Embodied Exploration: Facilitating Remote Accessibility Assessment for Wheelchair Users with Virtual Reality

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ABSTRACT

Acquiring accessibility information about unfamiliar places in advance is essential for wheelchair users to make better decisions about physical visits. Today's assessment approaches such as phone calls, photos/videos, or 360° virtual tours often fall short of providing the specific accessibility details needed for individual differences. For example, they may not reveal crucial information like whether the legroom underneath a table is spacious enough or if the spatial configuration of an appliance is convenient for wheelchair users. In response, we present *Embodied Exploration*, a Virtual Reality (VR) technique to deliver the experience of a physical visit while keeping the convenience of remote assessment. *Embodied Exploration* allows wheelchair users to explore high-fidelity digital replicas of physical environments with themselves embodied by avatars, leveraging the increasingly affordable VR headsets. With a preliminary exploratory study, we investigated the needs and iteratively refined our techniques. Through a real-world user study with six wheelchair users, we found *Embodied Exploration* is able to facilitate remote and accurate accessibility assessment. We also discuss design implications for embodiment, safety, and practicality.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; **Interaction techniques**; **User centered design**.

KEYWORDS

Mobility and Physical Disability, Wheelchair Users, Embodied Interaction, Virtual Reality, User-centered Design

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1 INTRODUCTION

Approximately 75 million people around the globe use wheelchairs [70]. Wheelchair users constantly observe and evaluate environments, attentively noting details such as the width of a corridor, the number of steps, and the height of counters [36]. In order to minimize danger and frustration, wheelchair users proactively gather and thoroughly understand the accessibility details of unfamiliar places [69] before making a decision about a physical visit. The uncertainties that need to be assessed can vary significantly, ranging from the availability of accessible restrooms to whether their wheelchairs can fit underneath a dining table or a workstation. The barriers to accessing unfamiliar places limit their access to education, employment, entertainment, and various experiences, which compromises their connection to society, leads to a sense of isolation, and reduced their Quality of Life (QOL) [26, 44].

To assess the accessibility of an unfamiliar space, there are various approaches available, such as checking the accessibility label on websites, browsing photos and reviews, and directly contacting the place. Government-enabled accessibility labels, such as the Americans with Disabilities Act (ADA) regulations[1] in the United States, aim to impose the lowest burden on people in wheelchairs. However, the information provided through these labels might be coarsely grained, with crucial nuances and details often hidden. Conversely, seeking assistance from family members or friends to check the environment or paying it a visit themselves can reveal more critical information, but it can also require a substantial amount of effort from wheelchair users. With this trade-off, wheelchair users

[1]Americans with Disabilities Acts (ADA): https://www.ada.gov.

are short-handed in reliable digital tools to assess the accessibility of remote and unfamiliar environments in advance [69]. In other words, the design space of assessment approaches leaves a vacuum for a new approach that achieves *high fidelity* of assessment and demands *low effort*. In this work, we aim to fill this vacuum by employing embodied interaction in Virtual Reality (VR). Our design builds on the theory of *embodied cognition*, which suggests that the mind is not an isolated entity, but an integrated part of the body's sensorimotor systems [21]. We aim to immerse wheelchair users in a virtual environment that replicates their spatial interaction with physical spaces, utilizing high-fidelity models of both users and physical environments, which are becoming increasingly available.

We aim to tackle three key Research Questions (RQs):

- **RQ1:** What are the current practices and challenges of accessibility assessment for wheelchair users?
- **RQ2:** How can we effectively design the system and interaction techniques of embodiment to ensure a VR experience that closely replicates a physical visit with high usability?
- **RQ3:** How do wheelchair users perceive embodiment in accessibility assessment?

Through a user-centered exploratory study and iterative design with wheelchair users, we generated three types of constituent tasks — *visibility*, *locomotion*, and *manipulation* — that wheelchair users need to execute frequently. We then designed and implemented *Embodied Exploration* using Meta Quest 2 by bringing wheelchair users into digital replicas of real-world environments with embodying avatars. Through a user study with six wheelchair users from five different states in the US, we demonstrated the efficacy of *Embodied Exploration* against two baselines—Photo Gallery (PG) and Virtual Tour (VT). When leveraging VR for remote accessibility assessment, it is important to acknowledge that VR technology itself brings about accessibility challenges to people with limited mobility [29, 51], which we will further discuss in Sec. 7. In summary, we contribute:

- interaction techniques of *Embodied Exploration* for remote accessibility assessment, generated by a user-centered iterative design;
- user studies that validated the efficacy of *Embodied Exploration* against two baselines;
- key findings of user perception and usability, leading to design implications for future accessibility assessment tools.

2 RELATED WORK

Our work is motivated by existing research that explored methods for accessibility assessment (Section 2.1). We discuss prior research that aims to create and simulate unfamiliar environments using VR for people with impaired mobility (Section 2.2), as well as design techniques for accessibility enhancement inside VR (Section 2.3).

2.1 Remote Accessibility Assessment of Unfamiliar Environments

In most countries, government-owned departments or organizations establish inspection routines for accessibility assessment. For example, the ADA Regulations require business owners to conduct the inspection and provide public accessibility information [55]. However, such a policy-based approach can hardly be enforced in all places, especially in less developed communities without full-fledged ADA-like policies. Despite this effort, the physical environments remain challenging for people with limited mobility [53] and prior work has taken a remediation approach to retrofit smart devices in environments to improve their access [41, 61, 73].

Recent works investigated how to facilitate *remote* accessibility assessments by making various digital information about physical environments available online. For example, Project Sidewalk [62] took a crowdsourced approach that first demonstrated accessibility assessment on urban streets at scale using google street views. Recently, Sidewalk Gallery [27], designed an interactive, filterable gallery of more than 500K crowdsourced sidewalk accessibility problems to help increase future accessibility of urban design. Likewise, Wheelmap [49] used the open-source map framework, OpenStreetMap, to allow users to search and tag locations with a wheelchair accessibility rating. UnlockedMaps [63] offered a web-based map that visualized the accessibility of urban rail transit stations, restaurants, and restrooms by highlighting their real-time accessibility status, for example, non-functioning elevators.

Prior works have instantiated the concept of Virtual Tours (VT). Commercially available platforms such as Beyonder [16] also attempted to help people with mobility impairment explore the world using VT techniques. In the research domain, Hosseini *et al.* [34] proposed a semi-automatic pipeline to build a global scale sidewalk map for people with disabilities. Recent works have also leveraged photo-realistic urban maps to deliver interactive experiences of unfamiliar environments using browsers and VR. For example, a 3D virtual tour rendered on a web browser is offered to help parents of children who have special needs plan out their visits [18]. Kim *et al.* developed a 3D modeling technique for environments [38] and later evaluated it in its uses for wheelchair users to assess whether clearances in environments are sufficient for wheelchair locomotion [37]. Closest related to this work, *Bring Environments to People* [23] investigated the efficacy of browser-based virtual tours in facilitating people with limited mobility to remotely assess the accessibility of environments.

Unlike prior works, we explored the feasibility of embodiment, a popular technique in HCI, but first leveraged in this work to facilitate wheelchair users in accessibility assessment using their embodying avatars. Stepping beyond prior research, *Embodied Exploration* was iteratively designed through collaboration with a wheelchair user who is also a VR producer, and evaluated on three major tasks — *visibility*, *locomotion*, and *manipulation*.

2.2 Simulating Physical Environments in VR for Wheelchair Users

With its unique advantages of immersion, VR has been used to help wheelchair users in the rehabilitation and training processes by featuring simulated environments. For example, Teófiloa *et al.* [67] uncovered the potential of VR in rehabilitation, helping people with motor impairment. Palaniappan *et al.* [57] designed a VR exergame to help people with limited upper extremities to more efficiently find comfort areas in the workspace by measuring user-specific motion data. In the same vein, Phelan *et al.* [59] explored the efficacy of VR as a physical therapy tool for children with upper limb motor impairment. They found that VR is an effective tool in physiotherapy, improving functional disabilities, alleviating perceived pain, reducing the perceived difficulty of rehabilitation exercise, and ultimately creating a positive perception toward therapy. Gotsis *et al.* [31] developed Skyfarer, a mixed-reality rehabilitation game that focused on upper body exercise for wheelchair users.

Researchers also demonstrated the feasibility of "teleporting" remote unfamiliar places for accessibility assessment without explicitly leveraging and researching embodiment. Perez *et al.* [58] and Harrison *et al.* [33] developed VR-mediated wheelchair simulators that allow wheelchair users to experience simulated environments in the co-design process to eliminate inaccessible elements in a building. Alghamdi *et al.* [19] demonstrated the effectiveness of using VR to assess if the building design satisfied the minimum accessibility requirement for people using wheelchairs. Moussaoui *et al.* [52] proposed a VR tool for helping older wheelchair users preview the accessibility of a new environment. Nearmi [42] demonstrated a framework that allows people with mobility impairment to access and re-orient cameras for details inspections of the specific point of interest. Further along this line, Kostic *et al.* [40] proposed a novel framework to automatically extract key information from the readily available architectural sources (*e.g.,* the building floor plans) that are required for wheelchair users to assess simulated environments.

2.3 VR Techniques for Enhancing Accessibility in Virtual and Physical Environments

Besides using VR to simulate environments, another thread of works explored techniques to help mobility-impaired users and able-bodied users to better access information in VR. For example, Gerling *et al.* [28] explored the challenges and potential design spaces to make VR games more inclusive to wheelchair users and indicated the importance of the design of embodied immersive experiences. Chowdhury *et al.* [24] investigated how different immersion conditions affected a user's information recall in a VR disability simulation, with their study finding that an embodied VR experience ultimately led to higher recall and engagement as compared to its desktop application counterpart. Gorisse *et al.* [30] also found that employing a first-person perspective was crucial in inducing a sense of embodiment toward a virtual body, especially in terms of self-location and ownership. They compared first-person and third-person perspectives, finding that the former allowed for more accurate interactions, while the latter provided better space awareness. Steed *et al.* [65] studied the effect of self-avatars on the cognitive load of individuals. In a series of letter recall and spatial rotation exercises, they discovered that users embodied by avatars experienced higher information recall and an overall alleviated mental load when compared to their less immersive counterparts. Several existing research address such designs by proposing novel interaction techniques. For example, wo-In-One [71] explored the design space that maps uni-manual input to bi-manual interactions for people who have full use of only one hand. Li *et al.* [48] also demonstrated the techniques of using virtual mirrors to help users access distant and/or occluded objects.

VR has also been used to train wheelchair users to accomplish daily tasks in physical environments. For example, John *et al.* [35] created a VR application to help new wheelchair users train and grow accustomed to everyday maneuvers required for powered wheelchair operation. This system was found helpful in developing wheelchair competency without the inherent risks of training in the real world. In a later related study, Day *et al.* [25] addressed the discomfort in prior work by building on this framework and creating a mixed reality application, finding that users enjoyed the same improvements in wheelchair competency without the motion sickness side effects. In a different method of solving the motion sickness, Vailland *et al.* [68] used a vestibular feedback system in conjunction with a VR wheelchair training environment, finding that the feedback increased the user's sense of presence as well as decreased cybersickness. Employing a novel approach to control and training modality, Younis *et al.* [72] combined a VR environment and Brain Computer Interface to allow control of a virtual avatar via EEG signals in a series of wheelchair training exercises. Users experienced large improvements in EEG-based wheelchair control as a result of these VR training environments, again without any risks of injury in the real world. On a similar note, Ogenga *et al.* [56] adopted an EOG approach for control of a powered wheelchair in a VR wheelchair training environment, finding that it was a promising control interface for users lacking mobility to steer a conventional powered wheelchair.

Compared with the closely related works (*e.g.,* [19, 33, 52, 58]), our approach supports assessments on a broader range of environmental factors (e.g., visibility and manipulation) beyond locomotion. This is achieved using only commodity devices, avoiding the need for expensive and heavy wheelchair simulators, thus ensuring scalability. To achieve this at little cost of perceptional accuracy, we leveraged embodiment with all interaction techniques built upon embodied wheelchair users — their embodying avatars in VR. Then we conducted systematic evaluations of our technique against two state-of-the-art techniques (*i.e.,* Photo Gallery and immersive Virtual Tours) as baselines to elicit the pros and cons of our approach, creating a foothold for future work.

3 PRELIMINARY EXPLORATORY STUDY AND ITERATIVE DESIGN

This study aimed to collect and summarize tasks requiring accessibility assessment, investigate common practices and challenges of assessment, co-design a user-centered system and pilot test the prototype. The findings and feedback generated from the study correspond to RQ1 and RQ2. We adopted a user-centered design approach with wheelchair users and conducted four iterations of preliminary exploratory study and design. This section describes the motivation, process, and results generated from each key iteration.

3.1 Iteration 1: Online Content Analysis

To ensure the usefulness of *Embodied Exploration*, we decided to first identify what wheelchair users look out for when assessing accessibility. Given the richness of video content on YouTube related to accessibility needs [20, 45–47], we began with a content analysis of tutorials and life-sharing videos on YouTube created by and for wheelchair users. This process enabled us to look at indoor scenarios through the lens of wheelchair users and thus formed the foundation for our in-depth interviews in the next iteration.

Methods. We first used prompts combining the wheelchair-related keywords (*e.g.,* wheelchair users, quadriplegic, accessible, accessibility, ADA wheelchair) and scenario-related keywords (*e.g.,* adaptation, renovation, home, home tour, bathroom, hotel, service) [20]. This searching process generated 13 representative videos (v1 - v13) using convenience sampling based on views (ranging from $7.3k$ to $495k$) and quality (rich information, active comment sections, and a reasonable length from 170 seconds to 960 seconds). The videos are listed in Appendix. Next, we used a mixture of emergent and priori coding approaches to analyze the collected data. Specifically, two researchers first familiarized themselves with the videos, then generated initial codes to describe the accessibility issues in the video. They then went through review and refined phases to generate the three most representative themes. This analysis process was conducted iteratively, and multiple meetings were held among researchers to reconcile the disagreement. Activities requiring only eyeballing were named "visibility tasks". Activities requiring larger movement were spatial transformation of wheelchairs, named "locomotion tasks". Tasks that require spatial manipulation (usually with hands) were named "manipulation tasks". After identifying what wheelchair users value for indoor accessibility, a second analysis was then performed to understand how people verify accessibility accommodation in advance. We collected information broadly on blogs [8, 17, 43, 64], forums [2, 4–7, 10–15], and app stores [1, 3, 9], and summarized them next.

Findings about tasks that require accessibility assessment. Our content analysis process unveiled many common issues, such as overcoming stair steps, fitting the lower body underneath furniture, reaching for objects, and viewing things in hard-to-see places. These issues were eventually categorized into three themes:

• **Visibility**. Visibility refers to tasks wheelchair users encounter when attempting to access and view visual information in their surroundings. When seated, people might have a limited field of view. Accessible places adopt designs to avoid obstruction to visibility of important visual information in the environments and improve the readability of signage. Examples include ADA regulations on the height of counters (v13). People also note the importance of visibility of items in high cabinets at home (v3, v5, v10), and the challenges caused by occluded items on the shelf top (v3, v5, v9, v10). The workaround could be as simple as placing frequently used items on a lower shelf (v3).

• **Locomotion.** Locomotion is tasks that require wheelchair users to move around the target environment. Examples of tasks include maneuvering around furniture in a room, entering/exiting a room, and rolling beneath tables/sinks with sufficient knee and toe space allowance. For example, video participants appreciate open space in the living room with few obstacles (*e.g.,* tables, couches) blocking the way (v2 - v5). Most subjects also check the steps that led from one room to another (v1, v4 - v7, v10), or obstructions and thresholds of patio doors (v1, v4 - v8, v10). In addition, sufficient room beneath tables/sinks/stoves is essential for the accessibility of environments (v1, v3 - v5, v7, v9, v10 - v12). People ask for a bed not higher than the wheelchair seat for ease of transfer (v2, v3, v7, v10). For bathrooms, people verify if there is enough space to turn around and close the door (v1 - v6, v9 - v12).

• **Manipulation.** Manipulation encompasses tasks of wheelchair users reaching for objects and operating them when seated. Wheelchair users often have different ranges of motion for their differences in the level of motor capability. We found a strong need for a personalized and convenient configuration of items that they would frequently use. For instance, a towel rack, shower head, soap dish, and toilet paper holder should be reachable (v1, v3 - v5, v9). It is important to have grab bars at a reasonable height in a bathroom (v1, v3, v4, v11, v12). The door handle or a faucet handle should not be too effortful to manipulate (v6, v9). The door should be light to open, or ideally automatic, or sometimes removed for convenience (v3, v4, v7). Facilities in the kitchen including fridge, dishwasher, and microwave should also be arranged with sufficient clearance and positioned at a comfortable height (v5, v7, v10).

Findings about current practices of accessibility assessment (RQ1). Our findings also unveiled the practices of wheelchair users in their accessibility assessment of unfamiliar environments. People would browse websites to review accessibility-related descriptions and photos/videos. People leverage labels enforced by ADA regulations, which are generally available for public spaces such as museums. People may also call the front desk and ask for verbal descriptions, or pictures and videos taken from multiple camera perspectives. Some wheelchair users have a customized checklist to go through before making the visit. Online platforms like iAccess Life, Google, and Yelp may also have pictures of indoor environments for reference. Some wheelchair users use Google Street View to confirm wheelchair access to entrances, and Virtual Tours to check indoor configurations. While all aforementioned approaches can be done remotely, the most straightforward approach is to visit unfamiliar environments in person themselves or ask their friends, family, or caregivers to do so. Some people will take this approach prior to important events or long periods of stay. However, the accuracy of this approach highly depends on if the delegated person has an accurate knowledge of what wheelchair users need.

3.2 Iteration 2: Needs-Finding Study

With insights generated from the first iteration, we then conducted a needs-finding study with real-world wheelchair users to understand the design considerations for *Embodied Exploration.*

Participants. We recruited three participants in the needs-finding study (U1 - U3). All participants were self-identified as daily wheelchair users. Their demographic information is listed in Table 1. We compensated their time for 40 USD per hour.

Procedures. Three researchers conducted a semi-structured interview with each participant separately via online meetings. Informed consents were obtained before we recorded the meetings for transcription. The goal of this study was to verify findings from the first iteration, further understand the challenges of existing assessment methods, and dig into potential of VR in accessibility assessment. A list of questions in this study can be found in Appendix. This needs-finding study took around 60 minutes for each participant to complete. All interviews were audio and video recorded.

ID	Age	Gender	Country	Occupation	Wheelchair Model	VR Experience
U1	29	F	UK	Freelance producer, journalist, AR/VR content creator	Both manual and power wheelchair	Much experience
U2	30	F	Canada	Freelance writer, creator, activist, consultant	Power wheelchair	No experience
U3	27	F	US	Writer, speaker, activist	Both manual and power wheelchair	No experience

Table 1: Demographic information of three participants (U1-U3) in the needs-finding study.

Data Analysis. Three researchers went through the six phases of thematic analysis [22] using transcribed audio recordings and notes from interviews. This process generated themes of "visibility tasks", "locomotion tasks", "manipulation tasks", "assessment fidelity", "assessment efforts", and "opinions on *Embodied Exploration* (EE) concept". This process enabled us to better understand the trade-offs of different accessibility assessment approaches that participants took and potential merits that *Embodied Exploration* could bring.

Findings about current practices of accessibility assessment (RQ1). Our analysis in the second iteration generated a taxonomy shown in Fig. 1 using two key dimensions that describe approaches of accessibility assessment, including *effort* which refers to the amount of work that wheelchair users need to commit, and *fidelity* which indicates the amount of information that an assessment approach could provide. We now describe our findings categorized into four themes:

• ***Visibility*, *locomotion*, and *manipulation* are the key types of tasks for accessibility assessment.** All participants confirmed our findings of the three types of tasks in Sec. 3.1. Participants listed examples of challenges based on their life experience: *"Even small bumps/steps can be an issue"* (U1) and *"I do not trust the Airbnb accessibility label. They are often not very accurate. Every room is different"* (U3). Participants also contextualized their experience based on our findings from Sec. 3.1. Examples include the need of evaluating visibility-related tasks, such as *"I am always below the reception desk, and I was too short for almost every counter. I face difficulty reading text every time I go out. I have access to a seat*

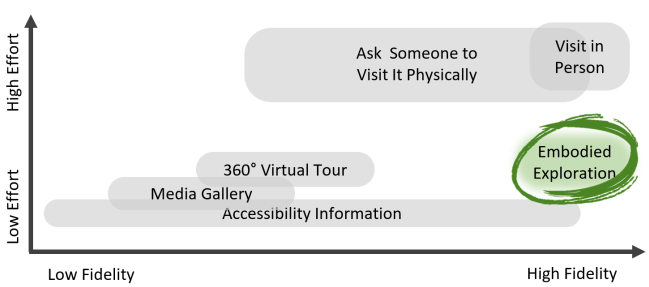

Figure 1: The taxonomy that highlights the difference between *Embodied Exploration* and conventional approaches for accessibility assessment in terms of effort and fidelity. Effort refers to energy, time, and money spent by wheelchair users when using an approach. Fidelity indicates the accuracy and effectiveness of information the approach could provide. For example, visiting the environment in person demands the greatest effort and has the highest fidelity.

elevator, but without access to that, it would be even more difficult to read things" (U2); challenges of using locomotion-related tasks to perform the accessibility assessment, such as *"In locomotion, surface material makes a difference too. Sand is hard, concrete is easy. Grass depends, like whether or not it rained the night before. A combination of things could be complicated too when the door is wide, but the clearance after it is not far enough for wheelchairs to pass through, in other words, tight corners / sharp turns. Also, with hands on the outside of the wheels, the whole system is wider than just the chairs, making it more difficult to pass through narrow spaces"* (U1); and challenges of manipulation-type tasks, especially during COVID-19 pandemic, *e.g.,* U2 commented that a tool for remote accessibility assessment would be very useful in avoiding risky exposure in an inaccessible environment.

• **High-fidelity and low-effort accessibility assessment approaches are in need.** All participants agreed that assessing accessibility using today's common approaches was difficult, particularly with comments: *"There are variances in wheelchairs users, so people face different levels of difficulties in the same environment. To be able to accommodate personal differences in disability is very important"* (U2). Participants shared their most used method for assessing unfamiliar places and expressed their frustration. For example, *"The majority of websites don't have their accessibility listed. Only publicly-owned buildings like museums/art galleries have them [...] the fidelity of information required for accessibility assessment is usually quite high [...] Depth perception is quite difficult with photos"* (U1). U1 also believed that videos are more helpful than photos. However, when information was not listed, she would call the place or ask social media for accessibility information. She also once asked a friend to visit a place for her, but *"My friend easily missed something like a small step to get in. The fidelity can be even less than watching a video"* (U1). U2 mainly adopted phone calls or asked their family to visit the place in person, yet she still complained: *"ADA is the bare minimum. When calling places or checking information online, their definitions of 'accessible' are inaccurate – a couple of stairs and inaccessible elements – there are little things that make the environment inaccessible, but people often conclude and say the environments are accessible if big things are accessible. This can be frustrating!"* While U2 believed *"I am lucky that my family is familiar with my mobility and knows my needs well, so I can trust them"*, this may not be applicable to individuals who do not have a trusted person to delegate tasks on their behalf. Overall, these comments pointed to the need for a high-fidelity approach to facilitate users with limited mobility to assess environments easily.

• **Promising Merits of *Embodied Exploration*.** After introducing the concepts of *Embodied Exploration*, participants held a positive opinion of embodying themselves with avatars to explore a physical environment remotely in VR. Example feedback included *"The* *closest we can get to physically being in a place without physically being there"* (U1); *"I feel like it really helps because I don't want to risk exposure unless it's gonna work out"* (U2); and *"Oh absolutely I like the idea that you can customize it to your specific dimension! I think the only thing that I could see being challenging is if it would be able to simulate a real-world situation"* (U3).

3.3 Iteration 3: Co-Designing through Low-Fidelity Prototyping

With insights yielded from Sec. 3.2, we continued creating the initial low-fidelity design by co-designing with real-world wheelchair users. This iteration aimed to dive deeper into **RQ2** from three aspects:

(1) What are the necessary details to be embodied in the avatar?
(2) What level of granularity should the digital environment have?
(3) What interaction techniques should we design for *Embodied Exploration*?

Participants. Our design process included U1 from the study in the previous iteration, and the same three researchers. The four attendees all have experience in VR content creation.

Procedures. Three researchers first presented the system of three components to U1, including avatars that embody users, a digital replica of the remote environment, and interaction techniques. In particular, the interaction techniques were designed for the identified types of tasks in Sec. 3.1 based on main-stream VR interactions, which included *visibility* with 1) first-person view at a seated position and 2) visualization (*e.g.,* visibility envelope); *locomotion* with 1) teleportation, 2) joystick 3) buttons, and 4) physical motions of hand controllers (*i.e.,* imitating wheel rolling); *manipulation* with 1) freehand interactions, 2) visualization (*e.g.,* reachability envelope), and 3) ray casting. The low-fi prototypes of these techniques were presented in sketches, screenshots, and demo videos in VR.

Researchers first had a thorough discussion with U1 on necessary details to be embodied in avatars and the granularity level of digital environments. Then U1 reviewed all low-fi prototypes of candidate techniques and gave valuable insights not only from the standpoint of a wheelchair user, but also from the vantage point of a VR producer. We eliminated less practical techniques from the candidate list according to her feedback.

Findings about design implications of the system (RQ2). We summarized findings from this co-design process around the aforementioned three aspects:

• **What are the necessary details to be embodied in the avatar?** To provide personalized embodiment modeled after each individual user's capability, we decided to embody three dimension parameters, wheelchair maximum width, wheelchair armrest height (from the ground), and seated eye height (from the ground). Thanks to the head and hand tracking supported by most commodity VR devices, our avatars also automatically embody users' head motion, reach range, and hand motion. *Embodied Exploration* also allows users to choose their preferred avatar appearance with various choices on skin tones, hairstyles, and clothing. This ensured that we delivered not only high-fidelity information but also a highly personalized and accurate experience tailored to each individual user's preferences, for better immersion and engagement.

• **What level of granularity should the digital environment have?** To enable the assessment of the three types of tasks, we need to reconstruct the physical environment to be rendered in VR. A precise spatial ratio between the environment and the user avatar is needed. Specifically for visibility and manipulation, we require segmentation of objects. We used Matterport to scan real-world environments in the 3D models and reconstructed a 1:1 true-to-size digital replica with all objects segmented in SkethUp. We found obtained digital replicas sufficient for supporting the assessment of the three types of tasks through piloting and discussions with U1. These digital replicas were integrated into VR for further developments on interaction techniques.

• **What interaction techniques should we design for *Embodied Exploration*?** Overall, U1 preferred interaction techniques modeled after reality. She commented "The interaction should reflect the challenges of performing physical tasks in the real world. A remote teleport or a remote pointer is good, but it's more like gaming, and not realistic". For this reason, she recommended using rolling motion with hand controllers to imitate the motion needed to roll real passive wheelchairs, and joystick for powered ones. Also, she mentioned that the visualization envelopes could not represent the individual difference, with herself as an example "My left hand is not as mobile as my right hand, the range of motion is very different". Therefore, we removed teleportations for locomotion, ray casts for manipulation, and visualizations using envelopes from the list of candidate interaction techniques.

Additionally, being able to see virtual reality from view perspectives beyond the first-person perspective could better help the assessment of its accessibility in terms of locomotion, as U1 noted. For example, wheelchair users can see how wide their wheelchair and body are compared to the space and have a precise sense of the spatial relationships between their body and the surrounding objects. U1 confirmed that the first-person perspective can more accurately deliver the sense of which parts of the room such as signage, windows, and utilities are visible. For consistency between different types of constituent tasks, and simplicity of control, we kept only the first-person perspective. After further discussions with U1, we confirmed that the first-person perspective was sufficient in delivering visual information needed by all tasks for accessibility assessment.

3.4 Iteration 4: Pilot Testing Mid-Fidelity Prototypes

Our final iteration aimed to generate the final design, using mid-fidelity prototypes developed with insights from the third iteration in Sec. 3.3. The same three researchers and U1 were involved in this process. By working closely with U1, we selected representative tasks and baseline techniques for the user study in order to understand pros and cons of *Embodied Exploration.*

Results of pilot testing. U1 praised the prototypes with comments such as *"It looks like to be a really, really useful tool for people"*, *"Amazing!"*, *"I think it looks great!"*, and *"I'm trying to think of some criticism but nothing comes up immediately!"* Some fine-tuning of

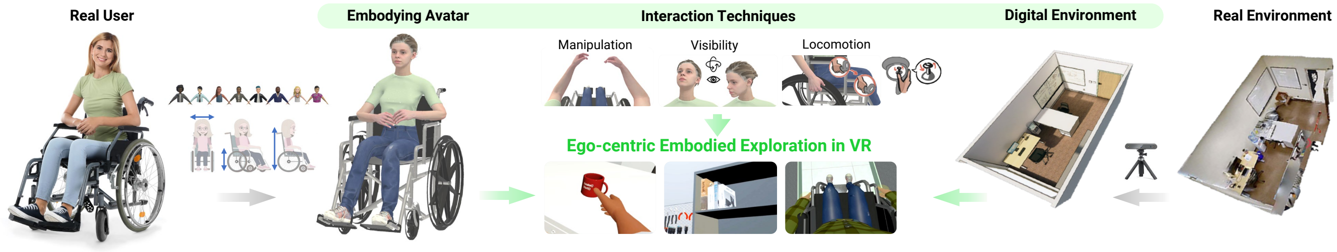

Figure 2: The *Embodied Exploration* system consists of three components - a digital environment, an embodying avatar, and interaction techniques, highlighted in green. The digital environment is synthesized by scanning real environments and manual post-processing the models in SketchUp. The user is embodied by an avatar, which is generated with biometric information about users and their preferred avatar appearance. With VR and digital assets, users can realistically explore the remote environment from the first-person perspective by looking around (visibility), moving around (locomotion), and reaching out for objects and using them (manipulation). Screenshots of egocentric views in VR are clustered in the middle at the bottom.

interactions using joysticks was suggested by U1 as she demonstrated how she would normally use their powered wheelchair. We finalized the set of embodied interaction techniques and developed the high-fidelity prototype for the user study after this round of iteration.

Baseline techniques. Through discussions with U1, we generated two baselines to simulate commonly used accessibility assessment methods, including photo gallery (PG) and virtual tour (VT) (Fig. 3).

• **Photo gallery.** This baseline technique allows wheelchair users to use a virtual pointer anchored to their dominant hand controller to flip through the photos. These photos would be taken from various angles in the environment to include much information needed in the accessibility assessment. This baseline represents the common practice unveiled in previous iterations and was confirmed by U1 in this iteration. For example, if the task is to determine whether a book was visible from a location, the photo would include the book and the hypothetical location of the user, denoted by a green arrow. This technique is referred to as PG in the rest of this paper.

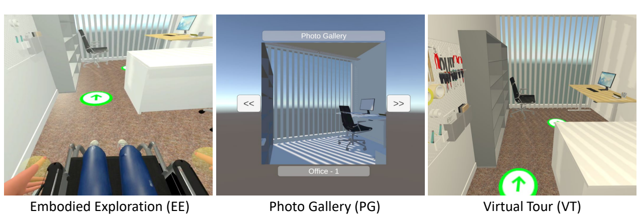

Figure 3: To evaluate *Embodied Exploration* (EE), we adopted two baselines to compare with - Photo Gallery (PG) and Virtual Tour (VT). With PG, users assess the accessibility of given tasks by looking at pre-taken photos of the room. They can browse through photos by clicking the left/right arrows. With VT, users can teleport around using controllers. They would observe the environment from the lens of a floating camera, without embodying avatars. An office is showcased as an example.

• **Virtual tour.** This baseline technique allows users to explore a virtual space from the perspective of a floating camera that would track headset movement but maintain a fixed height. users looked around from the vantage point of a virtual camera positioned at a fixed 1.6 m height above the floor. Users could navigate the space using either the joystick on the controller or a ray extended from the controller. These options offer both continuous and discrete locomotion. The hypothetical location and heading direction of the user would again be denoted by a green arrow. This technique will be abbreviated as VT in the rest of this paper.

Task selection. We purposefully created tasks to be challenging in certain situations in order to best tease out the advantages and disadvantages of each assessment technique. As stated before, the types of tasks to assess accessibility with include visibility, locomotion, and manipulation. Each of these types was assigned a constituent task (see Fig. 5). These tasks involve situations where visibility of the environment may be compromised by a seated vantage point. Similarly, seated positions might create challenges regarding the reachability of objects, and further manipulation of tools. We included various tasks to reflect these challenges.
The tasks prescribed to **visibility** included the following:

- V1: Reading titles of books on a high shelf in an office
- V2: Reading a safety sign on the back of a door in a lab
- V3: Checking what fruits are in a kitchen basket in a house
- V4: Watching birds from a bedroom window in an apartment

The tasks prescribed to **locomotion** included the following:

- L5: Moving from a door to a desk and rolling under it in an office
- L6: Moving from a cubicle zone to a conference table and rolling under it in a lab
- L7: Moving from a study area to a transfer spot between a couch and a stove in a house
- L8: Moving from a kitchen to a coffee table in the living room of an apartment

The tasks prescribed to **manipulation** included the following:

- M9: Retrieving a cup and filling it with water in an office
- M10: Writing on a whiteboard at a specified height in an office
- M11: Using a hot glue gun to attach objects on a table in a lab
- M12: Retrieving a milk carton from a countertop in a house

- M13: Opening a window in an apartment

4 EMBODIED EXPLORATION

Our system to deliver *Embodied Exploration* consists of three components, digital replicas of environments, avatars to embody users, and interaction techniques (Fig. 2).

4.1 Building Digital Replicas

We first performed 3D scans with Matterport and then recreated a delicate digital replica of the physical space from the original 3D scan using SketchUp (Fig. 4). This process allowed us to have an accurate representation of the physical layout and a fine-grained segmentation of objects. Many details of the environment were preserved including the clearance underneath a table, the width of a doorway, and room between furniture pieces.

4.2 Creating Embodying Avatars of Users

No two people are the same, and prior research found that discrepancies such as the difference between eye heights in the virtual and the physical worlds could cause confusion and thus lower the fidelity of an accessibility assessment approach [23]. Therefore, having an avatar that bares some physical resemblance to the user was crucial. To this end, we utilized the Meta Avatar SDK to generate an avatar for users. The Meta Avatar SDK supports fine-tuned personal avatars linked to Meta accounts. To reduce the workload on users while maintaining diversity, we opted to provide 32 unique avatar presets that span a large range of physical appearances for users to select. To ensure proper immersion, the user's avatar was also posed sitting in a wheelchair. The avatar would then follow the users' movement using inverse kinematics and controller tracking.

4.3 Interaction Techniques

All interaction techniques were built upon the assumption that users would be holding both hand controllers at all times. We used hand controllers instead of hand tracking to improve system robustness. Holding the controllers also offered tactile feedback which is missing from free-hand interactions. Overall, three interaction techniques designed through our iterative process can be well supported by hand controllers and system features of most commodity VR devices.

Visibility. The interaction technique consists of looking at objects within a user's field of view when seated. The height of the viewpoint in VR was set to the eye height based on biometric data collected from the user. The view of the user changes as they rotate their head. The user could rotate their torso or orient the wheelchair to adjust the field of view. This technique is relatively straightforward and involved no input from users' hands.

Locomotion. We took inspiration from reality and divided locomotion techniques into interactions for manual and powered modes. Manual interaction consisted of users grasping the virtual hand-rims of wheels in the air with controllers' trigger buttons and pushing the wheels in the desired direction. It allowed users to push the two wheels at different speeds and/or directions to make smooth or sharp turns. For powered interaction, we leveraged the joysticks on VR controllers to drive a user's avatar at a fixed speed, imitating a powered wheelchair.

Manipulation. We focused on reaching for objects and manipulating the objects. Users utilized the trigger buttons to grasp objects once their avatar was in contact with the virtual object, as we found this to be a common technique in VR and the most intuitive to participants in the iterative design process. As stated previously, reachability visualization via envelopes and ray casting was removed. Instead, we used direct manipulation allowing embodying avatar hands to directly interact with objects within the virtual environment.

4.4 Implementation

We implemented *Embodied Exploration* on a Meta Quest 2 headset using Unity (v2021.3.2f1), connected to a PC using a USB 3.0 Type-C cable. The PC had an AMD Ryzen 7 2700 CPU and an RTX 1550 Ti 4G GPU. All interactions relied on hand controllers. All interaction techniques were built on the Oculus Integration SDK that tracks controller movements and handles object grasping. UI elements such as outlines of grabbed objects, displays of the task names, and menus were implemented for ease of use.

5 USER EVALUATION

5.1 Method

Participants. To evaluate our final prototype, we recruited six participants from five states across the United States, including one female and five males. Their ages range from 28 to 54 (M = 40.7, SD = 11.3), with daily wheelchair experience from 2 to 26 years. Table 2 shows the demographics of the recruited participants, including age, gender, residential state, occupation, Spinal Cord Injury (SCI) level, wheelchair Years of Experience (YOE), caregiver(s), wheelchair type, prior VR experience. We also collected their approaches to assessing the accessibility of unfamiliar environments in advance, and the challenges they encountered during the assessment. Two participants had used VR before.

Procedure. Two researchers conducted the study remotely with participants on ZOOM. VR devices were mailed to their homes ahead of the study. The study took from 1.5 to 2 hours for each participant. The participants received a reimbursement at the rate of 40 USD per hour. At the beginning of the study, we first collected the participant's demographic information and information on their practices in accessibility assessment. Then we briefly introduced our system and our study procedure. Before participants put on the headset, we ensured that they understood safety protocols in VR by guiding them through a tutorial that provided instructions on how to sit comfortably in an open area, set guardian boundaries, and wear the headset correctly with the controllers securely fastened to their hands. We also instructed the first-time users on how to use the controllers and opened an app from the library. They were informed that they had the right to stop the study or pause for a break at any time. We obtained their consent to audio and video record the meeting.

Participants were invited to engage with three applications subsequently (i.e., visibility, locomotion, and manipulation) in a balanced order. Participants first selected options for the dominant hand,

ID	Age	Gender	State	Occupation	SCI Level	YOE	Caregiver(s)	Wheelchair Owned	VR Experience	Methods Used to Access the Accessibility of Unfamiliar Environments and Challenges in Assessment
P1	39	M	GA	Speaker	T12	26	Spouse	TiLite Manual	Twice	I have no ways to assess in advance because it is not reliable at all. What I do is to pay a physical visit to figure it out. I kind of put my feelings to that side to get things done. I just don't have the time or the energy to fight per se.
P2	54	M	GA	Scientist	C3	3	Self	Eagle 3 Power	No	I browse photos before going to any location. I make phone calls. However, people would claim ADA accessible even when there are stairs and thresholds 2+ inches high. Hydraulic doors slam into my arms all the time.
P3	28	F	OK	Teacher	T3	6	Spouse	Ethos Manual	No	I will call beforehand and check website accessibility information. ADA inspection is not always accurate, e.g. an ADA-accessible hotel room may be accessible for two people, but does not work when I stay with my husband and son (three people).
P4	35	M	NJ	Freelancer	L1	3	Parents	Medline Manual	Once	I call them for specific details (e.g. door threshold, ramp, elevators, stairs, etc.). Within the couple of attempts I have made, the information was reliable. I might just be lucky. My primary wheelchair is not very wide. The other one from Medicaid is much wider and heavier, for which I am not sure whether the assessment will work.
P5	33	M	MI	Engineer	T4	2	Parents	TiLite Aero Z Manual	Twice	I call them to confirm my checklist of quantified details including the table height, the width of doorways, and bathroom entries
P6	55	M	MS	Professor	T12	26	Parents	TiLite Manual	No	I do an Internet search to see if it is specifically wheelchair accessible or call the place directly to check ingress/egress, roll-in shower, 32-inch wide door, etc. Reliability depends on how people understand accessibility.

Table 2: Demographic information about participants in the main study. The last column shows how participants usually assess the accessibility of unfamiliar environments in advance and what challenges they encountered.

avatar appearance, and input wheelchair configurations (wheelchair maximum width, armrest height, and seated eye height) using menus. Participants then proceeded to a scene (i.e., office, lab, house, apartment) and tested three sets of interaction techniques, including two baselines (PG and VT, designed in 3 Iteration 4) and *Embodied Exploration* (EE). They would then be taken to the next scene until all scenes had been completed. In each scene, participants were asked to perform tasks on the list.

For each combination of interaction techniques (n=3) and tasks (n=13), participants were asked to give scores on a 7-point Likert Scale regarding two questions:

- **Accessibility Level.** How accessible is the environment in terms of performing the task? (7 being very accessible, and 1 being completely inaccessible)
- **Confidence Level.** How confident are you in your assessment of accessibility in the previous question? (7 being very confident, and 1 being very unsure)

Noted that participants were asked to assess the accessibility of the environment imagining they were in it at the location and with the orientation denoted by a green arrow when using PG and VT. However, for EE, participants were embodied in the avatar and interacted with the environment and attempted to "virtually" finish the task. They might fail or succeed in completing the task, depending on the difficulty of the task and the capability of the participant. The assessment and confidence scores were recorded for qualitative analysis. We conducted a semi-structured interview when participants finish all constituent tasks in one application. Questions included:

- What do you think of the usability of *Embodied Exploration*? And could you give concrete reasons?
- What are the pros and cons of each interaction technique? And which one do you prefer and why?

Participants then took a brief break before moving on to the next application of a different set of constituent tasks. The process was identical across all three applications. After the main study, they were invited to share feedback on *Embodied Exploration*, and speculate potential uses of the system. This marked the completion of the study.

Data analysis. We were unable to collect the ground truth of accessibility and evaluate how accurate the accessibility assessment was. However, we overcame this limitation by inferring from the confidence scores and the qualitative feedback from participants. First, we visualized the distribution of Likert Scale data on accessibility and confidence level for each interaction technique grouped for each task. Three researchers transcribed the notes and quotes from recordings and grouped them according to the three research questions (RQ1-3). Within each group, we performed the affinity diagram to further cluster the notes and quotes with similar contents. Once we reached a consensus on the clusters, we started the thematic analysis [22], refining the themes to center around the three research questions. We converged on three themes – 1) common practices and challenges of accessibility assessment, 2) usefulness and usability of *Embodied Exploration*, and 3) user perception of *Embodied Exploration*. There are also several sub-themes under each theme. We detailed findings around these themes next.

5.2 RQ1 Findings: Current practices and challenges of accessibility assessment

P1-P6 expressed the frustration and consequences of inaccurate assessment and explained how the embodiment can support a finer-grained evaluation.

Wheelchair users are frustrated about inaccurate accessibility assessments. P1 found there was no reliable assessment approach other than paying a physical visit. P2, P3, and P6 did online searches for wheelchair accessibility labels but had experienced places that falsely claimed to be ADA accessible due to some stairs and thresholds (P2), or limited room (P3). As a result, they had to spend much effort on-site, which was unpleasant. Most participants (P2-P6) made phone calls to verify the accessibility. P4, P5, and P6 emphasized the importance of having a checklist of critical details. They explained that if they relied on how place owners understood the accessibility, the outcome was usually disappointing. For example, P5 prepared a quantified list of details to check, including the table height, the width of doorways, and bathroom entries. P6 made phone calls to confirm features such as a roll-in shower and a 32-inch wide door. The process was neither convenient nor reliable and often required multiple attempts. P4 commented, "*I might just be lucky...*" and he was unsure whether this process would work for a wider and heavier wheelchair. Meanwhile, P5 sometimes chose to stay at home as a result of the time-consuming and frustrating communication.

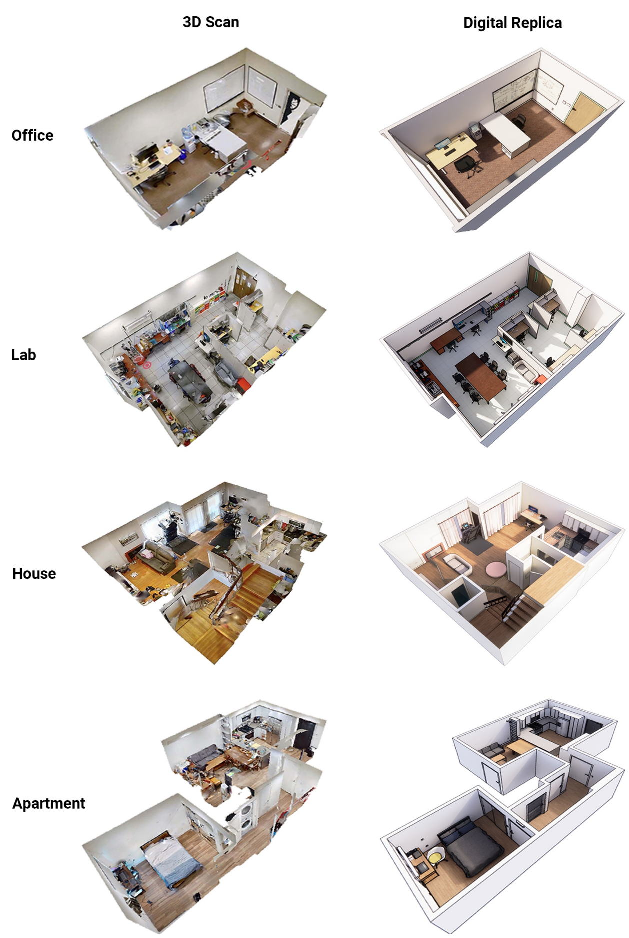

Figure 4: Original 3D scans (left) and processed digital replicas (right) of an office, a lab, a house, and an apartment.

Assessment methods without embodiment hardly provide the granularity needed. The concept of accessibility presented nuances in our participants' interpretations. Through careful observation of how participants assessed the accessibility level of tasks in the study, we discovered that the term "inaccessibility" was not confined to tasks deemed strictly impossible. Rather, participants maintained a personalized and often intricate understanding of accessibility, demonstrating the inherent granularity of this concept. In *visibility*, all participants agreed that they did not regard it as being accessible when they had to turn back/lean forward/bend down to be able to see something. P1 pointed out that these motions may cause potential injury to his body, which was much more severe than just the inconvenience. A common theme was that PG often skewed a user's depth perception, leading to inaccurate assessment (P3, P5, P6). For *locomotion* assessment, participants tended to perceive the space as inaccessible in several cases: 1) their wheelchairs will likely scrape against objects in the environment (P2, P5); 2) there is not enough room to fit their knees and toes so that their feet would hit furniture or walls (P3, P4); 3) the space is narrow and small and makes them feel restricted and uncomfortable, even if the space was technically accessible by terms in ADA (P1, P4, P5, P6). For assessment of *manipulation* tasks, participants tend to criticize the situations when "*Full extension is difficult*" (P1), or when objects were placed so high or so low that one had to extend, bend or twist the body a bit to reach for it (P2, P4). P6 noted that he would not reach for an object in an orientation facing the object, rather he would be facing sideways putting his shoulders closer to the object and therefore improving his reachable range. In conclusion, the assessment of accessibility at this granularity can hardly be supported without embodiment.

5.3 RQ2 Findings: Usefulness and Usability of Embodied Exploration

We collected participants' perceptions of the usefulness and usability of *Embodied Exploration*, with quotes grouped into sub-themes of "preference", "effectiveness", "intuitiveness", "ease of recollection" and "VR usability".

Preference and effectiveness. Participants preferred EE to other approaches. We asked the participants to rank EE, PG, and VT based on their willingness to use them in real life, and explained why. We noticed that their reasons focused on the perceived usefulness of each method, where effectiveness is the main factor.

In visibility tasks, P1 and P6 ranked "EE > PG > VT" while the other four participants gave "EE > VT > PG". All participants preferred EE more than the two baselines, regardless of their prior VR experience. P5 stated, "*[EE] allows me to put myself in that room, looking for that item*". P2 remarked that he preferred the EE method because it reflected his reality best. P3 said "*[EE] is definitely the best. I'd like to use [EE] in real life, e.g., bathroom, hotel room, table in a room.*"

In the locomotion tasks, P3, P4 and P6 ranked "EE > VT > PG", P1 and P2 ranked "EE > VT ≈ PG". P3 stated that she preferred EE as "*[EE] is the most accurate*", giving the example that having a proper perception of object heights like tables was crucial to their accessibility assessment. Other participants felt similarly about the accuracy of their assessments when using EE, due to the rich

Figure 5: We designed four constituent tasks of visibility (V1-V4), four constituent tasks of locomotion (L5-L8), and five constituent tasks of manipulation (M9-M13). Each snapshot block demonstrates how a user performs the task with *Embodied Exploration* techniques.

environment information, sense of space, and realistic perspectives. One exception is P5, who gave the ranking of "VT > EE > PG". He had comments on comfort, saying "*If motion sickness in [EE] wasn't so prevalent, I would prefer [EE] to [VT].*"

In manipulation tasks, P1, P4, and P6 gave the ranking of "EE > PG > VT" while the others ranked as "EE > VT > PG". All participants regarded EE as the most useful system and attributed that to the rich and embodied interaction that PG and VT hardly offered. P1-P4 said EE was significantly more advanced than VT and PG in usefulness and gave examples of the cases that VT and PG could not accomplish while EE could. P2 stated, "*I am 100% sure I can write from a seated position, even though before I was unsure based on [PG] and [VT]*". P6 also commented that "*[PG] and [VT] were not very helpful in guessing if things were manipulable.*"

In summary, participants preferred EE to VT and PG because VT and PG hardly delivered clear and helpful information about the environment, thereby affecting the accuracy of the assessment. P4 remarked that "*[PG] provided no help if the angle was poor*" and "*[It] was difficult to get a sense of space.*" P1 commented that the "*Angle is deceiving*" while referring to VT. This poor representation of the space and task placed more cognitive load on the participant as he had to consider the efficacy of his assessments, and ultimately negatively affected the perceived usefulness of VT and PG.

Intuitiveness. Participants perceived EE as intuitive and straightforward. For locomotion, P2 noted that for PG and VT, he had to "*Store a mini-map in the back of my head*" to evaluate accessibility and that was not as intuitive as EE. P4 immediately understood how to operate the virtual power wheelchair with brief researcher hints. For manipulation, P3 understood one of the manipulation tasks so quickly that she finished it before the researchers finished instructions. P1 mentioned that "*It is so intuitive that I can assess it instantly without thinking.*" P4 also commented that "*[EE] is very user-friendly. I have no experience with VR but it only took a few minutes to understand how everything works.*" However, for visibility, some participants expressed that VT was the most intuitive to use. P1 remarked that "*[VT] is easiest to use, but less immersive than [EE].*" We suspected that the lack of interaction in the visibility tasks nullified the largest differentiating factor between VT and EE. Overall, we noticed that the high level of intuitiveness in EE resulted in a more approachable and enjoyable experience for participants, regardless of their prior VR experience.

Ease of recollection. All participants reported that there was a trivial amount of effort in both learning and remembering how to use the PG technique, since people had done this (i.e., browse photos) all the time to review spaces. For this reason, PG has its innate advantage. Participants perceived EE as easy to recollect in tasks of visibility and manipulation. We believe this was because EE was modeled after real-life experience through embodiment. The grip button for "grasping" in manipulation tasks was right under their fingers, which increased the learnability, thus improving the ease of recollection. P1 noted that "*I can assess it instantly without thinking*". However, there were exceptions when it came to the tasks of locomotion. Since the system did not provide high-fidelity haptic feedback (*e.g.,* force, resistance of wheels) when participants pushed the virtual manual wheelchair with in-air gestures, all participants took noticeably longer time to learn the interaction. Accordingly, some of them found it difficult to recall how to operate the manual wheelchair (P1, P2). In contrast, all participants recalled the usage of the joystick for the virtual power wheelchair with ease. In the end, they all preferred to use the interaction for the power wheelchair over the manual one, even five of the six participants used manual wheelchairs in their daily life.

VR usability. Motion sickness is one of the greatest challenges for EE, especially in locomotion tasks. To alleviate nausea, VT adopted snap turns and teleportation rather than continuous rotation and movement. Meanwhile, continuous motion was inevitable in EE due to the nature of embodiment, so we chose a low locomotion speed for a moderate experience. Nonetheless, P1, P2, P3, and P5 experienced varying degrees of nausea during the locomotion tasks of EE. We were surprised to find that nausea was most prevalent during the locomotion using manual wheelchairs in EE. P5 remarked that he preferred VT in the locomotion tasks due to the motion sickness he experienced in EE. We attributed this feedback to three reasons: 1) participants rolled their wheels at a non-uniform speed, which meant they experienced intermittent bursts that worsened the motion sickness; 2) participants often looked down at the wheels to confirm that their hands were at the right position in the air, leading to unstable vantage points during the movement; 3) the learning curve of the motion-based in-air interaction was a bit high, compared with using a joystick in powered locomotion mode, leading to higher cognitive load. P3 commented, "*The power wheelchair was much easier to operate and resulted in less dizziness for me*". P1 commented that "*[EE] locomotion is more accurate but I am skeptical if the usability is too low.*" P2, P3, and P4 were more tolerant of motion sickness in EE locomotion, using the joystick-based interaction for power wheelchairs.

5.4 RQ3 Findings: Perception of Embodied Exploration

We were unable to invite participants to the four environments in person to collect the ground truth of accessibility. Instead, we relied on participants' daily experiences and asked them for scores on how confident they were about their assessment (Fig. 6). This evaluation is to investigate if participants received sufficient information for them to make assessments. A higher confidence score of a method indicates that the method is better at delivering sufficient information. Overall, we found EE to have the highest average confidence score of 6.68 (SD=0.67), compared to PG with a score of 5.95 (SD=1.48), and VT 6.35 (SD=1.01). However, we are cautious about this finding for the possibility of negative experiences caused by high confidence in errors. To address this, we plan to conduct future research with participants verifying their EE assessments through comparisons with in-person assessments. In the following subsections, we present findings from thematic analysis around themes of "embodiment", and "confidence".

Embodiment. Three findings were extracted from embodiment-related comments as follows.

• ***Embodied Exploration* is the most truthful replicate of real-life experience.** P2 mentioned that "*[EE] is by far the most realistic interpretation of what my mind and body will need to do to complete a task.*" P1 commented that "*By actually doing it, I realize it is not as easy as looking at it.*" P3 remarked that "*Embodiment gives me the best sense of space, and I feel it is the most accurate compared to [PG] or [VT].*" P4 commented that "*EE gives me a great idea of what the room space looks like, much better than manually calling a place for dimensions.*" P5 stated that "*The haptic feedback in [EE] is not far away from my actual experience.*" Lastly, P6 remarked that the control scheme of the powered EE experience replicated his everyday experience with a powered wheelchair joystick. Overall, our observation is that participants found embodiment through EE contributing to their accessibility assessment. Participants felt that being there virtually with an avatar and wheelchair to move around and being able to interact with objects led to a more precise assessment, with EE often correcting what was assessed incorrectly in PG and VT.

• **Perception of embodiment depends on the type of tasks.** We found that participants valued embodiment differently depending on the task. For example, P3 remarked that she would like to use EE to check if she could fit into a space such as a bathroom. In this context, embodiment would be crucial for an immersive and accurate locomotion experience. Interestingly, P5 stated that "*[VT] is great for larger rooms since it gives the most information in the least amount of time, but for a smaller space, EE gives more information.*" In other words, EE provided the fine-grained information needed for tight spaces through embodiment but such level of detail was not always required for environments with obviously sufficient room. However, for visibility, P2 remarked that "*Appearance and wheelchair personalization doesn't make a difference to me so long as my height is correct.*" This different opinion on the embodiment's importance is likely due to the isolation of visibility, locomotion, and manipulation tasks in our study design. It makes sense that manipulation and locomotion require embodiment for a truthful experience, as they involve more interactions with the environment. Contrary to this, visibility task alone has limited interaction and therefore has a lower requirement of embodiment, without which truthful experience can also be delivered.

• **Perception of embodiment varies across people.** Differences in individual biometrics and motor capabilities should not be neglected in assessing accessibility. For example, P4 could stand for short periods, P2 could walk a few steps, and P5 had only recently begun using a wheelchair. This led P2, P4, and P5 to perceive VT as views from a standing posture whereas others did not make such comments. P2 and P4 considered standing also as an option to reach for things in the manipulation task. Despite the differences between participants, this is not a detriment to the efficacy of EE, since the accommodation for personalized accessibility assessment is an advantage of EE we planned to have from an early stage of this research.

Confidence. From the score chart (Fig. 6), we observed how assessment techniques influenced participants' confidence in their assessment of the same task in the same environment. All participants commented that EE gave them the highest confidence in assessment for almost every task, with only one exception. P1 commented that "*[VR] nausea affected my thinking*" in locomotion tasks, which led to a lower score of EE. In general, participants have confidence in their assessment using EE techniques for the following reasons.

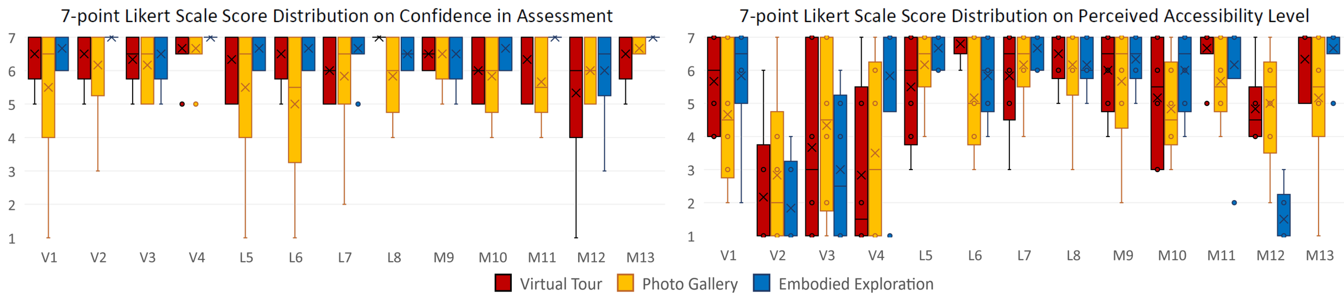

Figure 6: Distribution of 7-Point Likert Scale scores of each interaction technique in each task regarding perceived accessibility levels and confidence in assessment from all participants.

• **Finer-grained information contributes to confidence.** The rich interaction built upon embodiment allowed the delivery of finer-grain information, which was a major factor of high confidence in EE. In the manipulation task, P3 stated that both VT and EE provide a "*better sense of space*", however, EE ultimately felt more accurate due to the interaction with objects. P2 even stated that "*[VT] gives most information, more than [EE] and [PG].*" In the locomotion task, all participants indicated that VT gave more information than PG, but P1 stated that "*[VT] was like a guessing game*", and P2 commented that "*You still need to reprocess the signals in your brain*" to evaluate the accessibility properly while EE allowed him to easily assess through direct interaction. Explaining his low confidence in PG, P6 stated that he had to "*stitch together three or four photos to even make a guess*". As explained earlier, P5 preferred VT for larger traversals but "*For tricky situations, where the space is small, [EE] can help me a lot,*" emphasizing the advantages of embodiment in unveiling details.

We found that VT demanded a higher cognitive load for participants. They often had to hypothetically place themselves at different heights and guessed the accessibility of a task. Contrary to this, EE placed a lower cognitive load on participants, as it allowed participants to view the environment from a truthful height, which can even be adjusted by their movements. For manipulation, the same observation on cognitive load applied for participants not having to make guesses about the interactions with the objects. P4 commented, "*I wouldn't have noticed the milk was too far away to reach in the photo*". For locomotion, participants could move continuously through a space, unlike the discrete teleportation provided in VT. For instance, we found that participants maneuvered carefully around a narrow corner to see if that worked out. They also rolled the wheelchair towards a desk to check whether their armrest will hit the edge. These fine-grained interactions uniquely supported in EE were well received by participants.

• **Sense of embodiment contributes to confidence.** We found that the embodiment of participants greatly contributed to the confidence in accessibility assessment. For EE, participants mentioned frequently the concept of embodiment when explaining their high confidence scores. They did not use the exact wording but uttered similar expressions, *e.g.,* P1 "*This is how I see the world*", and P4 thought out loud "*Now I am pushing forward my wheelchair [... describing what he saw...] My armrests hit the table*". Truthful dimensions of their bodies and wheelchairs allowed them to assess the accessibility without having to guess. For example, P2 said "*I am confident that my legs would not fit under the table*" the moment when he saw his virtual armrest was blocked by the edge of a table. P6 made a similar comment when using EE, stating that "*The counter is way higher than I thought, there's no way I can reach that*". Additionally, P4 commented that *"You can virtually experience, and interact with the environment. Everything works smooth, and it gives me a great idea of what room dimension looks like."* after giving a high confidence score.

With VT and PG, participants were less confident. P1 explained in detail, *"Using [VT] and [PG] is more like guessing games. [VT] made me feel less confident because a floating camera cannot reflect my viewing perspective. With [PG], I am not sure due to the weird vantage point when using photos."* Similarly, P2 commented, "*[VT] angle is deceiving. It looks like the counter height is exaggerated*", which three other participants agreed with. In addition, P3 commented, "*Photos never tell the full story*". An opinion shared by P5 and P6 was that PG and VT decreased their depth perception – "*It's difficult to measure the distance between the window and the floor*" (P5) and "*It looks way more open than it actually is*" (P6). From their feedback, we believe that the uncertainty of the assessment in VT and PG came from the unrealistic perspective (i.e., not a first-person view, surreal eye height), lack of embodiment (i.e., no virtual wheelchairs for reference) and limited interaction with environments (i.e., information that lacks details).

• **Proficiency contributes to confidence.** We also noticed that proficiency with the assessment approach played a more important role than expected in user confidence. Results show that even though participants agreed that VT provides more information on depth and perspectives than PG, some of them could not help feeling more confident when using PG. People explained that they had been so used to assessing environments with photos. The low cognitive burden on learning made them feel more confident about their assessment until they realized it was inaccurate later with a different interaction technique. For example, in the manipulation task T12, P4 felt more confident when assessing with PG (score: 5) than with VT (score: 1) until he later realized his assessment with VT was more accurate. This is a typical source of error in using confidence as an indicator of effectiveness. Fortunately, participants well explained their thinking process rather than just giving numbers, which remediated our findings.

6 DISCUSSION

In this section, we first summarize our findings into positive and negative aspects of *Embodied Exploration*, serving as design guidelines for future integration of embodiment in accessibility assessment tools.

6.1 Summary of Findings

We summarize the findings of our user studies into two categories – one group focuses on the advantages associated with *Embodied Exploration*, while the other group delves into its difficulties and obstacles.

The findings below are positive aspects of *Embodied Exploration*:

- *Embodied Exploration* supports the granularity needed for accurate accessibility assessment.
- Participants regarded *Embodied Exploration* as the most truthful replica of real-life experience, contributing to accurate assessment.
- Participants generally found *Embodied Exploration* highly usable – intuitive, straightforward, and easy to recollect.

Findings pertaining to the challenges of *Embodied Exploration* include:

- Participant found it difficult to recall how to operate a manual virtual wheelchair in locomotion tasks.
- Motion sickness is a challenge for locomotion tasks in VR, which undermines the usability of *Embodied Exploration*.
- *Embodied Exploration* is not necessarily superior to other techniques in tasks that require little spatial interaction.

6.2 Design for Embodiment

Designers of tools for accessibility assessment featuring embodiment should attempt to replicate user real-life experience - how they view and assessed the environment in reality. One design to have a convincing first-person view that leads to realism is to set a proper eye height. Many users found the first-person view in VT (1.6m) unrealistic. Interestingly, P4 still felt embodied during VT. He explained that he could stand for short periods of time if necessary (*e.g.,* reach for a cupboard). When he imagined himself standing, the eye height in VT became realistic to him. Even with our relatively small user sample size, we found that every user had a different range of capabilities, which affected their definition of "convincing" and perception of embodiment.

Another important implication is that designers can enable various granularity of embodiment for different tasks to make the application lighter. For manipulation, virtual hands that are capable of interacting with the environment must be implemented to represent the actual reach ranges. This level of granularity cannot be provided by ray casts. For locomotion, the height of wheelchair armrests and the width of the wheelchair are essential to truthfully replicate maneuvers in the real world that expose obstacles in the environment. If multiple types of tasks need to be performed at the same time in the application, all these elements are necessary for the embodying avatar.

Incorporating avatars and wheelchairs that accurately represent users significantly enhances the sense of immersion. This finding aligns with existing research, which demonstrates that a precise avatar and wheelchair contribute to an improved sense of presence and offer a reliable frame of reference for size and scaling information [66]. Moreover, such representations assist users in making fewer errors in depth perception [50].

Besides, designers should be mindful of potential mental discomfort caused by untruthful embodiment in accessibility assessment. One participant felt unpleasant when the high vantage point in VT reminded him of his perspective prior to their injury, even though the vantage point in VT was not purposefully designed to embody eye height, but rather displayed captures from the scanning camera installed at a fixed height.

6.3 Design for Safety

Safety should be of paramount concern in the design of tools for accessibility assessment. Embodiment could involve a large range of movements that could potentially pose risks to wheelchair users who might have motor injuries. Our takeaway is, "Never assume that a task is safe". The risk level is subjective to each individual and designers should be knowledgeable about types of motions and their implications for users with different motor capabilities. For example, some participants we encountered had a spinal injury that prevented them from bending down or turning around without experiencing discomfort, making some tasks inaccessible or difficult to complete. One participant shared us with a previous experience of breaking a bone due to poor positioning and lack of feeling in that area of their body. We suggest that designers be cautious of potential dangers by collecting specific mobility information of target users and implementing precautions in the interaction techniques from the beginning of the design process and using a user-centered method. It is also possible to implement a personalized safety zone for users with a mechanism to prompt safety reminders (*e.g.,* "You are reaching out too much") whenever risky movements of users are detected.

6.4 Design for Practicality

Last but not least, replicating real-world experience is not always the primary goal to consider in the design of *Embodied Exploration*. We need to optimize the system towards usability too given constraints from many other factors for practicality. For example, although five out of six participants used manual wheelchairs in their daily life, they preferred the powered locomotion technique for its ease of use. From their feedback, we learned that the truthfulness of experience could be perceived as being less important than usability. In this example of manual wheelchair locomotion, the difficulty in performing the in-air gestures, lack of force feedback, and overall exhaustion from performing the movement lowered the usability of this interaction technique. Interestingly, participants commented that the locomotion interaction technique of a powered wheelchair was sufficient for their assessment as long as the wheelchair dimensions were the same as their wheelchairs. Moreover, this locomotion interaction technique of a powered wheelchair moved participants at a constant speed with smoother view transitions that mitigated motion sickness compared to the manual technique. Although prior work has found that realistic force feedback/resistance in simulating a manual wheelchair is paramount to immersion, implementation would require specialized equipment beyond the VR headset [33, 60]. With these observations, we argue that interaction techniques designed for the embodiment which often requires truthful replication of real-world experience should not be at the cost of usability.

7 LIMITATIONS AND FUTURE WORK

We acknowledge the following limitations of our system and study method, and propose future directions.

Confronting VR's challenges in accessibility. Although we leveraged VR to address accessibility issues in this work, we recognized accessibility challenges brought about by VR. These challenges were also discovered in prior work [29, 51]. Future work should aim to accommodate a more diverse user group with richer input modalities, which could lead to more successful personalization. For example, our current interaction paradigm used two hand controllers as the input device, which limited our user pool to people with full or near-full mobility in their arms and hands. We intend to adopt more inclusive input methods (*e.g.,* gaze tracking, free-hand tracking) for our interaction techniques in the future.

Improving workflows of the VR environment creation. The pipeline in our work required manual post-processing in SketchUp to create digital replicas of physical environments, which could be time-consuming and effort-taking. To improve efficiency in creating digital environments, AI could be introduced to achieve a more automatic workflow of environment perception, model reconstruction, and object segmentation. We believe that the ongoing advancements in these research fields [32, 39, 54] will lead to the improvement workflows, enabling stakeholders of environments to swiftly reconstruct their spaces using just smartphones in the near future.

Improving workflows of the embodying avatar creation. To create the embodying avatars, our current system required users to enter measurements of their biometrics. To our surprise, many participants were not aware of these biometrics at the beginning of the study and acquired them through help from family members and friends. We envision that future work could simplify this measuring process using computer vision techniques on smartphones with an easy setup. For example, users could set the smartphone in the environment while performing certain movements in front of its camera. Advanced reconstruction techniques using inertial sensors could also facilitate this process. For example, the arm length of a user could be measured by the user grasping a smartphone while rotating the arm.

Introducing force-based haptic feedback. The current implementation of our system heavily relies on the visual channel to convey information about environments to users. This is not exactly how users would perceive real physical environments. To address more complex scenarios, such as rough surfaces or steep ramps, we acknowledge the need to incorporate force-based haptic feedback. By introducing this feedback mechanism, we can enhance the truthfulness and fidelity of the user experience in VR, allowing for more accurate assessments.

Incorporating additional measures. Our current evaluation of *Embodied Exploration* relies solely on qualitative measures. We recognize the need to incorporate quantitative measures such as time taken to complete tasks, arm movements, and head directions for a comprehensive evaluation of participants' perceived workload and system usability. These measures could be readily supported by additional implementation in VR where virtual environments and users could be readily digitized without the need for additional sensors. Additionally, these measurements could facilitate the unveiling of common obstacles among users that can be prioritized by owners of environments in their improvements of access to the environment, furthering the impact of our proposed accessibility assessment approach.

Collecting ground truth data. To ensure the accuracy of our proposed accessibility assessment approach, it is crucial to collect ground truth data. The "confidence" in our current study design does not indicate accuracy (Sec. 5.4). By obtaining ground truth data, we can better validate the accuracy of *Embodied Exploration* and expose elements that lead to inaccurate assessment for further refinements.

Including more scenarios and tasks. Finally, findings from this research could be strengthened by considering more scenarios and tasks. For example, in crowded environments (*e.g.,* restaurants, parks, and museums) where the people traffic is an important factor to consider in accessibility assessment. This factor cannot be easily and truthfully reflected by our proposed approach. Another instance pertains to the evaluation of manipulation tasks using controllers. As a result, the current system cannot reveal accessibility information of finer-grained manipulation tasks such as estimating the weight of a kettle or feeling the texture of a cloth. To improve our approach on this front, our future system would need to integrate more IO modalities that are increasingly possible with recent advances in VR.

8 CONCLUSION

We present *Embodied Exploration*, an accessibility assessment approach that allows users to explore a digital replica of physical environments with themselves embodied with avatars in VR using a fleet of interaction techniques. We first conducted a preliminary study to investigate common practices and challenges, and categorized tasks in accessibility assessment into visibility, locomotion, and manipulation. We conducted a user-centered iterative design process to finalize interaction techniques. To evaluate the efficacy of *Embodied Exploration*, we recruited six participants who use wheelchairs on a daily basis in a user study. *Embodied Exploration* was compared with two baseline approaches – Virtual Tour and Photo Gallery. We summarized findings from the two studies as answers to the three research questions (i.e., RQ1-3). We found that users valued embodiment in their assessment and attributed that to their real-life experience but at various degrees depending on the task. Moreover, we identified that embodiment and embodied interactions boosted users' confidence in their assessments. This was achieved by providing an opportunity for users to explore environments in an authentic, immersive manner, supplemented by visual feedback. Such a method unveiled intricate information that was often challenging to discern using traditional techniques. The results of usability evaluation indicated that *Embodied Exploration* is effective and intuitive to use while keeping the convenience of remote assessment. We drew a set of design implications and identified future directions for research within this domain.

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