0.0 %	14.3 %	28.6 %	14.3 %	57.1 %	42.9 %	71.4 %	28.6 %	28.6 %
C.1. Voice (4)	0.0 %	25.0 %	25.0 %	50.0 %	50.0 %	50.0 %	75.0 %	0.0 %	25.0 %
D.1. Physical Mobility (4)	50.0 %	50.0 %	75.0 %	50.0 %	75.0 %	75.0 %	100.0 %	25.0 %	50.0 %
D.2. Use of Arms (3)	33.3 %	33.3 %	33.3 %	33.3 %	100.0 %	100.0 %	100.0 %	100.0 %	66.7 %
D.3. Use of Hands (4)	75.0 %	75.0 %	75.0 %	25.0 %	100.0 %	100.0 %	100.0 %	50.0 %	25.0 %
D.4. Head Movement (3)	100.0 %	66.7 %	33.3 %	66.7 %	100.0 %	66.7 %	100.0 %	66.7 %	66.7 %
E.1. Over 65 (10)	20.0 %	30.0 %	30.0 %	40.0 %	90.0 %	100.0 %	100.0 %	30.0 %	20.0 %
F.1. Non-disabled (10)	0.0 %	0.0 %	0.0 %	0.0 %	10.0 %	20.0 %	30.0 %	0.0 %	20.0 %

Table 7: Sample exclusion for participant groups with the provision of assistance and/or adaptation. The number in brackets after each participant group is the number of participants in that group.

	VRH	VRC	VR1	VR2	VR3	VR4	VR5	AR1	AR2
A.1. Vision (9)	0.0 %	0.0 %	44.4 %	55.6 %	44.4 %	22.2 %	33.3 %	44.4 %	55.6 %
A.2. Hearing (3)	0.0 %	0.0 %	0.0 %	66.7 %	0.0 %	0.0 %	33.3 %	0.0 %	0.0 %
A.3. Touch (3)	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	33.3 %	33.3 %	33.3 %
B.1. Thinking (7)	0.0 %	0.0 %	0.0 %	0.0 %	14.3 %	0.0 %	14.3 %	0.0 %	0.0 %
C.1. Voice (4)	0.0 %	0.0 %	0.0 %	50.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
D.1. Physical Mobility (4)	0.0 %	0.0 %	0.0 %	25.0 %	0.0 %	0.0 %	25.0 %	25.0 %	25.0 %
D.2. Use of Arms (3)	33.3 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
D.3. Use of Hands (4)	50.0 %	25.0 %	0.0 %	25.0 %	25.0 %	25.0 %	50.0 %	0.0 %	0.0 %
D.4. Head Movement (3)	66.7 %	0.0 %	0.0 %	66.7 %	100.0 %	33.3 %	33.3 %	33.3 %	66.7 %
E.1. Over 65 (10)	10.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	30.0 %	0.0 %	0.0 %
F.1. Non-disabled (10)	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %

Table 8: Key barriers in terms of vision, hearing, touch, thinking and voice encountered by participants when interacting with the VR content and any corresponding assistance and adaptions observed. The individual participants within each group who experienced these barriers are denoted by *P#*.

Category	Barriers	Assistance and Adaptations
A.1. Vision	• Unable to read text (P01, P04, P09, P21, P36)	• Screen reader imitation • Moving in physical space to get closer to virtual text
	• Low visibility of virtual hands (P04, P21)	• External tutorial and guidance
	• No colour adjustment options (P21)	• Visual guide to controller beam, redirecting gaze at the end of beam • Dragging moveable objects closer to eyesight • User moving in physical space to get closer to virtual objects
	• Lack of captions and image descriptions (P01, P09)	• None (for blind participant)
	• Unsure how to navigate environment (P01, P09, P04, P21, P26, P36, P38)	• External tutorial or audio prompts
A.2. Hearing	• Unsure how to navigate environment (P11, P32)	• External tutorial and audio prompts in BSL
	• Lack of captions (P11, P32)	• Mimicked captions printed on paper
A.3. Touch	• Difficulty mapping controllers with interactions (P06, P37)	• Additional instructions regarding the controllers' components
	• Complicated hand gestures for controller-free experiences (P06, P37, P41)	• Additional instructions and continuous reminders regarding hand-tracking gestures
B.1. Thinking	• Forgot instructions (P17, P18, P23)	• Mimicking a prompt for read-aloud instructions to be repeated
	• Fear of the unexpected (P40)	• Warning about upcoming sensory experiences
C.1. Voice	• None	• None

Existing accessible features were irregularly available throughout the study's selected experiences, consistent with the findings of Naikar et al. [34]. Where they lacked, participants scored a lower level due to their total or partial impossibility of performing specific sub-tasks. An interesting example is the lack of captions and image descriptions in *VR2: "As it is" 360° Video*, impacting the possibility

Table 9: Key barriers related to mobility encountered by participants when interacting with the VR content and any corresponding assistance and adaptions observed. The individual participants within each group who experienced these barriers are denoted by *P#*.

Category	Barriers	Assistance and Adaptations
D.1. Physical Mobility	• Mapping controllers manipulation and interactions (P02, P03, P13, P39)	• Additional instructions and prompts for controller operation
	• Can't operate both controllers due to using mobility aids (P02)	• Resting one controller on the lap to free the other hand
	• Disorientation (P03)	• None
D.2. Use of Arms	• Physical limitations to reach virtual objects (P15, P28)	• Raise physical height (i.e. elevating chair's seat) • Bending down with the support of mobility aids
	• Struggle operating controllers (P15, P24)	• Pressing multiple buttons simultaneously until achieving the intended goal • Resting both controllers on a flat surface, tipping them back and forth as joysticks and repositioning fingers to operate the grip
D.3. Use of Hands	• Mapping controllers manipulation and interactions (P14, P22, P27, P29)	• Additional instructions regarding controllers operation
	• Can't operate both controllers (P14, P22)	• Other person operating second controller • Using two hands to operate only one controller
	• Unavailable physical gestures (P14, P27, P29)	• None
D.4. Head Movement	• Movement issues limiting experience engagement (P16, P33)	• Other person helping participant to move
	• Physical limitations to reach virtual objects (P16, P34)	• Raise physical height (i.e. elevating chair's seat) • Other person helping participant move
E.1. Over 65	• Unfamiliar with immersive environments and interactions in VR (P07, P42, P43, P44, P45, P46, P47, P48, P49, P50)	• Tilting head to bring areas of interest into non-blurry field of vision
	• Difficulty seeing low-res images (P49)	• Tilting head to bring areas of interest into non-blurry field of vision
	• Struggle operating controllers (P07, P42, P43, P44, P45, P46, P47, P48, P49, P50)	• Scooping virtual objects instead of using grip

for some *A.1. Vision* and *A.2. Hearing* participants to fully engage with the experience and complete specific tasks. Similarly, *AR2: Van Gogh Room* lacked multi-sensory feedback that could support *A.1. Vision* participants. This finding complements similar discussions in previous work [10, 20, 46], highlighting one of the major accessibility problematic for people with these types of access needs.

In line with Creed et al.'s [11] concern regarding the lack of consideration for unique user characteristics, we detected that barriers in the VR and AR experiences foregrounded an overall need for more customisable features that could allow participants to configure particular content, interface or hardware elements to their individual needs. Barriers such as limitations in increasing text size, lack of colour adjustment, and required multi-modality outputs (i.e. instructions) are clear examples of areas with opportunities for further accessible customisation.

Physical limitations due to impairment or illness were another key barrier that restricted participants to either accomplishing specific sub-tasks or fully completing some of the VR and AR experiences. Gerling et al. [16] highlighted the trade-off between limited movement range for participants with movement access needs and enjoying the experience; our findings support this notion and bring to light the specific movement areas that could benefit from accessibility support. In this regard, VR experiences with increased interactivity (*VR3–VR5*) required a higher level of external support, usually in the form of another person aiding physical movement or holding the controllers for the participant. In this case, participants from *A.3. Touch*, *D.1. Physical Mobility*, *D.2. Use of Arms*, *D.3. Use of Hands* and *D.4. Head Movement* faced major barriers.

AR experiences presented a higher number of barriers related to physical limitations due to the size and ergonomic aspects of its hardware. For instance, *D.3. Use of Hands* participants required a person holding the device on their behalf, *mimicking* a tablet mount. Physical limitations to manipulating virtual objects were another barrier which required altering or adapting finger and hand gestures in order to accomplish the tasks and complete the experiences. Finally, the need to observe around the physical space to interact with specific elements also required external assistance for *D.4. Head Movement.* It was noted that participants consistently required additional instructions or guiding prompts to complete tasks. Seifert and Schlomann [40] note that the Digital Divide plays an essential part in this lack of engagement due to the lack of access to these technologies. Furthermore, in our study, assistance was provided because participants struggled to understand or remember: (1) how to map controllers with the virtual interactions; (2) instructions provided in a single sensory output (e.g., only written instructions); or (3) when the participant was focused on creating adaptations to accomplish the tasks and could not simultaneously take in the experience's instructions or goals.

It is important to highlight that although multiple forms of assistance and adaptations were found to be useful in this study, there

Table 10: Key barriers encountered by participants when interacting with the AR content and any corresponding assistance and adaptions observed. The individual participants within each group who experienced these barriers are denoted by *P#*.

Category	Barriers	Assistance and Adaptations
A.1. Vision	• Lack of multisensory feedback, apart from visual (P01, P09, P36)	• External spoken description of digital objects and environment
	• Can't access AR app (P04)	• Mimicking screen reader
	• Lack of clear instructions for interaction (P01, P09, P21, P36)	• External tutorial and audio instructions during experience
A.2. Hearing	• None	• None
A.3. Touch	• Can't hold device (P37)	• User stabilised device on lap
	• Confusion controlling digital assets through touchscreen (P37, P41)	• External tutorial with simple indications
B.1. Thinking	• Lack of clear instructions (P17, P23)	• External prompts and guidance
	• Difficulty interacting with digital assets (P17, P23)	• External step-by-step directions
C.1. Voice	• None	• None
D.1. Physical Mobility	• Holding and operating the device (P02, P39)	• Mimicking tablet mount
D.2. Use of Arms	• Unavailable physical gestures (P15, P24, P28)	• Different combination of finger gestures to move virtual objects
D.3. Use of Hands	• Can't hold device (P22, P27, P29)	• Mimicking tablet mount • User stabilised device on leg
D.4. Head Movement	• Physical limitations to manipulate virtual objects (P16, P34)	• Other person helps participant move • Mimicking tablet mount • Extra support to stabilise device
E.1. Over 65	• Complicated instructions (P42, P43, P45)	• External tutorial

were a few instances with no solution to the following barriers: lack of captions and image description for blind users (*A.1. Vision*), disorientation (*D.1. Physical Mobility*) and unavailable physical gestures (*D.3. Use of Hands*).

7 Discussion

This paper provides a unique empirical evidence-based insight into the state of accessibility of contemporary VR and AR systems.

As demonstrated in Table 6, our usability study found a high level of exclusion of disabled and older people from freely using and enjoying the range of assessed VR and AR experiences in their current format, without any additional assistance or adaptation. The exclusion levels are particularly noteworthy for the interactively more advanced experiences *VR3*–*VR5* (Table 6). These experiences involve complex interactions that require sophisticated coordination of perceptual and cognitive inputs along with the fine use of hands to navigate the experience on both micro and macro levels. Hence, they display a high rate of exclusion regardless of the specific type of access need.

The highest exclusion rates were found in the final VR experience (*VR5*), an experience that is based on the application of hand-tracking technology. This observation is rather worrying considering that hand tracking and gesture-based interfaces are becoming increasingly present in the latest VR hardware such as the Meta Quest 3 and Apple Vision Pro, and these features are likely to become a standard in the near future. While less exclusionary than VR, the two tested AR experiences also displayed relatively high levels of exclusion (*AR1* and *AR2* in Table 6), indicating that accessibility improvements are needed across the whole range of immersive experience types. The study results also show a significant exclusion when it comes to the handling of headset and hand controllers (*VRH* and *VRC* in Table 6), hinting that further work on accessibility is also required in the hardware domain, for example by providing customisable controllers or supporting multimodal input.

Our usability study advances the existing HCI research on the accessibility of immersive technology [10, 13, 15, 50] by implementing an inclusive design approach and the consequent involvement of research participants spanning the whole spectrum of single and co-occurring access needs. As above, the inclusive design approach contrasts with the focus on a single access need that has, to date, been the dominant approach to usability testing in the field of HCI [3, 16, 27, 32, 53], and brings the benefit of being able to compare the usability friction between different types of access needs.

The approach presented here also contributes to existing user frameworks through our novel user matrix (Section 5.1), which expands on previous access need classifications by adding fine detail into the particular user requirements and usability demands in VR and AR, such as the use of arms, hands and head movement as the key VR and AR-relevant sub-categories of the usual category of mobility.

Besides the disability-related access need categories, the user matrix includes the category of ageing, referring to users over the age of 65 who do not report a significant disability, but experience milder access needs resulting from age-related decline of faculties. The exclusion from VR and AR for this group is, on the whole, less prominent than for some of the dominant access need groups (Table 5; except for *VR3, VR4* and *VR5*). However, the exclusion rates for the ageing group are much more consistent across the evaluated experiences and higher than in the non-disabled group, which suggests that ageing users must be given particular attention when considering accessibility improvements for VR and AR.

In the non-disabled group, participants experienced minor usability friction only in the more complex experiences VR3–VR5. As shown in Table 6, the exclusion rate for the participants who were unable to complete the task or experience without an assistance or adaptation grew from 10 % for *VR3*, to 20 % for *VR4* and 30 % for *VR5*, with the increasing exclusions rates following the increasing interaction complexity of these VR experiences. Since this exclusion is not attributable to access needs, the usability friction observed in the case of the non-disabled group indicates that the level of experience complexity has a direct impact on how effectively and quickly a user is able to master a new VR experience, even when they are already familiar with the underlying technology. In turn, this observation arguably indicates that the exclusion rates can, at least to an extent, be reduced not only by design but also through clearer onboarding and improved instructions.

The high exclusion rates established in our empirical usability study follow the preceding analytical study (Section 4) to estimate the exclusion rates using the Exclusion Calculator based on the UK population statistics, which demonstrated that up to 8.4 % of the UK population may be excluded from using VR and AR when it comes to more complex immersive experiences (Figure 2).

Stemming from the physical product design context, the method of exclusion rates estimation had not previously been applied in the context of VR and AR, to the best of our knowledge. We used the Exclusion Calculator to reinforce our examination of the VR and AR exclusion, but also to bring the method to the attention of the HCI community, as the estimation is particularly useful when costly user studies cannot be conducted due to a lack of resources.

The considerable improvements in accessibility evidenced by the much lower exclusion rates in Table 7, resulting from the assistance provided to the study participants by the researcher and the participants' own adaptations (Section 6) give hope that future VR and AR technology can be made much more accessible and thus inclusive if human intervention is replaced by carefully crafted technology-powered accessibility affordances. The identified barriers and corresponding assistance and adaptation methods presented in Tables 8, 9 and 10 indicate the instances of needed accessibility improvements and how these may be achieved.

This paper presents the estimated exclusion rates and empirical accessibility barriers in VR and AR based on the population of disabled and older people in the UK. The paper also offers a methodological springboard for a much needed wider evaluation of VR and AR accessibility−−to involve disabled and older population groups across the globe. Such evaluation would require applying our exclusion rates estimation method in the context of population statistics for different geographies, as well as recruiting geographically diverse disabled and older participants for accessibility evaluations. The most current version of the Exclusion Calculator [49] includes population statistics for a range of countries other than UK, such as USA, Brazil, China and India. In expanding the evaluation scope, it is highly important to also consider cultural differences and ensure that the wider evaluation extends beyond the Western, Educated, Industrialised, Rich and Democratic (WEIRD) world.

The work presented in this paper adds to other relatively scarce recent research into the 'full-spectrum' accessibility of VR and AR. For example, Creed et al. [10, 11] conducted two sandpits in 2021 and 2022 to collaboratively explore the accessibility challenges with AR and VR experiences in conversation with a number of academic researchers, industry specialists, representatives from national charities, special needs schools and colleges and assistive technologists and 14 people with lived experiences of disability. These sandpits defined a valuable initial high-level set of use barriers in VR and AR for physical, visual and auditory impairment and neurodiversity-related access needs. Our work partly confirms and partly expands this set by adding much more granularity from the perspective of empirical user testing involving users in the performance of real tasks.

8 Conclusion

We hope that the exclusion rates presented in this paper will draw further attention of the HCI community to the importance of VR and AR accessibility. While the work towards more inclusive VR and AR is gathering pace [11, 13], the key challenge remains to develop the technological solutions that can help maximise inclusion by addressing the access needs spanning the widest possible extent of the disability and ageing spectrum. This aim requires further inclusive design-led user research leading to a more detailed understanding of fine differences in the access needs and requirements of people with disabilities and older people, in particular with respect to co-occurring access need types. More technology research and development is also needed into how to leverage the opportunities presented by the latest advancements in AI to enable inclusion features that can recognise and adapt to complex access need variations.

The focus on single-user immersive experiences in AR and VR within this study is the starting point towards a much wider exploration of the inclusiveness and usability in the context of social VR and AR environments and the growing metaverse. We see fruitful future work in developing toolkits for VR and AR content developers that can assist in both automatically providing exclusion rates and usability friction mitigation strategies.

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