Understanding Accessibility for Physically Disabled Users in VR: Interplay of Physical, Digital, and Experiential Layers

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Abstract

Virtual Reality (VR) promises to enable people to fully immerse themselves in virtual worlds. However, the body-centricity of VR results in accessibility concerns for people with physical disabilities. In our work, we build on existing research that focuses on physical accessibility and discuss the digital layer that includes the design of avatars and virtual worlds, and the experiential layer that addresses the experience that VR provides for people with physical disabilities. We present findings from a qualitative study (N=16) that combined semi-structured interviews with hands-on exploration of state-of-the-art VR hardware and applications. Leveraging Qualitative Content Analysis, our results show that physical, digital, and experiential accessibility concerns are often intertwined and must be seen in conjunction. Additionally, we show that application contexts (e.g., gaming or social VR) shape accessibility concerns and preferences. On this basis, we contribute a nuanced discussion of the complexity of VR accessibility and examine context-specific accessibility preferences using the examples of VR gaming and social VR that need to be accounted for to create accessible and enriching VR experiences.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; **Accessibility**.

Keywords

Virtual Reality, Accessibility, Disability, Experience

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1 Introduction

Virtual Reality (VR) promises to enable people to fully immerse themselves in virtual worlds, with applications ranging from education and training [50, 69] to healthcare [33, 56] and entertainment [60, 62]. At the same time, the technology is associated with a wide range of accessibility concerns [38], primarily rooted in its body-centricity with demands that are subsequently placed on users‘ bodies [23]. In the context of limited mobility, the Human-Computer Interaction (HCI) and accessibility research community has identified **numerous physical access barriers**, i.e., resulting from the design of VR hardware and interaction paradigms that involve the users' physical abilities. For example, Mott et al. [39] identified seven accessibility barriers, including setting up the VR system or manipulating the controllers. Likewise, Dudley et al. [12] reviewed existing efforts to improve VR and AR accessibility and described six high-level design principles underlying accessibility strategies, e.g., input and output redundancy and customizability. Additionally, research has provided initial solutions aimed at improving physical access. For example, Yamagami et al. [64] created a design space that allows the mapping of unimanual input into bimanual interactions, and Franz et al. [14] designed the Nearmi framework to help designers create customizable and accessible point-of-interest techniques for people with limited mobility that increase awareness and orientation in VR.

However, VR is a complex technology with elements extending beyond physical aspects. For example, there is a body of work focusing on **digital aspects** of social VR , exploring the design of inclusive avatars (e.g., see [2, 35, 71]), with findings suggesting that user representation should be customisable to allow for the representation of disability. Likewise, factors such as player experience in accessible games [21] or remarks describing enjoyment and presence while comparing accessible VR locomotion [16] foster an understanding of **experiential qualities** of VR in the context of accessibility.

We also note that **research often addresses a specific setting (e.g., only focuses on games or social VR) or is entirely agnostic of application**. Hence, it remains unclear how findings considering specific aspects , e.g., of physical, digital, or experiential nature, translate to other contexts with divergent demands.

Thus, to fully address VR accessibility, physical, digital, and experiential aspects, which we understand in this work as three intertwined layers, must be considered in isolation and interplay while accounting for the application context, which shapes user preferences and needs. Against this backdrop, we raise the following two research questions:

RQ1: How do people with physical disability interact with VR, and what aspects of the technology impact their engagement on the physical, digital, and experiential layer?

RQ2: How does the context of VR applications, i.e., gaming and social VR, interact with the physical, digital, and experiential layers of accessibility?

We address these questions through a qualitative research approach. We combine semi-structured interviews with hands-on exploration of state-of-the-art VR systems and applications, involving 16 participants with limited mobility. Through Qualitative Content Analysis [72], we craft categories concerning the physical, digital, and experiential layers of VR accessibility, in which we investigate the preparation of experiences and the functionality of hardware and interaction paradigms (physical layer), bodily representations and world design (digital layer), as well as comfort, safety concerns and experience itself (experiential layer). Additionally, we address the relevance of context, i.e., gaming or social VR, in each layer.

Our results support the perspective of intertwined layers and show that it is crucial to acknowledge that the extent of accessibility concerns and design decisions can not be perceived on an isolated layer. For example, safety concerns affect preferences on the physical and digital layer, but also need to be addressed to give way to an engaging experience. Additionally, application contexts shape accessibility preferences, e.g., participants having distinctly different perspectives on the design of avatars and associated interaction paradigms when considering games or social VR. Our work makes the following three key contributions: (1) We add a nuanced understanding of physical, digital, and experiential accessibility concerns of people with physical disabilities to extend the current literature, (2) we highlight the importance of considering application context when considering VR accessibility, and (3) we identify opportunities for future work, e.g., temporal mechanisms such as daily form or fatigue, that need to be accounted for when designing accessible hardware and interaction paradigms.

With our work, we highlight the importance of accounting for the full complexity of VR in accessibility research, which ultimately needs to be addressed so that VR experiences are not only accessible on a physical level, but also account for design decisions on the digital level, opening up the opportunity for enjoyable VR experiences for all.

2 Related Work

Here, we give an overview of the relevant work. First, we briefly introduce VR and outline how its key concepts and typical application contexts have informed our work. Then, we discuss VR research addressing disabled people and examine current recommendations for designing accessible VR.

2.1 Virtual Reality

The technologies associated with VR allow users to transpose themselves into alternative realities that can be experienced and interacted with as if real [31]. VR can be defined as a *real or simulated environment in which a perceiver experiences telepresence*, where telepresence refers to the extent to which a user feels present in such an environment [59]. Here, Human-Computer Interaction (HCI) research typically foregrounds the concepts of presence and immersion, which are central to VR experience. There are several concurrent definitions of presence and immersion. For example, Slater [54] understands presence in the context of VR as the *"sense of being in an environment"* and as a user's reaction to a given level of immersion. Hereby, immersion refers to a VR system's objective level of sensory fidelity that allows it to wrap around the user's senses [6, 54], e.g., the Head-Mounted Display (HMD) displaying stereoscopic images in front of the eyes to visually immerse a user. As a reaction to this immersion, the user can feel present in the virtual environment. This can be further facilitated by interaction paradigms such as body or hand tracking as the user's virtual representation performs the same actions as the actual body, e.g., raising a hand or walking forward [27, 47]. In this context, work such as that by Biocca [5] or Slater et al. [55] suggests that embodiment is a key contributor to the construct of presence, and advances in complex avatars, i.e., the *"digital representation of a human user that facilitates interaction with other users, entities, or the environment"* [42, p. 34], foster the so-called body ownership illusion – the perception of the virtual body as one's own [40, 55, 61]. Generally, this highlights the interconnectedness of the different elements of VR systems (e.g., hardware, interaction paradigms, and user avatars) to facilitate specific experiences within VR.

However, with current research agendas spanning different fields, it is hard to describe VR research as singular. On the one hand, there is work regarding the hardware, ranging from the development of custom controllers, e.g., with grasp recognition [65] or haptic feedback [68], to proof-of-concept HMDs [13, 63]. On the other hand, virtual elements, e.g., the design and perception of avatars [17, 18] or the generation of virtual environments [48, 57], are under investigation as well, which can often be seen as disjoint from specific VR systems. Likewise, there is research concerning specific experiences with VR, for example, with systems eliciting the experience of death [25], but also in regards to Player Experience (PX) in games [7] or simulator sickness [32].

Additionally, VR applications fall into different categories and contexts of use. Most prominently addressed within the HCI research community are social VR, e.g., for leisure or work [36, 37, 44], and VR gaming [21, 60, 62]. Likewise, a growing body of research examines how VR can be leveraged to augment education and training [50, 69]. These fields are also reflected in commercial VR applications with a range of games such as Beat Saber [19] or Half-Life: Alyx [9] that require extensive upper limb movement. For example, in Beat Saber, users hold virtual swords and have to hit moving blocks in rhythm with music. On the other hand, applications such as VRChat [30] and Engage [34] provide social VR platforms, where users can meet up in virtual chatrooms to have meaningful interactions with others. This highlights the need to differentiate between these contexts when investigating VR accessibility, which we discuss further in the following section.

2.2 VR for Disabled Users

Previous research has been conducted to investigate VR accessibility. Here, we give an overview of existing work, which we structure into the **physical layer of VR accessibility**, i.e., whether users can access hardware and interaction paradigms, the **digital layer of VR accessibility** which addresses user representation and world design, and the **experiential layer of VR accessibility** which explores whether disabled users have access to the same experiences as non-disabled persons.

Overall, we note that **accessibility research covers the physical layer of VR extensively**. Particularly for people with physical disabilities, gaining access to basic interactions with VR is challenging due to the inherently body-centric paradigms of VR [23, 38, 39]. For example, Mott et al. [39] interviewed 16 people with limited mobility and carved out seven barriers, for example, putting on and taking off VR HMDs or manipulating controllers. Similarly, Creed et al. [10] pointed out that there were, e.g., *"challenges around wearing AR/VR devices securely and accurately by users with limited physical movements"* after running multidisciplinary sandpits that included people with lived experience of disability, but also industry specialists. Other studies worked closely with specific user groups, e.g., wheelchair users, to investigate interaction paradigms generally [45, 46] or in the context of games: For instance, Gerling et al. [21] surveyed 25 wheelchair users' motives to (non-) engage with VR games and evaluated formulated design implications through three case studies. Detached from specific application contexts, Franz et al. [15] investigated scene-viewing techniques in the contexts of different virtual environments, and, in another work [16], employed case studies with 19 participants with upper-body motor impairments to evaluate the accessibility of locomotion approaches. Also, Yamagami et al. [64] created a design space addressing unimanual (one-handed) VR input through a video elicitation study with 17 people with limited upper body mobility. However, although more and more effort is being put into understanding physical VR accessibility, current applications are often inaccessible – in 2024, over a third of all free 106 Meta Quest 2 VR applications did not include accessibility features [41]. Of the 300 most used VR applications released between 2016 and 2023, only 49 support external (e.g., gamepad) input, and no more than 100 can be controlled one-handed, which is more so dire as the number of applications with these features seems to decrease each year [1].

Research regarding the accessibility of the digital layer of VR has overwhelmingly focused on investigating avatar design, building on general work on self-perception in VR (c.f. [17, 18]). Here, current research mainly explores the representation of disability for people with visible and invisible disabilities in social VR [2, 22, 26, 35, 71], showing that disabilities are often seen as part of one's identity, and that it is necessary to give options to depict them. In contrast, not much is known in the context of games or about the interplay between the design of virtual worlds and disabled people.

Finally, while there have been approaches to incorporate the experience into VR accessibility work, **there are unexplored research gaps regarding the experiential layer of VR**. For example, in Dudley et al. [12]'s review of the efforts to improve VR accessibility, the term *inclusive immersion* is introduced and defined as a *"design objective reflecting the pursuit of maximally accessible and enjoyable Virtual and Augmented Reality experiences for users with different capability levels"*. However, despite explicitly stating enjoyment as a design goal, there was no further mention of how that would be achievable or could be addressed. Nevertheless, the authors partly addressed experience in a later work by examining the nature of experiences in a survey with 101 disabled people [67]. They highlighted a demand for immersive experiences that were impossible for some people in the real world, e.g., white-water rafting or skydiving. Likewise, Franz et al. [16] noted that factors such as enjoyment or presence sometimes outweighed accessibility when comparing locomotion techniques for people with upper-body motor impairments. Also, Gerling et al. [21] examined elements of VR experience in the context of accessibility, focusing on player experience in the context of wheelchair use. However, while there is a link between presence and embodiment in general VR research (see Section 2.1), constructs such as presence and immersion remain underexplored in the context of accessibility research.

2.3 Recommendations for the Design of Accessible VR

Previous work has summarized insights into VR accessibility into guidelines and recommendations. Here, we present the most relevant work addressing VR for people with physical disability and limited mobility.

Primarily focusing on physical accessibility, Mott et al. [39] derived four recommendations based on seven accessibility barriers for people with limited mobility, e.g., inaccessible controller buttons or the setup of a VR system, that they identified based on an interview study involving 16 participants. They recommend designing VR for interdependence by taking assisting people into account and allowing customization, e.g., support for custom input devices. Further, they highlight that user diversity should be considered and propose an ability-based design approach for interactive systems. Likewise, Gerling et al. [21] contribute recommendations for VR for wheelchair users. These recommendations not only underlined the need to implement flexible control schemes but also noted that it is important to account for wheelchair characteristics. Additionally, they recommended avoiding mandatory disability representation on the digital level. Concerning the physical accessibility in the context of social VR, Yildirim [66] reviewed 16 mainstream social VR applications concerning one-handed interactions, and formulated four design implications predominantly addressing physical interactions, e.g., providing bilateral support for control input, but also addressed the digital layer by calling for changes in the virtual world, for example, by using world-anchored contextual menus rather than body-anchoring (c.f. [49]). Changes in world or avatar design are central concerns of research in the digital layer, and existing research mainly focuses on social VR, and is often targeted at broad groups of disabled people. For example, Mack et al. [35] interviewed 18 people with disabilities and related identities about their preferences and/or experiences with avatars and disability representations. They condensed their findings into three recommendations for avatar platforms: i.) support customizability and easy change, ii.) make disabled and multiply minoritized users feel welcome, and iii.) engage with disabled communities. Moreover, Zhang et al. [71] created a set of guidelines addressing avatars for people with disabilities through a systematic literature review and interviews with 60 participants. These guidelines covered five aspects of avatar design, including the avatar body appearance, for example, advocating for flexible customization of body parts instead of non-adjustable avatar templates (guideline G1.2) or recommending prioritizing equitable capability and performance over authentic simulation (guideline G2.3). Overall, we want to note that we did not come across guidelines specifically addressing the experiential layer of VR. However, there have been some efforts, such as the literature review by Dudley et al. [12], aimed at unifying existing recommendations for VR design. They described six common design principles underlying effective accessibility strategies: input and output redundancy, the integration of assistive technologies, customizability, enhanced assistance, and inclusive design. However, these principles remain abstract; many address physical access, and there is no tailoring to specific disabilities. Thus, there remains a research gap in understanding how the different layers of VR contribute to the accessibility of the technology and how they interact. Likewise, there is another research gap concerning the detailed understanding of the context of a VR application (e.g., social VR or games) and its implications for accessibility preferences and needs.

3 Interview Study: Exploring VR and Disability Through the Lens of Physical, Digital, and Experiential Accessibility

To address the research gaps and to answer our research questions, we conducted semi-structured interviews to explore physically disabled people's perspectives on VR, addressing both gaming and social VR. We offered participants the option to engage with VR before the interviews and used videos to further visualize key concepts. Here, we give an overview of our research approach.

3.1 Method

We designed a semi-structured interview protocol to cover VR's physical, digital, and experiential layers within social VR and games. As discussed in Section 2.2, we understand the physical layer of VR accessibility to address hardware and interaction paradigm-related concerns, e.g., the HMD setup or the manipulation of controllers. With the digital layer, we explore user representation and world design, and we use the experiential layer to investigate how VR experiences are shaped for people with physical disabilities, e.g., which factors impact presence or immersion (see Section 2.1). Exploring all layers in conjunction allowed us to exceed the scope of existing work on VR accessibility, which has so far focused on the physical and/or digital layer in isolation (see Sections 2.2 and 2.3). Aligning with these layers, we developed questions on VR hardware and interaction paradigms (Physical layer), virtual avatars, and world design (digital layer), and embedded questions regarding the experiential layer in each. The interviews were supported by videos we created to foster a shared understanding of key concepts. Additionally, in-person participants were invited to explore VR with us before the interviews.

3.1.1 Hands-on Exploration Phase. We invited in-person participants to engage with state-of-the-art VR hardware and applications. In particular, we wanted to allow participants without prior experience with VR to create a foundation for the interviews by gaining a first impression of VR (see Section 3.3). These sessions included the Meta Quest 3 (Meta, 2023), representing wireless consumer VR systems with two handheld controllers. We selected well-known applications that were either already in our possession or available for free and allowed fast entry into different typical VR contexts: the Steam VR home space [8] as hub to further experiences and to acclimatize with navigating virtual environments, VR Chat [30] as a well-known VR application for social interactions, and Beat Saber [19] to experience embodied interactions and a game context. While not depicting everything possible with VR, those applications allowed participants to form opinions about different aspects of VR relatively quickly. We did not record or require a minimum session or application time, as the current state of VR is not accessible for everyone. Participants were generally free to decide what to test when, and did not have to test all applications. We assisted with technical instructions (e.g., how to perform specific interactions) or explanations of what they could do as requested.

3.1.2 Videos of VR Systems and Applications. We created five videos to introduce different aspects of VR: The videos aimed to provide participants with detailed insights into VR hardware, interaction paradigms, and example applications addressing gaming and social VR. Given previous work highlighting accessibility challenges for disabled people related to hardware (e.g., see [23, 39]), the videos also provided a fallback solution for participants who could not gain full access to the VR applications included in the hands-on sessions or were interviewed remotely. The first video was created to introduce VR. It explained what VR is and in which contexts (here: social VR and gaming) it can be used. The second video focused on VR tangibles typically used, e.g., HMD and controllers. Again, we used the Meta Quest 3 as an example of a state-of-the-art consumer VR system (see Figure 1a). We omitted depictions of additional hardware, e.g., eye tracking attachments or locomotion peripherals like treadmills, to only depict basic VR equipment. The third video showcased different interaction paradigms to engage in virtual worlds. Again, this only included standard approaches such as controller input or hand tracking (Figure 1b). For locomotion, we included free-roam (i.e., moving in the real world leads to the same movement in VR), and two joystick-based methods: continuous locomotion, where tilting a joystick forward leads to forward motion, and teleportation, where a landing spot can be positioned on the floor using the joystick. The fourth video introduced the role of avatars in the virtual world. This included depictions of avatar creation processes in different applications (e.g., in Engage [34], see Figure 1c), but also full body avatars, floating upper bodies, or approaches where only the hands are visible, e.g., in the game Half-Life: Alyx [9]. The fifth video depicted the worlds of different applications and focused on environmental factors and atmosphere, highlighting details of various social VR or gaming worlds (Figure 1d).

3.1.3 Semi-structured Interview Protocol. The interview protocol was designed to allow differentiation between different layers and to examine the influence of application context, i.e., social VR and

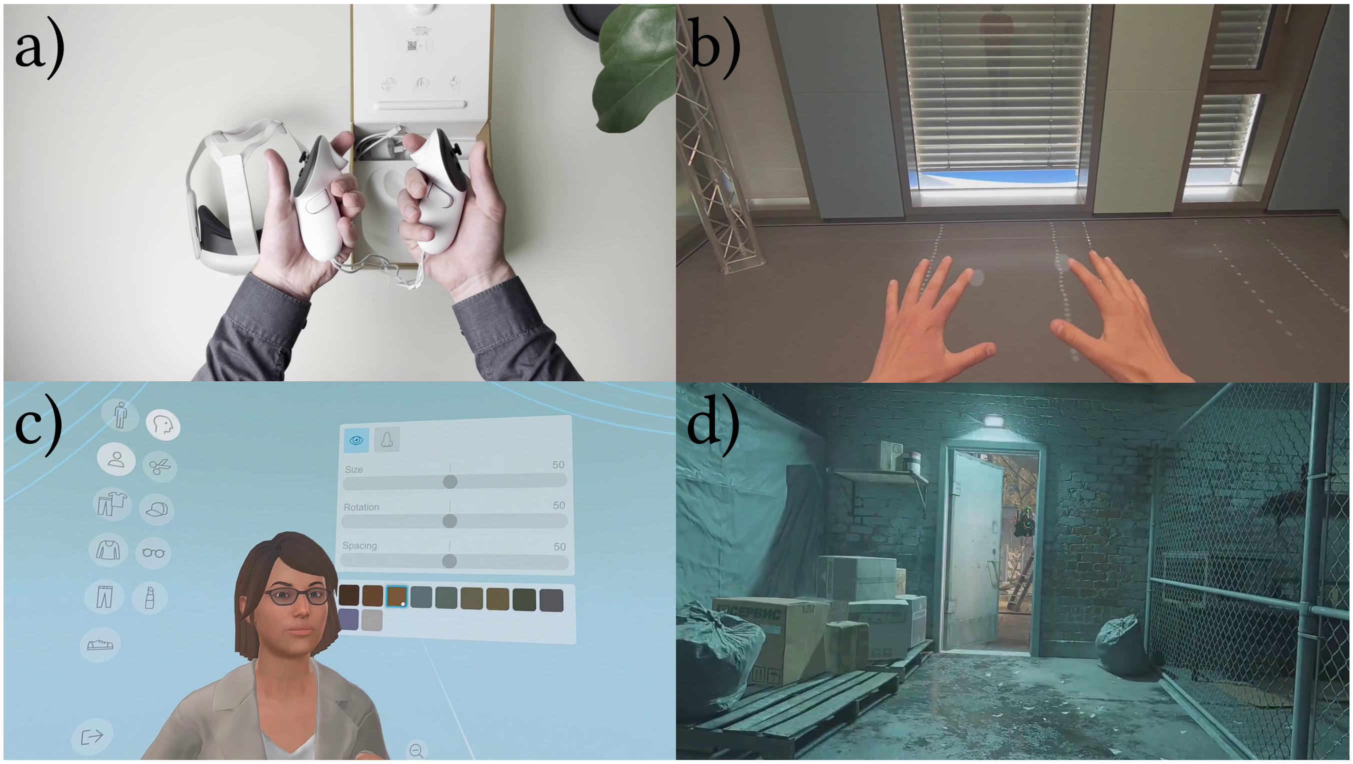

Figure 1: Videos informed about VR in general, hardware, interaction paradigms, virtual avatars, and VR world design. a) Exploring the hardware of the Meta Quest 3 b) Demonstrating hand-tracking interaction techniques c) Exemplary avatar creation in Engage [34] d) Touring the world of Half-Life: Alyx [9]

games. For this, we divided the protocol into seven sections; the first two assessed demographic information and previous VR experience, and the last one invited participants to raise remaining issues and ask questions.

The four main sections of the interview focused on hardware, interaction paradigms, avatars, and the design of virtual worlds. We grounded the first three sections in the current VR accessibility research foci discussed in Section 2.2. The section world design was added to incorporate the social model of disability (cf. Shakespeare [51]), where the environment is seen as an essential disabling factor. The four sections were each visually supported by videos that introduced their key theme (see Section 3.1.2). Most questions were asked in the context of both games and social VR. **The hardware section focused on VR tangibles**, for example, controllers or the HMD. We curated questions that allowed exploring the general impressions and accessibility of individual devices, building on previous work regarding physical VR accessibility by, e.g., Mott et al. [39]. Example questions are *"If you think of the aspects of the system you have seen, what would work for you?"*, and *"How would you describe its accessibility? In the context of games? Social VR?"*. **The section on interaction paradigms revolved around methods to interact with and move in VR**. Here, questions targeted the challenges and opportunities of different approaches, e.g., controller vs. hand tracking or locomotion approaches, and which paradigms were perceived as comfortable and why, for example: *"If you think of the different interaction approaches you have seen, what would you say would work for you? What not? What has to change to make it feasible?"*. **The representation section explored bodily representation in VR**. This included questions concerning avatars in different contexts, the representation and disclosure of disabilities, and possible influences on VR interactions to extend previous research (see Section 2.2), e.g., *"How do you want to be represented for the outside world? What do you want to see?"*. **The section on world design focused on the design of virtual environments** based on videos and/or previous experience. We developed questions exploring impressions of worlds, barriers in virtual environments, and the role of realism. Example questions are *"Did you feel welcome in the world?"*, and *"Where there barriers of the real world present in VR? For you? For others?"* The complete interview guide can be found in the supplementary material.

3.2 Participants

Our study included sixteen participants with physical disabilities (ten men, six women) between the ages of 22 and 67 years (M=45, SD=16). Of those sixteen participants, five were manual wheelchair users, six used a powered wheelchair, and two a lower limb prosthesis. Six participants had both upper- and lower-body impairments, eight only upper-body impairments, and 14 only lower-body impairments. At the time of the study, all participants resided in Germany.

Ten participants were employed, of whom two were in training. The remaining six were retired, but three were active in local organizations for persons with disabilities. In their free time, many engaged in fitness (n=8) or outdoor activities (n=5) but were also interested in games (n=12), (audio-) books (n=4), or movies (n=3). For digital gaming, participants mainly used computers (n=4) or consoles such as the PlayStation (n=4) or Wii (n=1). Their VR experience ranged from none (n=8) to single engagements (n=3) or a few sessions (n=5) and was gained mainly through exhibitions in museums or fairs. These experiences were made with PlayStation VR (n=3) or Oculus Quest 2 (n=2) systems, although many could not recall the specific systems. Stories about previous VR engagements often included negative experiences, for example, due to inaccessible controller buttons (P5 and P8), problems with the HMD (P3), or negative experiences within VR (P2). However, many were also eager to share their reason for participating with us - immersive experiences of activities otherwise impossible for disabled persons: *"[...] you can at least come close to gaining experiences that others have had in the real world, such as skateboarding, snowboarding, skydiving, bungee jumping, whatever"* (P5).

3.3 Procedure

We recruited our participants through e-mail newsletters, flyers, social media posts, word of mouth, and local organizations addressing people with disabilities. Eligible were all persons over 18 years with at least one self-identified physical disability who were able to consent to the interview and were fluent in either English or German. We did not require any previous VR experience and reimbursed participants 50 € each. We gave them the option of being interviewed in-person (13) or remotely (3) via BigBlueButton[1]. Additionally, we invited each in-person participant to an optional exploratory VR phase (see Section 3.1.1, where they could interact with a state-of-the-art VR system before engaging in their interview.

At the beginning, participants provided written consent, and we explained the interview protocol (see Section 3.1.3) to them. Then, participants who opted for on-site participation (n=13/16) could practically engage with VR. The hands-on sessions lasted up to 30 minutes, and all 13 participants of our in-person interviews were interested and could gain first (n=7) or additional (n=6) VR experience.

Afterwards, we entered the interview stage, which lasted between 39 and 80 minutes. Interviews were voice-recorded and conducted by the first author. We used the videos described in Section 3.1.2 during the interviews. They were explained in person, and participants were invited to share their thoughts directly during the videos. Each interview started with acquiring demographic data, and participants were encouraged to discuss previous experiences with VR. Then, participants watched the first video, during which we introduced them to VR and the context of social VR and VR gaming. Subsequently, participants were introduced to VR hardware, interaction paradigms, bodily representation, and world design using the respective videos, which were followed by discussions of the individual topics. We ended the interviews by giving participants space to raise their own questions.

Our study was approved by the Karlsruhe Institute of Technology ethics board (A2024-018).

3.4 Data Analysis

Interview data were transcribed using Buzz v1.2.0[2] locally, and we manually checked for consistency and formatting. We applied a directed Qualitative Content Analysis following Zhang and Wildemuth [72] to the data. For this, we deductively developed mutually exclusive a priori categories with descriptions and examples. The first categories were in line with the first research question, *RQ1: How do people with physical disability interact with VR, and what aspects of the technology impact their engagement on the physical, digital, and experiential layer?* and underpinned by the seven accessibility barriers identified by Mott et al. [39], previous work on virtual avatars (e.g., Angerbauer et al. [2]), and an experience-centric perspectives on accessibility in VR (see Section 2.2). Likewise, we developed additional categories for the second research question, *RQ2: How does the context of VR applications, i.e., gaming and social VR, interact with the physical, digital, and experiential layers of accessibility?* to explore the relevance of context in the layers directly. Table 1 gives an overview of the complete coding agenda with categories embedded in their respective layers. The first author applied all categories to two randomly selected interviews and discussed the results with the second author to ensure inter-coder agreement (Zhang and Wildemuth [72]'s analytical approach does not recommend calculations of inter-coder reliability scores). This led to iterative, minor adjustments to the definitions until sufficient coding consistency was achieved. He then applied the updated coding schemes to all interviews and checked for consistency. Next, the resulting codes and categories were discussed within the research team to achieve trustworthiness [58, 72]. As a result of the last iteration, we decided twice to merge categories due to linked themes: The initial categories *Comfort* and *Safety* merged into *C3.1: Comfort & Safety*, and the initial category *Usability* was absorbed by *C3.2: Experience*. We used maxQDA 2022 [24] for data analysis.

3.5 Positionality

In this section, we want to give insights into our positionality to allow readers to understand and interpret our work. We share our information acknowledging the limitations of such statements [20], and only include aspects we are comfortable reporting as part of our research. Generally, we believe that digital technology should be accessible to everyone and that there is a societal responsibility to ensure that emerging technologies are designed to account for disabled and non-disabled persons alike. Data collection and analysis were carried out by the first author, a white, non-disabled male in his thirties who lives in a Western country and works extensively on VR. Our broader research team has previously explored VR and video games for persons with disabilities, and stems from different academic backgrounds, including engineering, computer science, and psychology.

[1]BigBlueButton Inc., https://bigbluebutton.org/

[2]Williams (2024), https://github.com/chidiwilliams/buzz

		Category	Definition	Examples
Physical Layer	RQ1	*C1.1: Preparing for the experience*	All thoughts relevant to the system setup, including tasks such as preparing peripherals or putting on and taking off the VR HMD, extending accessibility barriers #1-4 of Mott et al. [39].	*"Especially the straps here, they are a bit tricky and that's where [the setup] could also fail"* (P15)
		C1.2: Physical functionality	Assessment of the functionality and practicality of hardware and interaction paradigms with respect to individual participants' capabilities, e.g., which approach can be employed for whom? This partly ties back to Mott et al. [39]'s accessibility barriers #5-7.	*"I can't do anything with the controllers. They are simply not manageable for me. I can't hold them, I can't control them"* (P8)
	RQ2	*C1.3: Relevance of context - physical layer*	Thoughts related to the setup and hardware components such as the HMD and controllers, as well as interaction paradigms (C1.1-C1.2), where participants voiced differences between leisure and social VR contexts.	*"In social applications, I think it also just feels more natural when I don't have to have a controller in my hand"* (P1)
Digital Layer	RQ1	*C2.1: Representation*	Thoughts regarding the design of one's virtual avatar, sense of embodiment, and the representation of disabilities in VR, for example, through disability signifiers such as wheelchairs or prostheses, and their influence on social interactions and avatar capabilities (cf. Angerbauer et al. [2]).	*"If I were to create my avatar, it would be important to me that it is as close to me as possible"* (P10)
		C2.2: World design	Everything regarding the design of virtual worlds, e.g., what is important and what is not, but also thoughts regarding barriers in virtual environments, e.g., linking to the social model of disability, where disability is, among other things, driven by environmental factors [51].	*"If it's virtual and I want to feel comfortable, then it has to be deceptively real. In any case"* (P7)
	RQ2	*C2.3: Relevance of context - digital layer*	Preferences and opinions regarding avatars, the representation of disability, and thoughts related to the design of virtual worlds (C2.1-C2.2), where participants voiced differences between leisure and social VR contexts.	*"If I'm doing anything social, I can definitely [show my] wheelchair"* (P6)
Experimental Layer	RQ1	*C3.1: Comfort & safety*	Impressions regarding the comfort of operating VR, such as statements of personal preferences of input paradigms when multiple options are viable (e.g., controller vs. hand tracking), as well as concerns regarding safety, both in the real (e.g., fear of falling), and within virtual worlds (e.g., harassment, data protection), or as an effect of the transition (e.g., jumping into and exiting VR).	*"If I have a carpet or a chair or anything else standing somewhere, even in a large apartment, and I would suddenly bump into it, that would be far too dangerous"* (P12)
		C3.2: Experience	Thoughts related to the quality of VR experience. This includes mentions of past or desirable future experiences with VR, drawing upon VR constructs such as presence and immersion (see Section 2.1).	*"It's fun when you're so completely immersed and really moving around in a world"* (P8)
	RQ2	*C3.3: Relevance of context - experiential layer*	Remarks commenting on past or desired experiences, comfort, and safety concerns (C3.1-C3.3), where participants voiced differences between leisure and social VR contexts.	*"I always look for meaning in the game I play"* (P12)

Table 1: Coding agenda with categories aligned to the physical, digital, and experiential layer and our research questions.

4 Results

In this section, we present the main results of our analysis, structured into the physical, digital, and experiential layers of VR. For each layer, we discuss core categories and comment on the relevance of context (i.e., gaming and social VR).

4.1 Physical Layer of VR Accessibility: Hardware and Interaction Paradigms

Here, we report findings regarding the physical layer of VR and implications for accessibility, focusing on the preparation of the experience and physical functionality.

4.1.1 Preparing the experience. The preparation of VR experiences was associated with accessibility issues, echoing previous findings [39]. Most prominently, many participants perceived putting on the VR headset as a significant barrier. Some participants had already encountered this problem in previous VR experiences, e.g., explaining their struggle trying to put on the HMD with one hand: *"So, you practically have to put [the HMD] on from the front, and... I can't hold the front and pull the back"* (P16). However, there was heterogeneity among participants. For example, one participant with spastic tetraparesis, which complicated fastening the overhead straps, pointed out that once preconfigured, he would be able to perform the setup alone: *"I think I would need help adjusting the glasses to me and my head, [...], and if it's made in such a way that it stays that way so that I really only have to put it on, that could work"* (P10). In this context, we want to note that access barriers caused by straps also extended to the controllers. Here, one participant with ataxia highlighted the difficulty of tightening the straps: *"Especially the straps here, they are a bit tricky and that's where [the setup] could also fail"* (P15). After using a wired VR system as a wheelchair user, one participant pointed out that *"The biggest problem was actually the cable because I had the feeling from time to time that it could get caught in a wheel"* (P13), but we want to note that many modern VR systems now use a wireless connection. Finally, in terms of learnability of the VR setup, many participants felt confident in repeating the workflow after minimal demonstration, e.g., a first-time VR user pointing out that *"Well, I assume that once you've done it two or three times, like so many other things, you'll get into a routine of how to do it very quickly"* (P12).

4.1.2 Physical functionality. The functionality of different hardware devices in combination with interaction paradigms was a prominent topic within our data, particularly when taking individual capabilities into account. While it was generally acknowledged that the bodily demands of VR were extensive (c.f. Gerling et al. [22]), all participants but one could access the state-of-the-art VR systems included in our work at least partially. Participants with lower-body disabilities especially described it to be *"Easier than with the Xbox, [...] it was actually fine"* (P1), or commented that *"The handling itself was very good"* (P13). For others, there was a more pronounced barrier when using VR hardware, echoing findings of Mott et al. [39], with one participant with a muscular disorder pointing out that *"I can't do anything with the controllers. They are simply not manageable for me. I can't hold them, I can't control them"* (P8). Concerns also extended to the HMD, with participants highlighting that the weight would stop meaningful VR engagement, e.g., *"The weight [of the HMD] was a big problem. I don't have much head control when I'm sitting upright, when I'm wearing [it] like this, my head falls forward"* (P8), which is a widely acknowledged barrier that continues to persist [12, 22, 38]. Regarding interaction paradigms, participants found that upper-body VR interaction often required fine motor control and/or simultaneous actions. For example, bimanual input was already perceived as particularly challenging during the hans-on exploration phase, with one participant later pointing out that *"So two controllers at once just doesn't work"* (P16), a challenge that also extended to locomotion techniques that require bimanual interaction (e.g., operating joysticks on each controller). When commenting on the free-roam alternative, participants questioned whether they would have a large enough, unobstructed space at home for this to be viable. Wheelchair users also drew attention to the challenge of operating one while wielding controllers, *"If I have controllers in my hand, I can't use my wheels. But if I don't have them in my hand, I can"* (P2). Additionally, participants highlighted that their ability to engage in specific interactions depended on daily form and decreased with time. For example, one participant stated that *"I can't always do that. Especially as I would have to raise my arms, [...], and then I don't have the strength at some point"* (P3) after reflecting on the amount of upper limb movement necessary to play the game Beat Saber. Interestingly, our findings also show that the current implementation of hand tracking - which could be seen as a way of addressing a range of issues with controller input - introduced new challenges, e.g., because of bodily differences not accounted for by the system. Here, one participant highlighted that *"When I stretch out my hands, it doesn't recognize [them] because my reach is insufficient. My arms are too short for me to reach far enough for the camera to recognize them"* (P5). These non-functionalities led our participants to wish for alternative solutions, namely individually adaptable hardware and interaction paradigms. *"Perhaps so that it is stationary, so you don't have to hold it yourself. [...], in any case, not both hands"* (P11), proposed one of our participants, while another wished for non-exhausting interaction paradigms: *"If I could play without having to overexert my motor skills. That would be something that I could say would be progress for me."* (P9). Additionally, participants with previous VR experience emphasized the need for VR applications to support external input.

4.1.3 Relevance of context. The physical layer only played a limited role for VR accessibility in different settings, with many participants not seeing a difference when contemplating using hardware or interaction paradigms in productive or leisurely settings. When considering interaction paradigms, some participants noted that games are typically more complex and faster-paced than social VR applications, for example, pointing out that *"It will be more hectic in the game than in a chat room or something like that"* (P1). Here, controllers were often seen as more suited for gaming environments than hand tracking, with one participant stating that *"I think it's easier to do [gaming] using controllers. It's easier to press several buttons in quick succession than [to perform hand tracking] gestures"* (P13). Regarding locomotion, participants also attributed games with larger virtual worlds. They highlighted the need to be able to move in VR while being physically stationary, for example, through joystick-based locomotion. This also included teleportation, although *"Of course, it has to fit in with the game concept. So if it's part of the concept that you can teleport, then that's great"* (P13). Likewise, application content and expectations also shaped participant views on the physical layer of VR in other settings. When considering social VR, many participants without upper limb impairments preferred hand tracking, because *"I think it also just feels more natural when I don't have to have a controller in my hand"* (P1). Additionally, the need for complex and time-critical interactions was less relevant, e.g., *"I don't think you have to act that much [...]. In a meeting, you tend to sit still and maybe have to write something down or make a presentation or something like that"* (P11). Similarly, naturally depicted, continuous locomotion methods were preferred over teleportation. Overall, this suggests a link between the physical and digital layers, with preferences regarding VR hardware and interaction paradigms not just being shaped by accessibility concerns, but also through consideration of their suitability for the specific type of VR application.

4.2 Digital Layer of VR Accessibility: Representation and World Design

In this section, we report findings regarding the digital layer of VR and implications for accessibility, focusing on representation and world design.

4.2.1 Representation. The importance of bodily representation in VR was evident in our data, and participants generally suggested that the representation of disabilities can be valuable, especially when done realistically and respectfully. For example, *"Portraying me as I really am, other people can see that too and might say, okay, he knows what he's talking about. He's in a wheelchair himself"* (P5). However, many participants warned to be mindful of stigma, as they acknowledged an avatar's impact on the perception of one's self and others, echoing previous findings on representation of disabilities [2, 4]. Detailing what good representations should entail, realistic, truthful appearances were often preferred, e.g., *"If I were to create my avatar, it would be important to me that it is as close to me as possible"* (P10). This also extended to others, where *"It would be nice if I could recognize them"* (P3), and participants thought it to be *"More pleasant to have a full body in front of you. Not just a flying head"* (P16). To achieve this, participants highlighted the need for exhaustive avatar creation tools that also include options to represent disability, as their disabilities or assistive devices were often seen as part of them: *"Yes, why not? It's part of my life"* (P1). On that note, a wheelchair user highlighted the need for accurate representation of assistive devices, pointing out that *"The [sports] wheelchair shown there looks more like mine than the hospital wheelchair in the corner. Because that's simply the more realistic image, and it just... I'll say it looks more dynamic, fitter, when you're sitting in one of those things."* (P13). Here, some participants also pointed out conversations that representation would facilitate, e.g., *"Wheelchair users have simply had completely different experiences. And you can therefore interpret some topics of conversation differently"* (P6). Finally, our data show that some participants were interested in avatars beyond the question of disability that is prominently discussed in literature (see Angerbauer et al. [2] and Zhang et al. [70]) and appealed for non-normative and fun options, stating that *"I hope they are also creative. [...], I'm open to that."* (P7). Regarding the implications of disability representation for interaction with the virtual world (e.g., locomotion or range of motion), participant perspectives differed: While some found realism necessary for immersion, other participants pointed out that such influence is highly individual and hard to determine, e.g., *"I believe that the virtual world is not able to recognize what I can and cannot do with my prosthesis"* (P7), an aspect which we discuss further in Section 4.2.2.

4.2.2 World design. The successful design of virtual worlds was often associated with authentic environments, but participants also commented on elements such as stairs that could be, similar to the real world, perceived as barriers. In detail, they appreciated the visual fidelity, e.g., *"I just find the graphics [...] impressive"* (P9), and assessed realism as a major driving factor for good world design, for example, because *"If it's virtual and I want to feel comfortable, then it has to be deceptively real"* (P7), further supporting previous findings (cf. Hvass et al. [29]). Regarding the inclusion of disability in world design, many participants appreciated the option, e.g., *"You can also depict representations within such a world. [...] Yes, a world can also reflect disabilities"* (P8), and proposed the incorporation of features such as disabled parking spaces to raise awareness. On the note of realism and disabilities, participants also added that elements that could pose as barriers were inherently part of realistic and immersive world design. For example, one participant explained why identical barriers in virtual and real spaces are important for everyday interactions, stating that *"It doesn't do me any good if I don't experience any barriers [in VR] and then experience barriers in real life. That's how you make life your enemy"* (P15). However, some participants pointed out that good world design should prevent people from getting stuck, e.g., *"If there are barriers, I need to be able to overcome them easily"* (P3), or *"I would feel content where I don't have things that I can't overcome"* (P11). As this often affected locomotion, participants noted that *"With the teleporting, because you can be wherever you want to be [...], you can also overcome any barrier"* (P15). Similarly, many proposed making barriers optional and thus only employable in specific scenarios, and some even questioned whether barriers need to be a part of virtual spaces at all, pointing out that *"If I can design a completely barrier-free world without any problems, [...], I can't think of any big reason why [it should not be] barrier-free"* (P13). Overall, this highlights that reflection of disability in world design - similar to representation of disability through avatars - is highly personal.

4.2.3 Relevance of context. Within the digital layer, the context of use (i.e., gaming or social VR) was relevant for participant preferences regarding avatar and world design. In particular, games were associated with the opportunity to experience fictional scenarios and participate in fantasy. For example, participants highlighted that *"There is really no limit to imagination"* (P2) and that *"It's also cool in a game when things seem like they're from another world"* (P5). This was also reflected in views on game avatars, e.g., *"I can be whoever I want in a game, [...], from golem to elf"* (P3). Here, views on the representation of disability ranged from *"I don't necessarily see the need to depict disabilities in games"* (P13) to participants stressing the need for more options as long as it fits the theme of the game, e.g., *"In games, I also think it's crucial, especially if there is a free character editor, that you also have the option of depicting disabilities. [...] If the game makes it possible for the character to sit in a wheelchair, then of course it should happen. [...] I also think that games in general should include disabilities"* (P8). However, the conflict between disability representation and implications for user interactions with the virtual world was also relevant here, with most participants not favoring barriers that would impact gameplay. In the context of social VR, the desire for realistic world design was very prominent, e.g., participants highlighted that the virtual world should be *"Just like the real world"* (P15). Additionally, personalized worlds were seen as a way of expression that can drive interpersonal interactions: *"I can act differently with the inviting party, especially if [their environment] reveals something about themselves"* (P3). While barriers within the virtual world were seen as part of realism, participants raised the point that most real-world barriers are human-built and could be avoided by better design: *"I would make [it's] wheelchair-accessible, without steps, edges..."* (P6). Additionally, participants differentiated between using social VR for work or leisure. For example, they expected the context to be reflected in avatar design: *"In a work context, it would be important to me that if the character is not real, not based on the original, that this is also evident. [...] In a leisure context, yes, I don't care if I'm watching a movie with a squirrel"* (P10). Generally, avatars were seen as significantly more important for social VR, and many participants favored depictions of themselves including their disabilities or assistive devices: *"If I'd be in a social VR setting, [...], then I would want to be as close to myself as possible"* (P8), and *"If I'm doing anything social, I can definitely [show my] wheelchair"* (P6).

4.3 Experiential Layer of VR Accessibility: Comfort and Experience

In this section, we report findings regarding the experiential layer of VR and implications for accessibility, focusing on comfort, safety, and experience.

4.3.1 Comfort & safety. Being comfortable and feeling safe while interacting with VR was a theme prominent in our data. Generally, the feeling of comfort was linked with safety concerns and bodily demands of VR. While most participants commented that they did not experience problems such as motion sickness, some noted that VR can initially be disorientating and could cause eye strain. For interaction paradigms, participants wished for methods that were non-exhausting and painless with reduced physical demands (c.f. Section 4.1.2), mirroring the goal of user experience research of pleasure instead of pain Hassenzahl [28]: *"So it should be as comfortable and less strenuous as possible because otherwise, I'm more concerned with avoiding pain and can't get engaged"* (P8). Regarding interaction paradigms, most participants found hand tracking more natural and comfortable than the controller, as *"You tend to work with your hands. [...] It makes it more natural to use your hands for it than the controller"* (P7). Concerning locomotion, many participants favored free-roam over joystick-based locomotion because of its naturalness, and participants who were wheelchair users highlighted that the combination with hand tracking would be a more comfortable experience for them, as they would not need to unequip handheld controllers to propel their wheelchairs, which would also positively affect embodiment and thus presence (see also Section 2.1). Raising safety concerns, other participants preferred continuous joysticks locomotion due to the risk of collisions or falls during free-roam movement, e.g., *"If I have a carpet or a chair or anything else standing somewhere, even in a large apartment, and I would suddenly bump into it, that would be far too dangerous"* (P12). Additionally, it was remarked that joysticks allow users to stay stationary. Regarding interactions with others, some participants were also concerned that disclosing a disability may create negative experiences by risking exclusion, while their primary motive to engage with VR was escapism and relaxation from daily life. Another concern was the uncertainty with whom one is dealing in VR, with one participant commenting that *"It would be very apt that [their avatar] at least corresponds to reality in terms of appearance and type"* (P3), who considered being tricked by inaccurate representations an emotional concern. Considerations regarding representation also extended to how users would be perceived by others. Here, one participant who experiences involuntary movement in their hands did not consider sharing his hand movements in multiplayer scenarios safe, pointing out that *"Because then I can hide my hands and then it doesn't matter that [I am] fidgeting all the time [laughs]. Yes, that's something that really bothers a lot of people, but I can't change it"* (P10). Finally, the transition between the virtual and real world at the end of the experience was a concern, with adjusting to the real world after being immersed in VR for longer periods being perceived as challenging: *"You can't forget your role. [...] VR suspends that, [...] but when you're back again in the here and now, you have that function again"* (P15).

4.3.2 Experience. Past and future experiences were prominent topics in our data. This included descriptions of or wishes for subjective experiences and thoughts regarding key concepts of VR, e.g., presence and immersion. Comments regarding the experience, for example, first impressions after the hands-on exploration phase, were often positive, e.g., *"Super good. It's really fun, yes"* (P4), and participants explicitly expressed high presence: *"You really feel like you're in the game"* (P15). Pronounced features that could decrease this sense of presence often touched upon the usage of teleportation that can be hard to anticipate (see also Section 4.1.3), or were concerning the loss of realism in the context of removed barriers (Section 4.2.2) or surreal avatars. Nevertheless, the general view on VR experiences was positive and often exceeded expectations: *"It's fun when you're completely immersed and moving around in a world. [...] It's just something that doesn't come across like that when you're just looking at a screen"* (P8).

Regarding future experiences, views on what would contribute to a good experience differed. Some participants were interested in slower-paced, forgiving applications, for example, *"Games that require me to think"* (P3). In contrast, others looked forward to experiences that require movement, e.g., a participant with a hemiparesis pointed out that they *"would find it more exciting to have some applications where you actively do something"* (P16). Additionally, there were many instances in our data where participants imagined types of VR experiences. There was a strong focus on hard-to-access real-life experiences that have also been reported in related work [67]. For example, one participant highlighted that they would like to use VR to *"[...] do what I find difficult in real life, [...]. It's always a question when you go somewhere you're unfamiliar with: Is it barrier-free? Can I enter here or not?"* (P16). One wheelchair user, who could not stray from paved beach paths during his last vacation, was happy to have unrestricted movement in VR, stating that *"It's positive that you can basically get to any place, [...], that if you want to get closer to the beach, you simply have the opportunity to get there"* (P12). Similarly, others highlighted opportunities to access culture, e.g., *"Museum visits, for example. Some museums I might not be able to get in because there are stairs and no elevator"* (P8), or wanted to experience different kinds of sports, commenting that *"You can at least come close to gaining experiences that others have had in the real world, such as skateboarding, snowboarding, skydiving, bungee jumping, whatever"* (P5). However, we also want to note that there were many instances in our data where participants suggested fictional experiences, e.g., *"I would love to sit on the bridge of [Star Trek's USS] Enterprise"* (P10).

4.3.3 Relevance of context. Different contexts of use (i.e., gaming or social VR) played a vital role in the experiential layer. While gaming was often seen as an opportunity to disconnect from reality, many participants considered social VR a chance to foster real-world connections with unique expectations regarding experience. Comments regarding escapism (i.e., according to the APA dictionary of psychology, *"the tendency to escape from the real world to the delight or security of a fantasy world"* [43]) often referred back to the association between games and fantasy settings, e.g., *"In these fantasy stories and so on, I can well imagine that this is simply a way of doing something [...] completely detached from everyday life"* (P11). Additionally, physical effort was viewed more favorably in games because of the combination of exertion and play, suggesting a complex interplay between previously discussed comfort (see Section 4.3.1) and engagement. Some participants even considered using VR for physical benefits: *"I always look for meaning in the game I play. What does it positively change for me? What can I learn from it? And if I can train my coordination, dexterity, speed, and attention, then [...] I think it's great"* (P12).

Social VR, on the other hand, was often associated with a desire for more realistic experiences, foregrounding interpersonal interactions. Here, participants expressed their desire to use VR to spend time with friends or leverage it for work as an alternative to non-immersive communication tools such as Microsoft Teams or Zoom. For example, one participant pointed out that *"If I have a team at work that is spread over a wide area, then it would of course be quite fun if you had VR as an opportunity to hold a meeting. It's simply different from a [Microsoft] Teams meeting"* (P13). However, we want to note that there were no explicit mentions of factors influencing presence or immersion in social VR settings in the data aside from the previously discussed role of realism (Sections 4.2.1 and 4.2.2).

5 Discussion

In this section, we first answer our research questions. Then, we discuss the complexity of VR in the context of accessibility research.

5.1 RQ1: How do people with physical disability interact with VR, and what aspects of the technology impact their engagement on the physical, digital, and experiential layer?

Our results show that how people with physical disability interacted with VR was highly individual, with dependencies between the physical, digital, and experiential layers of the technology. **Accessibility of VR on the physical layer is closely linked with users' physical bodies and individual ranges of motion**. For example, many manual wheelchair users included in our work experienced relatively few accessibility issues when setting up the VR system and engaging in basic upper-body interaction. Yet, extensive upper-limb movements were an access barrier for others, where the holding of the controllers was a challenge itself, supporting previous findings (see [16, 21, 39]). Here, our work adds nuance, highlighting the relevance of temporal factors for participants' ability to interact, e.g., fatigue or daily form, suggesting a need for real-time adaptation of interaction paradigms, an approach not yet broadly supported by VR applications [1, 41]. Here, we want to note that it is vital to view disability as fluent rather than static, which is in line with postmodern perspectives on disability such as Barnes' Minority Body Theory [3].Concerning **accessibility on the digital layer, our results show that user avatars and world design are intertwined, and need to be considered in conjunction** when addressing the representation of disability in VR. In particular, realism and the experience of presence (see Sections 4.2.1 and 4.2.2) were associated with virtual environments that reflected disability through realistic avatar design, but also through digital worlds. In this context, the design of accessible worlds was seen as an opportunity, however, some participants suggested that the complete removal of barriers might be detrimental (see Section 4.2.2), to some extent contradicting existing recommendations for avatar design (see [71], guideline G2.3). Overall, our results also show that while the representation of disability was an issue of concern, many participants did not want their experience to be defined by their disability. In particular, there was interest in alternative avatars previously highlighted as an opportunity to avoid social stigma (e.g., Angerbauer et al. [2] or Zhang et al. [71]). Here, our findings offer a different explanation, suggesting that alternative avatars can offer escapism in specific contexts, and designing them is an expression of play.

Further, our work showed the importance of investigating the **experiential layer of accessibility, where our work highlights that safety and comfort are essential conditions for people to have a positive VR experience**, and to explore higher-order constructs such as presence and immersion, which were often linked with realism (see Section 4.3.2). For example, comfort was linked to the absence of pain (see Section 4.3.1, similar to experiential perspectives on user experience (cf. Hassenzahl [28], and natural interactions (e.g., hand tracking) were seen as a precursor for presence, supporting findings of, e.g., Biocca [5] or Slater et al. [55]. Additionally, our data showed that safety concerns often exceeded the physical locomotion-related worries currently acknowledged by developers[3], and that further concerns, such as uncertainties in interpersonal interactions, need to be addressed as well. In terms of desirable experience, we want to highlight the interest in activities participants deem otherwise inaccessible. However, we want to caution that VR access to experiences does not absolve societies from ensuring real-world access. Considering dependencies between the layers, we want to note that **physical, digital, and experiential accessibility need to be considered in conjunction**. For example, safety concerns can affect multiple layers, e.g., the fear of collisions is a crucial factor in the choice of locomotion. Still, it also needs to be addressed in the context of the experiential layer, where it can be detrimental to the experience of presence. Finally, we want to highlight the diversity in preferences and needs in our sample, underscoring the need for personalization and adaptation.

5.2 RQ2: How does the context of VR applications, i.e., gaming and social VR, interact with the physical, digital, and experiential layers of accessibility?

Our results highlight that participants had distinct perspectives on social VR applications and for VR gaming, spanning individual challenges, expectations, and preferences on the physical, digital, and experiential layers. **Games were often seen as an opportunity**

[3] e.g., Meta: Locomotion comfort and usability. https://developers.meta.com/horizon/resources/locomotion-comfort-usability (accessed on April 8th, 2025)

to disconnect from the real world, with participants appreciating the freedom to be someone and experience something else (see Sections 4.2.3 and 4.3.3). Escapism and fantasy are well-established motives for general populations to engage with games (e.g., see Sherry et al. [52] or De Grove et al. [11]). Interestingly, previous work on accessibility has primarily interpreted non-human avatars as an opportunity to avoid stigma [71] or a result of internalized ableism Angerbauer et al. [2] in social VR. Here, our work adds nuance: For many participants, the predominant factor of interest was high-quality entertainment, and representation of disability through avatars or worlds was often seen as a secondary feature, only welcome if it fit the theme of the game (see Section 4.2.3). Participants also noted flexibility regarding the physical layer of accessibility, preferring input devices and interaction paradigms that provided them with a high degree of freedom that were not necessarily the most body-centric option for VR control, e.g., controllers instead of hand tracking (see Section 4.1.3). Hence, disability and body-centricity should not be foregrounded in every setting, and **disabled users of VR games should be afforded to practice escapism and leverage VR to explore alternative worlds in the same way as non-disabled users**. In contrast to games, social VR was viewed as a medium to stay connected with others for leisure and work (see Section 4.3.3), echoing the findings of general work on social VR [36, 53]. Anticipated **experiences in social VR were associated with realistic worlds, avatars, and interaction paradigms, particularly concerning the representation of disability, which was regarded as highly relevant** (see Sections 4.1.3, 4.2.3, and 4.3.3). Here, **world design should be kept accessible via good design choices (e.g., provision of elevators alongside stairs) instead of unrealistic behavior in VR (e.g., flying over stairs), facilitating a coherent experience**. Contrary to games, social VR was often perceived as slower, and thus preferred interaction paradigms were usually realistic and natural-feeling options, e.g., hand tracking instead of controller (see Section 4.1.3), echoing existing work addressing social VR [36, 53]. Overall, this shows that **the context of VR applications needs to be taken into account when considering the integration of accessibility features**: While gaming and social VR share the same technological platform, they each come with a unique set of characteristics, and users approach them with fundamentally different expectations, which need to be taken into account to cater for individual preferences that are shaping the experiential layer of VR accessibility.

5.3 Appreciating the Complexity of VR: Interpreting Layers and Application Context in Accessibility Research

Throughout our results, it has been evident that VR accessibility is a complex subject with multiple facets affecting physical, digital, and experiential concerns. Although we examined the respective layers separately, we found many aspects spanning multiple layers, such as when safety concerns address physical and experiential factors (see Section 4.3.1). These concerns may not have been noticeable when focusing on a singular layer alone. Thus, in the context of VR accessibility, **research should not be focused on singular aspects alone (e.g., physical access), but should examine aspects on a physical, digital, and experiential layer**. This could be done through the formulation of implications concerning digital elements or by reporting experiential measures in the context of physical accessibility, as already done by Gerling et al. [21] and Franz et al. [16]. For example, facilitating embodiment in a game with a one-handed main character is complicated when a proposed interaction paradigm requires bimanual interactions, and a new input device may be physically accessible, but that does not mean people have fun using it. Likewise, our results showed that different application contexts come with distinct user expectations and characteristics and address the physical, digital, and experiential layers differently (see Sections 4.1.3, 4.2.3, and 4.3.3). Here, desirable interactions were often measured by functionality in the context of games or by naturalness (e.g., hand tracking) in the context of social VR, and further contexts may introduce new perspectives. Hence, we want to additionally highlight that **research should consider application contexts and their implications** – the expectations and requirements for an accessible world differ between a medieval sword fighting game and a functional office environment. Additionally, numerous subtleties within different layers and contexts warrant exploration, similar to Franz et al. [15] 's work, which highlighted that differences in world design (e.g., openness or other actors) can affect preferred scene-viewing methods. In summary, **the interplay between the physical, digital, and experiential layers of VR and the implications of application contexts must be addressed when researching VR accessibility**. Only then can we understand recommendations or implications for design comprehensively in the context of accessible VR, eliminate the risk of discovering pitfalls affecting different layers at later stages, and create accessible VR that provides access and enjoyment according to Dudley et al. [12]'s idea of inclusive immersion.

To showcase the contributions of our work, we summarize key findings that go beyond the current recommendations in the literature (e.g., of Mott et al. [39], Zhang et al. [71], or Dudley et al. [12], see Section 2.3) as actionable items with indications for game and social VR contexts in Table 2. Although the recommendations are grouped by their origin layer, we want to emphasize that individual items affect multiple layers and their implications should not be considered in isolation. These recommendations offer nuance and extend current guidelines, and can, for example, serve as a starting point for transferring social VR-specific work, such as Zhang et al. [71]'s guidelines for inclusive avatar design, to other contexts, e.g., VR games.

6 Limitations and Future Work

In this section, we discuss limitations of our work and give prospects for future work. Regarding the participants of our interview study, only a few had previously experienced VR, and short sessions such as those offered as part of our study can not replace a more profound experience and should thus be seen as first impressions. While we believe that the exploratory sessions allowed for a more nuanced dialogue compared to the video elicitation-only formats employed by prior work (e.g., [14]), we also observed that some participants found it challenging to differentiate between games and social VR

	#	Recommendation	Game context	Social VR context
Physical layer	R1	Consider highly individual issues and offer **personalizable input** that can be used across VR systems (see Section 4.1.3).	Focus on providing the same degrees of freedom as conventional controllers to cover all necessary game interactions.	Provide natural interaction paradigms, such as roomscale locomotion and hand tracking, but plan for alternatives, e.g., through button input.
	R2	Account for **temporal factors** such as fatigue and daily form to support non-exhausting long-term engagement (see Section 4.1.3).	Offer alternative and/or adapt interaction paradigms in real-time, e.g., by amplifying movements, especially when movements are inherently part of the game loop.	Support natural interactions by offering alternatives and/or adapting them in real-time, and depict instantaneous actions (e.g., teleportation) as continuous.
Digital layer	R3	Provide optional ways of representing disability via **avatar design** (see Sections 4.2.1 and 4.2.3) and understand that context may impact relevance and user preferences.	Ensure that if disability is represented, this is done in a way that fits the game theme and does not negatively impact gameplay.	Allow alternative, non-normative avatars to avoid stigma, as an expression of play, and for escapism.
	R4	Design **virtual worlds** that reflect disability via the design of the built environment and include disabled users (see Sections 4.2.2 and 4.2.3).	Create engaging worlds that offer the opportunity to experience fantasy and fiction, regardless of user capabilities.	Focus on realism. Worlds can contain barriers, but should also incorporate adequate solutions (e.g., pair stairs with elevators).
Experiential layer	R5	Resolve **safety and comfort** concerns to improve presence and immersion (see Sections 4.3.1 and 4.3.3).	Provide clear entry and exit strategies to facilitate disconnecting from and reconnecting to reality.	Acknowledge interpersonal concerns, e.g., who can see what/whom when, to foster virtual real-world experiences.

Table 2: Key findings as actionable items beyond current recommendations in the literature (see Section 2.2) with indications for game and social VR contexts. While divided into physical, digital, and experiential layers, we want to emphasize that individual design choices can affect multiple layers, and their implications should be considered holistically, rather than in isolation.

due to missing experience. Here, we want to note that broad distinctions between VR games and social VR do not hold universally due to genre variability. For example, labeling all games as fast-paced is not always true. Additionally, we want to add that there is potential in exploring the dimensionality of multi- and single-player applications in the context of games. While we aimed for balance in demographics, people with physical disabilities are a very heterogeneous group. Thus, our sample does not reflect all lived experiences with physical disabilities, also considering that our research was carried out in Western Europe, and may not generalize to other cultural settings. In terms of VR applications, we opted to operationalize different types by focusing on gaming and social VR as two distinct options. However, there is an opportunity to address additional types of applications in the future, for example, by extending to training applications, or VR for therapy and rehabilitation. In terms of opportunities for future work, the research presented here highlights the relevance of temporal factors such as daily form or fatigue, which is an opportunity to further explore the potential of real-time adaptation of VR interaction. Additionally, our results showed that the currently discussed implications for avatar design in social VR (e.g., Angerbauer et al. [2] or Zhang et al. [71]) should be reevaluated in other contexts, e.g., gaming. Finally, we call for considering effects spanning multiple layers and contexts in future work (see Section 5.3), acknowledging the trade-off between comprehensiveness and thematic depth for a more holistic approach to VR accessibility research.

7 Conclusion

VR is a complex body-centric technology, with experience emerging from the interplay of VR hardware, interaction paradigms, user avatars, and the design of the virtual world. In our work, we operationalize these different facets of VR by means of physical, digital, and experiential layers of VR accessibility, demonstrating their interplay and implications for VR accessibility for people with physical disability. Additionally, our work makes a differentiation between the application contexts of VR gaming and social VR, highlighting that accessibility features need to consider the affordances of specific application types. Overall, our work suggests that there is room for more nuanced work addressing VR accessibility. In particular, our community needs to further build upon the established literature that addresses physical accessibility, complementing it with additional research that accounts for the digital and experiential layer while being mindful of application context, striving to create enriching VR experiences for disabled users that live up to the promise the technology holds.

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