"I just went into it assuming that I wouldn't be able to have the full experience"

Understanding the Accessibility of Virtual Reality for People with Limited Mobility

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ABSTRACT

Virtual reality (VR) has the potential to transform many aspects of our daily lives, including work, entertainment, communication, and education. However, there has been little research into understanding the usability of VR for people with mobility limitations. In this paper, we present the results of an exploration to understand the accessibility of VR for people with limited mobility. We conducted semi-structured interviews with 16 people with limited mobility about their thoughts on, and experiences with, VR systems. We identified 7 barriers related to the physical accessibility of VR devices that people with limited mobility might encounter, ranging from the initial setup of a VR system to keeping VR controllers in view of cameras embedded in VR headsets. We also elicited potential improvements to VR systems that would address some accessibility concerns. Based on our findings, we discuss the importance of considering the abilities of people with limited mobility when designing VR systems, as the abilities of many participants did not match the assumptions embedded in the design of current VR systems.

CCS CONCEPTS

• **Human-centered computing**; • **Accessibility**; • **Empirical studies in accessibility**;

KEYWORDS

Virtual reality, accessibility, limited mobility, head-mounted displays, motion controllers

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1 INTRODUCTION

Virtual Reality (VR) is an emerging technology that immerses users in various virtual environments. VR is prevalent in many domains, including gaming [61], 360{°} video [47], communication [55], education [59], and training simulations [23]. Although it is still a niche consumer product, VR systems have continued to grow in popularity as hardware becomes more affordable and as developers continue to create compelling applications and experiences [27]. As systems continue to improve in cost and quality, more people will have the opportunity to experience VR. Also, as in-person gatherings and events become scarcer due to the COVID-19 pandemic, VR might move beyond a niche product to a critical technology that allows people to work, socialize, and play while physically apart, which could be particularly beneficial for people with underlying health conditions such as movement disorders.

Although numerous researchers have investigated how to improve interactions with VR systems, it remains unclear how accessible VR is for people with limited mobility as the result of injury, medical condition, or advanced age. Prior research efforts have studied how VR can be used for therapeutic and rehabilitative applications for people with motor disabilities [56], but these applications differ from the everyday use of mainstream VR. VR devices, like all computer devices, are designed with implicit *ability assumptions* [63]. These ability assumptions dictate how users can interact with computer devices, and users often encounter accessibility barriers when their abilities do not match these assumptions [65, 66]. To make VR systems more accessible to people with limited mobility, and to challenge the ability assumptions embedded in their design, we must understand the challenges people with limited mobility encounter, or might encounter, when interacting with VR systems.

In this paper, we describe a semi-structured interview study with sixteen people with mobility limitations that affect their head, arms, hands, and/or legs. We asked participants about their thoughts on, and experiences with, VR systems. Although our participants possessed different abilities, we found that they had similar concerns regarding the accessibility of VR systems. We identified seven barriers related to the physical accessibility of VR devices, including operating controllers with two hands, controller buttons that were difficult to access, and headsets that were challenging to put on and take off. In addition to describing accessibility barriers, participants suggested potential improvements to VR systems that would address some accessibility concerns. Potential improvements included controlling VR interfaces with alternative input devices such as switches, and adjustment knobs on VR headsets that could tighten and loosen automatically.

Our paper makes the following contributions: (1) the identification and description of seven barriers that present accessibility challenges to people with limited mobility when using VR systems; (2) a description of participants' suggestions for improving the accessibility of VR systems; and (3) a discussion on opportunities for future research to design more accessible VR systems that support the abilities possessed by people with limited mobility.

2 RELATED WORK

Our work builds on previous research on understanding presence and performance for people with ambulatory impairments while in VR, gaming in VR for wheelchair users, the accessibility of head-mounted displays for people with upper-body motor impairments, and the accessibility of desktop and mobile systems for people with limited mobility.

2.1 Presence and Performance in VR for People with Ambulatory Impairments

Presence in VR is the feeling of one's body occupying the virtual space rather than their physical space [31]. Researchers employ various questionnaires to understand users' sense of presence [58, 62], with a strong sense of presence indicating that the virtual experience felt more real [51]. Presence can be important for people with ambulatory impairments who engage in rehabilitation practices that include physically walking while in VR [20]. Guo and Quarles [19] investigated the difference in the sense of presence experienced by people with and without multiple sclerosis (MS) while performing walking and reflex tasks. They found that participants with MS experienced more fatigue and slower reflexes in VR compared to participants without MS. They also found that participants with MS found physically walking in VR more natural than those without MS. Guo *et al.* [22] also found that people with motor impairments thought using avatars during the walking task made the virtual environment appear more realistic than people without motor impairments. Samaraweera *et al.* [49] investigated the effect latency has on presence while walking in VR for people with and without motor impairments. The authors found that higher latencies affected the gait of both sets of participants, but that participants with motor impairments were less sensitive to changes in latency. Guo *et al.* [21] studied the effect different virtual environments have on the gait and physiological responses of people with and without motor impairments and found that gait changes caused by different environments were relatively similar for both groups.

These research projects were primarily concerned with understanding and improving presence for people with limited mobility—mainly people with ambulatory impairments—using VR for rehabilitation tasks. Although these studies have highlighted important differences people with limited mobility experience while in VR, these studies are not concerned with the accessibility of mainstream, commercial VR systems or how people with upper-body motor limitations might interact with such systems.

2.2 Gaming in VR for Wheelchair Users

Recent efforts have explored how to improve the accessibility of VR games for people who use wheelchairs. A survey by the Disability Visibility Project [67] found that people who use wheelchairs might have difficulties performing actions such as crouching or moving while playing VR games. WalkinVR [70] is a driver for SteamVR games that allows users to move their virtual avatar using controllers instead of physical locomotion. WalkinVR also allows users to shift the height of controllers in VR, and to create a virtual controller to replace a physical one. Gerling *et al.* [17] surveyed wheelchair users about their thoughts on VR accessibility and found that survey respondents had concerns about the accessibility of VR, but they also appreciated that VR might offer a means for escaping reality and enjoying new experiences. The authors used insights from their survey to create three prototype VR games for wheelchair users.

Our work complements these prior efforts by identifying and describing VR accessibility barriers encountered by people with limited mobility. Improving the accessibility of VR devices can improve the accessibility of VR games, which would allow more users to take part in the unique gaming experiences VR offers.

2.3 HMDs and People with Upper-Body Motor Impairments

Researchers have investigated the accessibility and suitability of head-mounted displays (HMDs) for people with upper-body motor impairments. Malu and Findlater [34] investigated the accessibility of Google Glass, finding that their participants experienced difficulties using the touchpad located on the device, but that the hands-free nature of the device offered benefits over mobile and desktop systems. In another study, Malu and Findlater [35] conducted a larger investigation of the accessibility of Google Glass and created a touchpad input system to control the device. In their study investigating the acceptability of Google Glass for people with Parkinson's disease, McNaney et al.[36] found that their participants experienced difficulties with the device recognizing their speech, and with performing tap gestures.

Prior research on the accessibility of HMDs highlights the importance of identifying accessibility barriers for emerging technologies and the need to design and test alternative input methods. Our research shares similarities with this work, as VR systems also use HMDs. However, VR systems employ more advanced input controls that can pose additional accessibility barriers to people with limited mobility. In addition, VR HMDs are bulkier and heavier than Google Glass, and VR HMDs tend to cover the eyes completely.

2.4 VR for Older Adults

A recent thread of research has been the investigation of VR use by older adults [60]. Hodge *et al.* [26] outlined challenges around VR design for people with dementia and described directions for future research, which included a focus on personalization and improving the physical design of VR devices. Roberts *et al.* [48] explored the perceived usefulness of VR for older adults and found that their participants had a generally positive view of VR but that VR systems would benefit from improved ease of use and social features to connect with friends and family. Baker *et al.* [3] conducted a two-week evaluation of a VR system with older adults in a care facility and found that many participants enjoyed the interactions afford by VR. In another investigation, Baker *et al.* [2] explored the potential benefits of social VR for older adults and presented design recommendations for improving communication in future social VR applications.

It is important to ensure that VR devices are accessible to older adults, especially as developers begin to create experiences and applications specifically for older adults. Older adults might also experience limited mobility, such as low strength and fatigue, which makes our research applicable to this population of users.

2.5 Accessibility of Mobile and Desktop Systems

Numerous researchers have investigated how to improve the accessibility of desktop and mobile computing systems for people with limited mobility. These investigations have focused on new interaction techniques to improve 2D target selection [57, 64], methods for improving touch accuracy [38, 39, 43, 45], gaze-based interaction [32, 44], novel voice control mechanisms [24], and utilizing a wheelchair as a mobile computing platform [7, 8]. Many solutions to desktop and mobile computing accessibility barriers stem from understanding users' behaviors when interacting with computing devices. For example, research on understanding the accessibility of 2D pointing by people with tremor [30] led to the creation of several accessible pointing facilitation techniques [14, 57, 64].

Input devices and interaction techniques for VR systems differ from traditional desktop and mobile computing devices. Although there are many lessons we can learn from prior efforts to improve the accessibility of desktop and mobile systems, VR systems offer unique challenges that require investigation. Some examples include the use of dual motion controllers to manipulate objects while in VR or controlling the user's view according to their head movement. By detailing the accessibility concerns people with limited mobility have about VR systems, we hope to lay the groundwork for future efforts in designing novel input devices and interaction techniques for this audience.

3 METHOD

We conducted semi-structured interviews with sixteen people with limited mobility to understand their thoughts on, and prior experiences with, VR systems. The goal of our interviews was to better understand what challenges people with limited mobility might encounter when interacting with VR systems, what strategies—if any—they might employ to overcome those challenges, and what suggestions they might have to improve the accessibility of VR systems.

3.1 Participants

We recruited and interviewed sixteen people with limited mobility (13 male, 3 female, average age of 35.6 years, *SD*=11.7). We conducted interviews in-person (n=9) and remotely (n=7) with participants who could not travel to our lab. We used Skype to conduct interviews with remote participants (a phone call was used for one non-Skype user). We held in-person interviews at our research lab. We recruited participants through email listservs, newsletters, Twitter, and local and national organizations that support people with limited mobility. Participants had to be at least 18 years old, located within the United States, and self-report as having limited mobility. Since many people have not yet tried commercial VR systems, and because accessibility barriers might prevent people from trying VR, prior VR experience was not a requirement for participation. A single researcher conducted the interviews, which lasted approximately one hour each. We compensated participants with a $75 Amazon gift card, as well as reimbursing transportation costs to visit our lab (when applicable). Table 1 summarizes participant details.

Four of our participants had prior VR experience. P2 owns the PlayStation VR headset and controllers and reported using it intermittingly over the past three years. P4 has owned the Lenovo Explorer headset for one year. P6 used the Google Daydream VR headset but stopped due to lack of comfort and the device overheating. P16 was in a VR club at his university and reported previously using the HTC Vive headset.

3.2 Interview Protocol

Our interview protocol was constructed to gather thoughts and opinions from participants with and without prior VR experience. Participants with prior VR experiences (n=4) were asked questions to better understand their VR usage, if they experienced any accessibility barriers while using VR, and what strategies they used, or might use, to improve the accessibility of VR systems.

We employed two approaches to gather feedback from participants without prior VR experience (n=12). First, we used a video elicitation approach [25, 37] by showing participants three videos depicting various aspects of a VR system. All participants without prior VR experience, both in-person and remote, were shown all three videos (n=12). Second, in-person participants without VR experience (n=7), were given the opportunity to try one or two VR applications with the Oculus Rift S headset and motion controllers. We describe the video elicitation protocol and the in-person VR experience protocol in the following sections.

3.2.1 Video Elicitation Protocol. Video elicitation is a form of photo elicitation, a method where photographs, videos, or other visual images are used during semi-structured interviews as means to "*evoke different kinds of participant knowing than they might through verbal interactions alone*" [37]. Participants (n=12) watched three videos, each approximately two and half minutes in length, that showed different aspects of the HP Microsoft Mixed Reality VR system. Participants were asked to comment on each video after

Table 1: Demographic information for our participants. Categories for self-reporting mobility limitations were from Findlater et al. [14].

					Self-reported impairments†										
ID	**Age**	**Sex**	**Mobility Constraints**	**IP/R**	**Mo**	**Sp**	**St**	**Tr**	**Co**	**Fa**	**Gr**	**Ho**	**Se**	**Dir**	**Dis**
P1	20	M	Muscular dystrophy	IP	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y
P2	31	F	Muscular dystrophy	IP	Y	N	Y	N	Y	Y	Y	Y	N	N	Y
P3	54	M	One-armed, limited mobility, low vision	IP	Y	N	Y	N	Y	Y	N	N	N	Y	Y
P4	25	M	Unable to use arms & hands, cannot walk	R	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
P5	38	M	Arm weakness	IP	Y	Y	Y	Y	Y	Y	N	N	N	N	Y
P6	25	M	Spinal muscular atrophy	IP	Y	N	Y	N	Y	N	Y	Y	N	N	N
P7	36	M	Muscle & nerve loss in one leg	IP	N	N	N	N	Y	N	N	N	N	N	N
P8	36	M	Paralyzed from chest down	R	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
P9	26	M	Advanced muscular dystrophy	R	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y
P10	41	F	Cerebral palsy	IP	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
P11	49	M	C-5 quadriplegic	R	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
P12	48	M	C-4/5 quadriplegic	IP	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N
P13	32	M	Paralyzed from neck down	R	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
P14	58	F	Left-side weakness	R	Y	N	Y	N	Y	N	Y	Y	Y	Y	Y
P15	23	M	Cerebral palsy, limited right side movement	IP	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y
P16	27	M	Spinal muscular atrophy	R	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y

†Mo = slow movements, Sp = spasm, St = low strength, Tr = tremor, Co = poor coordination, Fa = rapid fatigue, Gr = difficulty gripping, Ho = difficulty holding, Se = lack of sensation, Dir = difficulty controlling direction, Dis = difficulty controlling distance. IP indicates in-person participants and R indicates remote participants. Highlighted rows indicate participants with prior VR experience.

viewing and were also asked follow-up questions by the interviewer. Our interview questions are in the supplementary materials.

Video one[1] (V1) showed the setup process for the VR headset and the motion controllers. By showing V1, we sought to identify accessibility concerns participants might have about setting up a new VR device. Video two[2] (V2) demonstrated basic VR interactions such as selecting, rotating, and scaling virtual objects with dual motion controllers. V2 allowed participants to comment on potential accessibility concerns regarding input devices and interaction styles commonly used in VR systems. Video three[3] (V3) demonstrated the use of voice commands to manipulate objects in VR. V3 allowed participants to offer opinions on a hands-free alternative input method.

These videos were chosen because they clearly explained the actions that were being performed, showed a person perform the actions, and showed the results of the actions in VR. Although the videos depicted only one VR system, the system shares similarities with many other types of VR systems, such as common interaction methods for manipulating virtual objects, the use of dual motion controllers, similar initial setup procedures, and a similar form factor for the HMD. The video elicitation process enabled us to be more inclusive by allowing participants to provide feedback about tasks that they might be unable to perform, and by making the study less of a test of participants' abilities. Overall, the video elicitation provided participants the opportunity to reflect and offer their thoughts on setting up and interacting with a VR system. Our video elicitation protocol is in the supplementary materials.

3.2.2 VR Experience Protocol. After the video elicitation portion of the study, we asked in-person participants (n=7) if they would like to experience VR for themselves. Six participants tried one or two VR applications with the Oculus Rift S headset and motion controllers (whether they experienced one vs. two applications was dependent on the remaining interview time). P12 declined to try the VR applications because he could not hold the motion controllers. Participants tried the VR application(s) after the interviewer described the functionality of the headset and controllers. We chose the following VR applications because they employ interaction methods that are common in many VR applications. The first app was *Oculus First Contact*[4], a tutorial-based virtual environment where users explored the functionality of the Oculus touch controllers by interacting with a robot and various items in a workshop. The touch controllers allowed participants to mimic hand postures and actions, such as performing a thumbs-up or grasping an object, by pressing down or placing fingers on specific buttons.

[1] https://www.youtube.com/watch?v=294cpW-2YIA
[2] https://www.youtube.com/watch?v=V_2r7_MR424
[3] https://www.youtube.com/watch?v=WMHmkK_PO7I
[4] https://www.oculus.com/experiences/rift/1217155751659625/

Table 2: Summary and description of seven barriers to VR accessibility for people with limited mobility.

Seven VR Accessibility Barriers for People with Limited Mobility
1. *Setting up a VR system:* concerns related to preparing VR peripherals and defining the VR play boundary.
2. *Putting on and taking off VR HMDs:* concerns related to putting on and taking off a VR HMD by oneself or with assistance.
3. *Adjusting the HMD head strap:* concerns related to tightening and loosening the HMD head strap, or with the head strap interfering with wheelchair headrest.
4. *Cord management:* concerns related to running over, tripping over, or getting entangled in cords stemming from VR HMDs.
5. *Manipulating dual motion controllers:* concerns related to holding and using two motion controllers simultaneously.
6. *Inaccessible controller buttons:* concerns related to reaching, pressing, and holding buttons on VR controllers.
7. *Maintaining view of the controllers:* concerns related to keeping VR controllers in view of cameras located on VR HMDs.

The second app was *AltspaceVR*[5], a multi-person VR application that allows people to attend events and explore various virtual worlds with other users. Participants completed AltspaceVR's tutorial, which showed participants how to perform interactions such as teleporting, walking, and grabbing objects. Two participants also tried the VR version of *Google Earth*[6]. Google Earth required the use of both motion controllers to fully experience the application, but since using both controllers was difficult for some participants, it was replaced with AltspaceVR, which can be used with either one or two controllers. Participants were asked to think aloud and describe their experience while using the application(s), and the interviewer asked follow-up questions after participants finished using the application(s).

3.3 Analysis

We recorded and transcribed each interview. We also took photographs and recorded video of consenting participants when they tried the VR applications. Two members of the research team analyzed the transcripts. We used the qualitative methods of open and axial coding [10] to identify themes around accessibility concerns and suggestions for improving the accessibility of VR systems. We synthesized these themes into seven barriers that might pose accessibility challenges for people with limited mobility when interacting with VR systems.

4 FINDINGS

Our participants expressed numerous concerns regarding the accessibility of VR systems. At a high level, these concerns related to the physical demands required during the initial setup of a VR system, and the physical accessibility of VR hardware, which includes VR HMDs and controllers. In this section, we discuss the seven accessibility barriers we identified from our sixteen interviews (Table 2). Although not all participants expressed the same concerns, these barriers represent significant challenges that people with limited mobility might encounter when interacting with VR systems. We also present potential solutions offered by participants for how to improve the accessibility of VR. We designate quotes from our participants using *P#*, followed by *R* to denote remote participants and *IP* to denote in-person participants.

4.1 Setting up a VR Device

Seven participants expressed concerns with the initial setup process of the VR system demonstrated in V1. One concern centered around the need to perform actions that required fine motor skills, such as placing batteries inside controllers or plugging cords into a computer. *"I would have to have somebody help me with the setup as far as plugging in cables and those kind of things, I wouldn't be able to do that. Definitely couldn't check batteries and all that. . ." (P11-R).* This finding is consistent with prior research that has shown that setting up computer peripherals for traditional desktop systems can pose a challenge for people with limited mobility [46].

Although setting up a VR device might share accessibility challenges with other computer devices, defining the boundary for the play area is a unique VR experience that can pose issues for people with limited mobility. After watching V1, P5-IP described his concerns with defining the play boundary: *"Yeah, I think setting up the boundary, the play area looked kind of hazardous. Because I'm having to hold a thing [the HMD] straight up like this [in front of them] and move backwards, or to the side. Basically, I'm kind of wondering is it going to be able to do that with my jerky movements? How long is it going to take to do this? Because I can only do this for a limited amount of time before I need to set things down."*

Participants mentioned that they would require assistance to set up a VR system. How much assistance participants thought they might need depended greatly on their amount of motor control: *"I might need help like putting in the batteries say, because I don't have very good fine or gross motor movement with my hand" (P10-IP).* Participants with more severe motor limitations commented that assistance would be a necessity: *"I would need somebody to handle all the physical aspects of it." (P12-IP).*

4.2 Putting on and Taking off VR HMDs

Seven participants mentioned challenges with putting on and taking off a VR HMD. The weight of the headset was important in determining if participants felt they could put on and remove the HMD themselves. P2-IP, who had prior VR experience, mentioned: *"It's pretty heavy and the head strap is difficult to get right. I think*

[5]https://altvr.com/
[6]https://vr.google.com/earth/

probably for anybody, but I have a difficult time trying to get it on and getting it to stay on." For some participants, putting on the HMD themselves was impossible. When asked about his experience putting on a VR headset, P4-R responded, *"I can't do any of that myself. I guess really bad is how I'd describe it."* Other participants mentioned that equipping the HMD was doable, but with considerable effort: *"I might be able to get the headset on myself, kind of wrestle it on." (P12-IP).*

P4 noted that the inability to remove a VR HMD himself would limit his opportunity to experience VR to when another person is present: *"I still need help getting it on and off. I don't like being unattended with it, in case something goes wrong or whatever. I'll usually only play it if someone else is in the house with me." (P4-R).*

Participants suggested that lighter headsets may be easier to equip: "It can be heavy, and I have very limited use of my left side. So it might be easier if it can be handled by one hand and possibly lighter weight" (P10-IP). Asking for assistance was a strategy participants said they would use when putting on or taking off a VR headset: *"not so good with lifting and especially if it's over my head, I might just ask somebody else, especially because I don't want to break anything"* (P2-IP). Although asking for assistance is a viable approach, P16-R commented that headsets are not designed to be equipped collaboratively: *"I think they are definitely challenging to put on because they're designed to have to put on yourself, not to have someone else put it on for you."*

4.3 Adjusting the HMD Head Strap

Although adjusting the HMD head strap is part of putting on and removing a VR HMD, eleven participants had specific comments and concerns regarding the head strap. The knob to adjust the head strap is positioned on the back of the headset for both the HP Mixed Reality headset and the Oculus Rift S headset (see Figure 1, left). Several participants mentioned that the knobs were poorly positioned. Some participants thought the head strap would interfere with the headrest of their power wheelchair, making VR more uncomfortable: *"One thing I noticed is, the back, the strap thing on the back is thick, so it does touch my headrest, so that is another factor that makes it a little more difficult to move my head" (P1-IP).* P4-R explained his process for dealing with the head strap: *"I actually do have to take off the headrest on my wheelchair to use it. My headrest completely blocks me from wearing it all because I'm not able to sit up by myself. There's no clearance between the back of my head and my headrest. Headsets are pretty big, so, yeah, that's definitely a big hindrance."* To avoid issues with the head strap knob and her wheelchair headrest, P2-IP interacts in VR outside her power wheelchair: *"I usually transfer onto the couch when I play. So yeah, I don't think I've ever tried in my chair."*

Positioning the adjustment knob on the back of the headset also made it more difficult for users to access the knob. P6-IP explained: *"I can't reach back that much. This would be a challenge for sure."* P10-IP mentioned that reaching the knob was doable but would be challenging: *"It's not that I couldn't do it, but it would probably not be very easy because looking at the video, you have to be able to bend your arm, it looks like 90 degrees, and for people with disabilities that's not going to be very practical for some of us."*

Participants suggested that the head strap knob, or other head strap controls, could be located near the front or side of the headset to improve reachability: *"I feel like a better way, would be to put some sort of buttons on the sides, or the front, or whatever and have that tighten and loosen the thing" (P15-IP).* P12-IP suggested that head strap adjustment could be done automatically instead of manually: *"Something that was self-tightening. Like if you could either push a button or a command from the PC maybe to sort of go ahead and tighten up. Any kind of small physical affordance I think would be kind of a challenge unless it was just really simple like a button."* In lieu of more accessible adjustment control methods, P8-R expected others to ask for assistance: *"I think there will definitely need to be some sort of means for a person to adjust that strap with limited mobility. I don't know exactly how that could be accomplished. But I would say [the] majority of people likely have, if not like a parent or family member, some home health aid or something that could adjust the strap."*

4.4 Cord Management

Many VR systems are tethered, which requires users to connect their headset to USB and display ports on their desktop or laptop computer. Eight participants expressed concerns about tethered HMDs. One concern with tethered HMDs expressed by some participants was the fear that the headset cord would get caught in their power chair: *"I wouldn't want that to get tangled up. Someone walking might not get tangled up on the cord, but I could see myself, if I was close to the computer and the cord hit the ground, I might get it very tangled in the tires of my chair" (P1-IP).* Other participants expressed concerns about potentially rolling over the cord. P12-IP explained, *"I think that could be an issue, rolling over it. If I rolled over that cord with this chair and got it pulled on, that would probably do some damage pretty quickly."* In addition to people using wheelchairs, cords might pose challenges to people with balance issues, as described by P7-IP: *"Yeah, it's more that I would step, or trip, or just tangle myself on something."* P2-IP described the difficulty of moving in VR with a tethered headset: *"But with all the cords, being in a wheelchair doesn't really help in that regard. . .I'm doing all this moving. How on earth am I supposed to do some of these more active games? I do hate all the wires and cords and stuff."*

Participants suggested a simple solution would be to use a wireless headset: "obviously be easier wireless. . .the person in a wheelchair you don't have to worry about a wire getting caught under a wheel or falling down, because if it fell down, I'd have to have someone help me" (P10-IP).

4.5 Manipulating Dual Motion Controllers

Nine participants had various concerns regarding the use of two motion controllers to interact in VR. Some participants mentioned that they could potentially hold and use one controller, but that using two controllers was a major barrier: *"I can only use one hand for the controller. So I use my right hand to control one of the sticks. And I think having the one hand barrier is quite common for people who have strokes. . ." (P14-R).* Some participants mentioned the difficulty of trying to move in the physical world while using two controllers in VR. P1-IP explained: *"Okay, if I was moving around, I wouldn't be able to hold, it would be difficult to hold two of them because one*

Figure 1: (left) The head strap adjustment knob is typically located on the back of VR HMDs. (center) P1 supports their left arm using their right hand to steady the VR controller. (right) P6 demonstrates using both hands to press and hold down the joystick to walk in AltspaceVR.

hand I have to drive my chair. One at a time might be easier than two at a time, I know that much.” For participants with little or no movement in the arms or hands, motion controllers are completely inaccessible: *“But then the controllers wouldn’t work for me at all since I can’t move my hands at all” (P12-IP).*

Certain direct manipulation tasks in VR, such as rotating and scaling virtual objects, require users to coordinate moving both controllers simultaneously. Some participants noted performing these manipulations would be difficult: *“I’m not sure that would be possible for me to do them simultaneously. If I had to do, I can do it one handed. But if I have to do both hands at the same time, that’s not going to work” (P10-IP).* P2-IP mentioned that she would avoid interactions that would require the use of two controllers: *“I probably just wouldn’t do the ones that required too much coordination. It’s a little frustrating to not really be that good at it.”*

4.6 Inaccessible Buttons

Nine participants described challenges with reaching, pressing, and holding down buttons on the motion controllers. For some participants, the size of the controllers was an important factor: “*The hands are a little too small to comfortably want to use this thing. My hands are small. . .in order to reach all the buttons, and reaching things was difficult” (P1-IP).* For P5-IP, the weight of the controller played a role: *“The heavier the controller is, the more difficulty I’m going to have. My tendency is basically when I click on this [button] I press both [buttons] at the same time, even though I only intended to press this.”* For P3-IP, the smoothness of the controller made it difficult to access the buttons: *“Too smooth. Yeah. Like, I’d be putting on some you know the medical tape that sticks to each other? ...see if you push this button it wants to move. And the three buttons you got on the inside, if you had to hit two of them at the same time, you would have a problem.”*

Participants also expressed concerns about interactions that required them to press and hold buttons simultaneously. P6-IP explained the challenge of using the controller to walk in VR, which required participants to press and hold down a joystick (Figure 1, right): *“Yeah I think walking was pushing it down. Push one of them down. Yeah then I have to use two hands and leave the other controller to do it. Yeah as soon as I heard that you have to push it down, I was like, ‘Yeah nope. This is not happening.”’* P15-IP described difficulties with pressing buttons on other types of controllers: *“I play video games and I have to press down on something, it takes me three to four tries to press down but pushing down [and holding] is just a little bit more difficult.”*

4.7 Maintaining View of the Controllers

Multiple VR systems use inside-out tracking [15] to track the positions of motion controllers, meaning the controllers must be in view of the headset’s cameras for their position to be tracked. Keeping the controllers in view of the cameras allows users to see a virtual representation of the controllers while in VR. Applications—AltspaceVR for instance—can overlay additional information on the virtual controllers, such as commands that can be issued by pressing certain buttons. Some participants expressed concerns with keeping their arms and hands elevated so that the controllers would remain in view of the headset cameras: *“holding my hands up for extended periods of times is difficult, and going up and down like this is going to be more, holding them up like this is more difficult. I mean, I just don’t see how I can really do it, because I have my arm on the [wheelchair’s] hand rest” (P5-IP).* P6-IP described how the headset lost track of the controller, making it difficult to know which buttons to press: *“When you’re wearing the headset you can’t see the remote. It was confusing, ‘Okay which part am I pressing now?’ It’s not really intuitive.”*

4.8 Alternative Input Methods

Participants discussed alternative input methods for performing interactions while in VR. The primary interaction methods discussed were voice and gaze input. In this section, we summarize participants’ views on these input methods for manipulating objects in VR.

4.8.1 Alternative Controllers and Input Devices. Given the limitations and accessibility concerns with the VR controllers, some participants suggested the use of different controllers and input devices for interacting in VR. P9-R suggested using the Xbox Adaptive Controller[7]: *"...it takes a while to adjust to it, because you're so used to playing with a traditional controller. So having to think about other buttons can sometimes be complicated. But once you get used to it, I think it feels natural, and it's been a good experience."* P16-R mentioned that switches might be a useful alternative to motion controllers: *"using alternative input like switches and filters so you don't have to physically use a controller or move your arm."* P8-R described one possible type of switch setup: *"...and then you could put Velcro strips across it or something to that effect, and use that to place large or small switches anywhere across the front of the user. And if they've got a physical disability where they can't really move their arms very well, chances are, anything that's close to the abdomen would be within their range of motion."* Overall, participants mentioned that more controller options and customizations would be useful, *"I just think customizing, having a few different options for controllers, would be my biggest thing"* (P1-IP).

4.8.2 Voice Input. The third video (V3) demonstrated the use of voice commands to select and manipulate objects in VR. Many participants felt that voice input would be an accessible alternative to using motion controllers for VR: *"For me, that would definitely augment...what's frustrating to me about not being able to select [objects] or whatever by hitting a button on a controller" (P11-R).* P9-R mentioned: *"I use voice all the time already, and I think it's really accessible. And it definitely can make things easier."* Some participants noted that voice commands in VR seemed useful but had concerns that the voice recognition would work well for them: *"I usually don't prefer using my voice just because sometimes it's hard for the voice recognition to understand my voice. In this case, I think I would want to use my voice, because it wouldn't require me to do multiple motions at one time" (P1-IP).* An opportunity exists for VR to take advantage of prior work on multimodal input, such as the classic "put-that-there" [5], to improve accessibility, although voice recognition may not work well for some people with disabilities [40].

Several participants mentioned that using voice in addition to a motion controller would be a useful input method: "I think it's pretty useful. Some people when they're talking, they move their heads around. It would be cool if you could use voice with the controller" (P15-IP). P3-IP shared a similar sentiment: "I'm always looking for one-handed controllers. Like with me, it would be controller for one hand and voice for the other hand."

4.8.3 Gaze Input. VR and augmented reality (AR) HMDs are beginning to incorporate eye tracking into their design (Microsoft's HoloLens 2 and HTC's Vive Pro Eye are two recent examples). Eye tracking in these systems are used for explicit input, such as a user selecting a virtual object with their gaze, implicit input, such as automatically scrolling once a user has read the final sentence on a page, and for understanding users' attention as they interact with applications[8]. Some participants mentioned that gaze-based input might be useful as an input control for VR systems: *"I also have a Tobii eye tracker, so I was just thinking about watching that video and how moving objects with eye tracking would be a really good accessibility option" (P09-R).* However, participants also expressed caution about the drawbacks of gaze-based interaction: *"My first thought after using it [eye tracking] for about 10 minutes was that this is really gimmicky. I personally wouldn't use it because I like to look around at things and I'd be accidentally clicking on things or doing stuff that I don't mean to do in the game space just because my eyeballs stray to a random corner of the screen" (P08-R).* P15-IP had concerns about the accuracy of eye trackers: *"I think that could be useful. I'm just wondering, because I've used an eye tracker before, and it didn't work as well as I thought it would."*

5 DISCUSSION

Researchers have investigated how to make mainstream VR more accessible, but most prior works have focused on sensory or cognitive disabilities [1, 54, 68, 69], with fewer attempts made at understanding VR accessibility for people with limited mobility [17]. Our findings highlight the accessibility concerns people with limited mobility have regarding VR systems. From these concerns, we identified seven accessibility barriers (see Table 2) that people with limited mobility might encounter when using VR systems. These barriers relate primarily to the physical accessibility of VR devices. Highlighting the inaccessibility of VR devices is important, as VR, more than other computing technologies, depends on users' physical abilities [41]. For example, a user might be able to press a button to throw a ball in a desktop computer game, but a VR game might expect the user to press and hold multiple controller buttons simultaneously to grip the ball, and to perform a throwing motion with their arm and shoulder while holding a controller. If VR devices are inaccessible, then users will be unable to successfully interact with the underlying applications, as "*an input device is part of the means used to engage in dialogue with a computer or other machine"* [6].

It is important to note that our findings are not suggesting that all VR accessibility barriers are hardware barriers. Our method did not lend itself as well towards identifying barriers in software experiences or in social activities like collaboration in VR. Also, there are potentially other hardware barriers we were unable to uncover through the videos and short VR demonstrations. Although it is important to understand accessibility barriers at the device level, it is also important for future work to understand what barriers exists in all aspects of VR use.

In this section, we discuss design strategies for improving the accessibility of VR systems for people with limited mobility. In particular, we focus on considering the support users can receive from friends and family, how customization could improve the accessibility of VR devices, the importance of considering the diversity of users' abilities and perspectives, and how an ability-based design approach could inform the design of accessible VR devices. We also reflect on the differences between responses we received from remote and in-person participants.

5.1 Design for Interdependence

A common strategy participants mentioned when discussing setting up a VR system and putting on and taking off a VR HMD was to ask for assistance. Asking for assistance during VR setup could be beneficial for users who might have difficulty performing fine motor

[7] https://www.xbox.com/en-US/xbox-one/accessories/controllers/xbox-adaptive-controller
[8] https://docs.microsoft.com/en-us/windows/mixed-reality/eye-tracking

tasks, such as placing batteries in the VR controllers. Assistance could also be beneficial for putting on and taking off a VR HMD, but as noted by P16-R, VR HMDs were not designed to easily allow one person to put the HMD on another. Placing a VR HMD on another person requires communication, as the wearer must say if the HMD feels comfortable and secure.

It is important to facilitate good communication between the user of the VR system and the person aiding them. This communication requirement provides an opportunity for VR systems to be designed for *interdependence* [4]. Unlike designing for independence, which presumes users are interacting with systems alone, designing for interdependence explicitly highlights the need for collaboration between users and other people. Prior works have demonstrated interdependent designs for people with limited mobility by suggesting *pair photography* as an approach to improve the accessibility of smartphone photography [42], and by allowing the joint co-creation of AAC speech [13]. Current VR design relies on others to help people with limited mobility use devices without supporting the communication needed to make that assistance more cooperative. Using interdependence as a framework for designing VR systems could potentially result in more accessible setup procedures. For example, perhaps the process of setting the VR boundary could be changed so that one person physically traces the boundary while the other sees the boundary being formed in the virtual space. This form of collaboration would allow the user of the VR system to more effectively communicate their needs to the person aiding them. Users might also experience a greater sense of control, as they would still be involved in the setup process. Instead of users having someone else set up their system for them, a more collaborative approach would allow users to be a more active participant during the setup process.

Designing VR systems to facilitate interdependence could help address design barriers 1 and 2. VR designers and researchers should consider the role friends, family, and caregivers play when helping people with limited mobility access computing systems. By understanding and focusing on these relationships, VR systems can provide more accessible and empowering experiences to people with limited mobility. Designing for interdependence could also help other populations that might encounter accessibility barriers, such as children and individuals experiencing situational impairments.

5.2 Design for Customization

Some participants mentioned that motion controllers in general would not work for them. These participants expressed interest in using alternative controllers and input devices, such as the Xbox Adaptive Controller or switches, to interact in VR. For people with limited or no movement in their hands and arms, alternative input devices are a necessity. Researchers have developed novel input devices for VR to enhance various aspects of the VR experience [9, 11, 33, 53], however, significantly fewer devices were built with accessibility as a primary goal [50, 54, 68]. The opportunity exists for designers and researchers to create novel input devices that can improve the VR experience for people with limited mobility. People with limited mobility exhibit a wide range of ability, so new input devices can be specialized for certain group of users (e.g., quadriplegics) or could be designed to be customizable enough to fit the needs of a larger population.

Motion controllers typically have several buttons, a trigger, and a joystick or touch pad on each controller. Participants expressed concerns about the location of buttons (i.e., some buttons being positioned too close together) and about the dexterity required to press and hold multiple buttons simultaneously. Interaction styles that required users to press and hold buttons for an extended period of time (e.g., pressing down the joystick to walk in AltspaceVR) were especially problematic. Users of VR systems should have the option to remap interaction styles or controls that might require accessing too many buttons simultaneously. Users might want to perform the remapping themselves, but there is also the possibility that users could complete an assessment so that the system itself could suggest remappings based on their abilities, similar to the approach used by the Supple system to accessibly lay out traditional GUIs [16].

Some participants who used power wheelchairs also noted that using two motion controllers while attempting to move in the physical world would be difficult, as one hand was needed to control the joystick on their chair. A possible solution could be to borrow the design principles of *chairable computing* [7] to create VR input devices or controls that can be attached on or near a person’s wheelchair. Allowing users to interact in VR while also moving in the physical world might provide enjoyable VR experiences for people who use wheelchairs.

Participants were both excited and skeptical about using voice or gaze as input methods in VR. Participants highlighted the potential for voice and gaze to replace the need to use physical controls. However, participants were skeptical about the accuracy of both input methods (their skepticism is warranted according to research that shows the inaccuracy of voice and gaze input [12, 40]). Participants mentioned how speech recognition systems often had a difficult time understanding their speech. Other participants noted that gaze-based interaction can be problematic due to the Midas touch problem [28], and that the accuracy of eye trackers can be hit or miss. Voice and gaze-based interaction have the potential to be useful input methods in VR for people with limited mobility, but these methods also have drawbacks including fatigue, erroneous input, dependence on environmental conditions, and challenges with social acceptability in multi-user settings, among others [12, 29].

Positioning the adjustment knob on the back of the HMD was problematic for participants who were unable to raise their arms above their chests or were unable to reach behind their heads. It was also problematic for participants using wheelchairs, as participants described having to remove the wheelchair’s headrest or leave their wheelchair altogether to use VR. While the position of the head strap might be inconsequential for most VR users, our findings demonstrate that these design decisions could have profound impacts for people with limited mobility. A simple proposed solution was to relocate the adjustment knob to a more reachable position on the headset. Repositioning the adjustment knob to the front or side of the device could potentially alleviate some participants’ concerns. Controls for automatic adjustment of the head strap instead of manual adjustment, as proposed by P12, could also be a solution. Designers should consider providing different adjustment options, or allowing the adjustment knob to be repositionable, would allow people to choose the method that works best for them.

Another concern was that cords attached to VR HMDs might get caught in or run over by wheelchairs. Cords may also be problematic for people with balance issues, such as P7, who mentioned the fear of tripping over the cord. VR developers are creating more wireless VR HMDs (the recently released Oculus Quest is one example), which could alleviate concerns expressed by participants. Wireless headsets, however, might pose different challenges, such as additional weight due to batteries, that should be considered and accounted for. If a VR headset must be tethered, designers should consider alternative methods for cord management.

Allowing more customization of VR devices would help address design barriers, 3 through 7. VR designers should consider how to enable as much customizability as possible, as people with limited mobility will possess various levels of motor control, making a "one size fits all" solution impractical.

5.3 Design for Diversity

Our results describe the accessibility barriers people with limited mobility might encounter when using VR systems. However, many of these barriers could be encountered by people without mobility limitations, or people experiencing situational impairments [52]. For example, reaching behind the head to adjust the head strap might be uncomfortable or inconvenient for many people. Also, over longer periods of use, ensuring that one's hands are in view of the headset cameras can be fatiguing even for people with no mobility limitations. Addressing the concerns raised by our participants would result in more accessible VR experiences for all people.

It would be incorrect to presume that people with limited mobility might not be interested in using mainstream VR games and applications. Participants expressed various sentiments about how they could potentially use VR. One sentiment was the desire to use VR applications even if the full experience was inaccessible to them. P2 described her experience as: "So mostly I was playing it just to. . .for the sake of playing, not really any skill involved. I would do those for causal, like 'Oh, I'm just trying this out.' Because that's mainly what I did with the VR, is I just went into it assuming that I wouldn't be able to have the full experience."

It is important to realize that people with limited mobility may have any number of reasons to want to experience VR; indeed, the opportunities afforded by virtual environments may be particularly beneficial to audiences who experience constraints in the physical world. For example, prior work has found that people with mobility restrictions are interested in virtual experiences of real-world activities (*e.g.,* paragliding) that might be inaccessible to them [18]. Although VR is still in its infancy as a consumer technology, it is important to establish the foundation of VR accessibility, so that as VR devices become more ubiquitous people with limited mobility will have access to a range of VR experiences.

5.4 An Ability-Based Design Approach to VR Accessibility

Design frameworks can be useful in helping researchers think in structured ways about addressing accessibility barriers. Researchers can propose solutions and devise strategies based on the principles and guidelines from design frameworks to improve accessibility. One design framework that can help inform solutions to VR accessibility barriers is *ability-based design* [65, 66], which is a design approach that focuses primarily on considering users' abilities when designing interactive systems. Placing an emphasis on *ability*, rather than *disability*, will allow researchers and designers to focus on creating accessible VR devices that leverage the abilities possessed by people with limited mobility. In Table 3, we apply five principles from ability-based design to address the VR accessibility barriers identified in our study.

5.5 Reflections on Remote vs. In-Person Interviews

We conducted interviews with in-person and remote participants. Five of our seven online participants had no prior VR experience, and since their interviews were conducted online, they were unable to try VR in our lab. Although remote participants were unable to try VR devices, they were still able to provide useful feedback through our video elicitation method. Remote participants commented on the accessibility of the actions performed in the videos, often by comparing what was done to what they could or could not do. For example, after watching the demonstrations of manipulating objects using two controllers in V2, P14-R commented that he could only use one controller at a time, making dual controller interactions inaccessible to him. In contrast, in-person participants were able to comment on specific aspects of the devices that would be difficult or impossible to infer by watching a video, such as the weight of the HMD, the smoothness of the controllers, and the pressure needed to press a button.

The clarity of the videos was important in helping elicit responses from participants. Each video clearly specified the action being performed and the motion needed to perform the action. Having clear and descriptive videos allowed participants to identify when there was a breakdown between what they could do and what the system expected them to do. As a result, remote participants were still able to provide useful feedback on challenges they would expect to encounter when using a VR system, even if they could not comment on the full range of aspects that may be exposed through actual system use (e.g., weight of devices).

It is important to refine video elicitation methods, and to carefully consider their benefits and limitations, as remote user testing might become more commonplace if social distancing guidelines remain in place due to the COVID-19 pandemic. In general, video elicitation can be useful when receiving feedback from people with disabilities, as fatigue or other accessibility issues might prevent individuals from interacting with applications or devices. Also, early-stage prototypes would benefit from receiving feedback from people with disabilities, but there is a tension of not wanting to waste people's time and limited energy on early-stage prototypes. Video elicitation could be a useful approach for receiving feedback on prototypes and concepts early in the design stage, which would allow accessibility concerns to be surfaced and addressed before final design decisions are made.

Table 3: Definitions for five of the principles of ability-based design [65, 66] and how they can be applied to VR devices.

Principle	Definition	VR Devices
Adaptation	Interfaces may be self-adaptive or user-adaptable to provide the best possible match to users’ abilities.	VR HMDs could allow users to position adjustment knobs to more convenient locations.
Transparency	Interfaces may give users awareness of adaptations and the means to inspect, override, discard, revert, store, retrieve, preview, and test those adaptations.	VR controllers and HMDs could be modular, allowing users to change their configurations or substitute other controls (*e.g.*, switches, eye gaze, etc.).
Performance	Systems may regard users’ performance, and may monitor, measure, model, or predict that performance.	Motion controllers could detect tremor and inform interfaces to make targets larger.
Context	Systems may proactively sense context and anticipate its effects on users’ abilities.	Motion controllers could sense users’ grips and change input controls appropriately.
Commodity	Systems may comprise low-cost, inexpensive, readily available commodity hardware and software.	Low cost input devices such as dials, sliders, and trackballs could be used to create chairable input controls for VR systems.

5.6 Limitations

People with limited mobility have a wide range of abilities and experiences. All these abilities and experiences could not be captured through our interviews. Although we were pleased with the diversity of experiences represented by our interview participants, it is important to acknowledge that there are still thoughts and perspectives held by people with limited mobility that should be considered. We had three female participants and it would have been beneficial to have more female participants in our study to include their perspectives on the design of VR technology. Our interview participants included four people with prior VR experience, so most of our participants could not speak to the experience of using VR on a consistent basis. However, as VR devices become more commonplace it will be important to understand the perspectives of people with limited mobility who use VR regularly. There are a variety of commercially available VR headsets and controllers that each vary slightly from each other. We were not able to elicit feedback on all of these devices, but the form and functionality of these devices are similar enough to the devices employed in our study that our findings would apply to the majority of commercial VR systems.

6 CONCLUSION

We have presented results from our investigation to understand the accessibility of VR systems for people with limited mobility. From our semi-structured interviews with sixteen participants, we found that people with limited mobility had numerous concerns regarding the accessibility of VR. We identified seven barriers related to the physical accessibility of VR devices that people with limited mobility might encounter, ranging from the initial setup of VR systems to keeping VR controllers in view of cameras embedded in VR headsets. We also summarized participants’ suggestions for how VR systems could be more accessible. Finally, we discussed design approaches that could alleviate accessibility barriers for people with limited mobility. Our results highlight the importance of understanding the experiences of people with a wide range of abilities, as we can identify accessibility improvements by understanding when the ability demands of VR systems do not match the abilities of users.

It is important for VR to be accessible to all people. We end with a quote from P3-IP, who described how VR could be useful to people with limited mobility as the result of injury: *“But you’re actually part of everybody, you know, you’re out there playing and all that, and through the controllers, you have two arms out there. You’re running two miles instead of ten steps. That could make someone who’s been in an accident feel a lot better. Because that’s what helped me after my accident.”*

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