Designing Bespoke VR Input Devices for People With Physical Disability

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Virtual Reality (VR) promises to immerse users in virtual environments, but access barriers for people with mobility disability that are related to the body-centricity of the technology remain. While existing research has begun to develop software solutions, there is a lack of accessible VR input devices with dedicated interaction paradigms for people with mobility disability. In this work, we present two complementary Research through Design (RtD) case studies creating bespoke VR solutions: We designed unobtrusive VR gloves for a manual wheelchair user to allow complex interactions while simultaneously operating the wheelchair, as well as a VR gamepad with a personalized button layout as an alternative to conventional handheld input devices for a powered wheelchair user. Our results show the potential of employing RtD for experience-focused VR accessibility research. We provide recommendations for designing accessible VR input devices and interaction paradigms, and reflect on the challenge of achieving scalable, bespoke VR.

CCS Concepts: • **Human-centered computing → Accessibility systems and tools**; **Virtual reality**.

Additional Key Words and Phrases: Virtual Reality, Accessibility, Research through Design

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1 Introduction

Virtual Reality (VR) holds the promise of immersing users in virtual worlds [32], involving the entire body in interaction to facilitate the sense of really being in the virtual environment [7, 52]. However, because of this body-centricity, VR is associated with a large number of access barriers for disabled people[1] [11, 14, 25, 26, 40, 41, 60]. This is particularly relevant in the case of persons with mobility disability, where VR hardware and interaction paradigms can pose significant challenges, from the basic setup of VR hardware to advanced interactions such as the simultaneous manipulation of two handheld motion controllers [41]. More recently, the accessibility research community in Human-Computer Interaction (HCI) has begun to address these barriers through software solutions. For example, Franz et al. [19] proposed a framework that allowed people with an upper-body mobility disability to gain awareness of points of interest in their vicinity and to automatically re-orient themselves towards them. Yamagami et al. [62] proposed a design space to facilitate the creation of accessible methods for bimanual VR interactions based on unimanual input. And Wentzel et al. [59] have addressed the issue of motion remapping more holistically using transfer functions based on modular geometry, creating the foundation for the integration of different and potentially more accessible input in VR.

However, what has not yet been addressed is the design of concrete accessible input devices and interaction paradigms for people with mobility disability. Given that the experience users can make in VR is closely linked with a good fit between system and body [26, 60], this is a missed opportunity for designing accessible VR: For a user to experience presence and embodiment, i.e., the feeling of being in the virtual environment [52] and perceiving a virtual body as one's own [34], VR systems need to be immersive and wrap around a user's senses [7, 52]. For this, VR hardware needs to be unobtrusive, body-fitting, and should give users agency through interactions with predictable action consequences [28, 34]. Consequently, for people with physical disability to have equitable access to VR, there is a research need to explore the design of VR hardware and interaction paradigms that align with bodies beyond a narrowly defined corporeal standard [26]. A key challenge for designers and developers in this process is the extensive range of different capabilities among disabled users [14, 60]. For example, while manual wheelchair users may be interested in interaction paradigms requiring extensive upper-body input, such solutions may not be accessible for powered wheelchair users [25]. Thus, we need to move beyond one-size-fits-all design solutions and ask what makes VR accessible to an individual user with a physical disability before addressing broader groups. This requires us to imagine new and bespoke VR input devices and interaction paradigms through sensitive bottom-up design processes that facilitate hyper-personalization [26]. One prominent HCI research approach for this is Research through Design (RtD), which enables thorough contextualization of development work [71] and has already been successfully applied in combination with co-design practices involving people with disabilities in related work [17, 30, 43], but not yet in the context of VR accessibility. Therefore, we raise the following two research questions (RQs):

RQ1: How can Research through Design be leveraged in a technical accessibility project to tailor VR input devices and interaction paradigms to the bodies of people with physical disability?

RQ2: What is the impact of bespoke VR input devices and interaction paradigms on disabled users' access to the experiential qualities of VR, i.e., immersion, presence, and the sense of embodiment?

We address these questions through two complementary and iterative case studies in which we develop VR hardware and interaction paradigms to ensure equitable access for two specific users: First, we design unobtrusive VR gloves for a manual wheelchair user that combine the advantages of hand tracking and handheld controllers to allow complex interactions while simultaneously operating the wheelchair. We then create a VR gamepad with a bespoke button

[1]Our paper uses a mix of identity-first and person-first language. Different groups of people and different cultures appreciate different terminology.

layout for a powered wheelchair user that serves as an alternative to handheld input devices such as conventional VR controllers. The outcomes of these case studies demonstrate the promise of RtD for designing bespoke input devices and interaction paradigms for accessible and immersive VR. On this basis, we discuss implications for the design of bespoke VR and reflect on the scalability of individualized results in accessibility research.

Our paper makes the following three key contributions: (1) Two bespoke hardware artifacts with detailed descriptions, as well as one bespoke VR environment, (2) a comprehensive documentation of our RtD approach that can serve as a blueprint for the application of RtD to accessibility research, and (3) implications for the design of bespoke VR hardware for people with physical disability.

2 Related Work

Here, we provide an overview of research on VR accessibility and discuss the application of Research through Design in accessibility research.

2.1 VR Accessibility for People With Physical Disability

A broad range of works has identified barriers to VR accessibility for disabled persons in general, and for people with physical disability in particular. This is complemented by research seeking solutions to key barriers, most prominently by exploring accessible interaction paradigms.

2.1.1 Barriers to VR Accessibility. VR accessibility for disabled persons has been approached from different perspectives, with research underscoring that VR is a technology that places extensive demands on users' bodies [26]. For example, Creed et al. [11] conducted sandpits with expert stakeholders to examine the accessibility of augmented (AR) and virtual realities. Considering users with physical disability, their work identified software issues, e.g., fatigue when engaging with interaction paradigms over longer periods, and safety issues caused by full immersion in virtual worlds [p. 63]. Additionally, they highlight the inaccessibility of current VR hardware (e.g., weight, size, and reachability of buttons) and emphasize the importance of aligning input devices with other assistive devices used by persons with physical disability [p. 63]. Specifically addressing VR hardware in the context of physical disability, Mott et al. [41] identified seven barriers as a result of a qualitative study with 16 persons with mobility disability. They include the setup of VR systems, handling the head-mounted display (HMD) and adjusting its strap, cord management (which is no longer an issue with more recent VR systems [60]), the demands of bimanual interaction, which remains a prevalent technique in VR applications [64], insufficient button accessibility, and keeping controllers in view while also operating assistive devices. As potential mitigation strategies, the authors highlight the potential of alternative controllers and input devices. Many of these barriers are also discussed by Gerling et al. [25], who examined the accessibility of VR gaming for wheelchair users and also highlighted the need for adaptive and alternative control schemes. Adopting a holistic perspective on VR accessibility for people with physical disability, Wolf et al. [60] contribute a qualitative study with 16 participants that examined VR accessibility on the physical, digital, and experiential layer. They highlighted the need to understand individual accessibility concerns and solutions on multiple layers, as, for example, physical concerns can inevitably affect digital and experiential qualities. We also want to note that many of these findings are echoed by Dudley et al. [14], who provide a literature review of VR and AR technology, and who conclude that the movement-centricity of VR poses an access barrier for people with physical disability in particular [p. 2996-2997].

2.1.2 Solutions to Improve VR Accessibility. Beyond the exploratory research presented in the previous section, research has also begun to address access barriers to VR for people with physical disability through the concrete development of dedicated interaction paradigms and VR applications. Most importantly, solutions have explored the design of more accessible VR interaction paradigms for people with physical disability through software. For example, in the context of accessible locomotion, Franz et al. [20] compared six techniques that users could perform while seated, such as thumbstick control or body leaning. Their evaluation with 19 persons with upper-body disability showed that users performed best with controller-based input, but that experiential qualities (e.g., enjoyment or presence) sometimes outweighed accessibility concerns. Similarly, Pei et al. [46] contribute a technique for embodied exploration that simulates real-world wheelchair use: users hold both controllers and move by imitating pushing movements (manual wheelchair) or using joystick input (powered wheelchair). However, with this technique, user movement was restricted to the virtual world, and the simultaneous use of controllers and real-world wheelchair locomotion remains unaddressed.

Concerning upper-body interactions, research has begun to address the need for alternatives to strictly two-handed input: Yamagami et al. [62] propose three interaction techniques that map unimanual user input onto bimanual VR interactions, e.g., by inferring the location of the second hand through computer assistance. Their video-elicitation study with 17 participants showed that although remapping increases practical accessibility, automated solutions may reduce perceived agency for some participants, which is relevant to the sense of embodiment [53]. Adopting a wider perspective on input remapping, Wentzel et al. [59] present MotionBlocks, an approach that facilitates remapping of upper-body input based on transferring modular geometric shapes to adjust a user's range of motion. An initial evaluation with ten people with mobility disability showed the potential to improve accessibility, but the authors also reemphasized issues regarding controller size and conflict with wheelchair propulsion [25, 41, 60].

In contrast to these efforts regarding the design of accessible interaction paradigms, to the best of our knowledge, no research has addressed the design of accessible VR input devices for people with physical disability. In the context of screen-based gaming, Loewen et al. [37] have engaged in speculative efforts to explore how controllers can be adapted to users' bodies and how they would impact player experience, suggesting that bespoke solutions are a promising way of increasing accessibility of interactive media. Likewise, there are a few commercially available, accessible input devices (e.g., the Xbox Adaptive controller[2]) that enable personalization; however, these systems are not motion tracked and typically offer not enough degrees of freedom for VR control. For VR, research on the design of bespoke VR hardware currently only addresses people who are blind or have low vision [69]. However, research for general audiences has contributed custom-built input hardware, for example, controllers reacting to one's grasp [63] or providing haptic feedback [66]. Still, there remains a research gap in the design of bespoke VR input devices for people with physical disability that are tailored to users' bodies and address the accessibility concerns of VR hardware repeatedly raised by previous work.

2.2 Research through Design

The concept of Research through Design describes a reflective approach that combines research methods with design practices, allowing for the coupling of their different interests [4, 5, 70]. Here, we describe its origins and applications in Human-Computer Interaction research, as well as examples of how RtD has been leveraged in HCI accessibility research.

2.2.1 Research through Design in HCI. RtD was first described as a method for research in art by Frayling [22], which included not only the outcome of development work, i.e., an artifact, but also a contextualization through design process

[2]Microsoft (2018), https://www.xbox.com/en-US/accessories/controllers/xbox-adaptive-controller

documentation. This could be a written research diary, tales of explorations, reflections, or justifications for design decisions [4]. For instance, Oogjes and Desjardins [44] established a vocabulary of temporal events, such as *transitions*, which could refer to changes in materials or design, or *encounters* (interactions between separate actors) to assist structured reporting. In the context of Human-Computer Interaction, Zimmerman et al. [71] describe the advantages of RtD as knowledge gain both in terms of *true*, actionable knowledge (e.g., new models, theories) and *how* knowledge (e.g., the implementation of technical or scientific approaches by engineers). However, there is no one single defined formal methodological approach to RtD [15], and accounts of RtD often vary in focus, structure, and argumentative grammar [9, 44]. Here, Gaver [24] advocated for understanding RtD studies as part of a diverse methodological portfolio, in which artifacts embody both theoretical and practical knowledge.

RtD has previously been employed across various areas of HCI, for example, to support outdoor play for children through a play watch by extending the dynamics of the children's game "tag" [16], to explore mechanical sympathy for human-machine relations [35], or to describe the design of alternative data encounters [12]. In the context of immersive technologies, RtD was used to design shared environments such as VR memorial spaces from the perspective of the dying and bereaved [3], or collaboration and meeting spaces for social VR users [45]. For example, Xiao et al. [61] created a mixed reality (MR, environments where virtual and real objects co-exist [39]) game technology stack and structured their RtD process in three phases: a literature survey, an ideation and iteration block, and a reflection phase with a workshop, which allowed the formulation of three generative design implications for MR application development, i.e., 1) seamful design, seamless experience, 2) think outside the screen, and 3) play with virtuality and reality. RtD has also been applied in HCI accessibility research (e.g., see Ellis et al. [17]), where it has been utilized in the context of co-design, a combination which we explore in more depth in the following section.

2.2.2 Applying RtD and Co-Design to Accessibility Research. Within the HCI and accessibility research community, previous work has leveraged RtD to support the documentation of design when working with and designing for disabled people [17, 30, 43]. Here, we note that existing research has strongly emphasized co-design approaches, in which research teams work with persons with disabilities to draw on individual expert knowledge grounded in lived experiences [6, 36, 50]. This is especially important given the power imbalance inherent to research (cf. Bratteteig and Wagner [8], Kensing and Blomberg [33], Muller et al. [42]), as participants can now regain a degree of control over the design of technology that is intended to meet their needs [29, 47, 57]. This requires a respectful relationship between the researcher and participant to make design probes effective [58]. For instance, co-design was used to develop an inclusive planning tool for accessible public spaces with eight participants with mobility and/or sensory impairments [18]. Likewise, Pei et al. [46] co-designed the necessary details for a low-fidelity prototype with wheelchair users to investigate the embodied exploration of virtual representations of real environments.

While co-design is often highly individual and associated with a small number of participants, we also want to emphasize that the results of individual case studies can be extrapolated to gain insights into implications for designing for and with a larger target audience. However, this requires a thorough contextualization of the design approach, which can be achieved through RtD. For example, Nevsky et al. [43] explored highly personalized accessibility interventions based on audiovisual media personalization with four participants with aphasia and used RtD to investigate the nature of such personalization. Similarly, Homewood et al. [30] documented what they call a RtD-driven co-creation of non-medical crip pacing technologies, i.e., devices that allow for balancing exertion with periods of rest based on the input of eleven participants who have energy-limiting conditions such as long COVID. Reflections on their approach primarily focused on the tension between providing users with technologies according to their wishes and the author's moral code based on crip theory that focus on social and political aspects of disability rather than the medical viewpoint. Finally, Ellis et al. [17] used RtD to contextualize their process of co-designing a bespoke one-handed braille keyboard with a blind person. In their work, they provided a comprehensive design story, from defining individual challenges to accounts of prototype iterations, which helped them reflect on the technical process and the procedural knowledge gained.

In our work, we build on these previous efforts to design bespoke VR hardware and interaction paradigms for people with physical disability by leveraging a structured RtD approach for co-designing case studies. This enables us to combine co-creation with detailed reporting and reflection, and allows us to critically appraise the extent to which bespoke design can address key barriers to VR.

3 Developing Bespoke VR Input Devices and Interaction Paradigms: Design Rationale and Research Approach

In this section, we give an overview of the design rationale and research approach for the exploration that we engaged in with two people with physical disability to understand how to tailor VR input devices and interaction paradigms, as well as the implications for VR access and experience.

3.1 Design Rationale

In line with our research questions that sought to understand how bespoke VR input devices and interaction paradigms can support VR experience, we ground our design approach in considerations thereof. In particular, we leveraged existing considerations regarding the experience of immersion and presence. Regarding sensory immersion [7, 52], our design is guided by the question of how it can be supported by input devices that are well-connected with users' bodies (cf. Gerling and Spiel [26]), enabling the experience of presence or the sense of actually being in a virtual environment [52]. Given the close link of these constructs with embodiment, we further draw upon research by Kilteni et al. [34], who explored what contributes to the sense of embodiment (SoE) in VR and described three subcomponents: (1) The sense of self-location, which refers to the spatial experience of being inside a virtual body, (2) the sense of agency, where action and motor control can be experienced, and (3) the sense of body ownership, the feeling that experienced sensations originate from the virtual body. Furthermore, we engaged with critical explorations of VR accessibility [26] and embodied interaction [13, 54], challenging us to rethink normative assumptions when designing body-centric systems to guide our design process. Consequently, this requires us to critically reflect on what input devices and interaction paradigms fostering VR experience look like for different bodies, engaging in a participant-led process to understand how VR can be adapted to individual needs and preferences, while addressing key constructs of VR experience.

In the context of our work as accessibility researchers, we came in contact with two persons with mobility disability who have distinct requirements for VR use, a manual wheelchair user and a powered wheelchair user (see Sections 4 and 5 for detailed descriptions). Considering core aspects of VR experience presented here, it is clear that the requirements for VR input devices and interaction paradigms for each person would be unique. Thus, rather than trying to attempt to identify commonalities between them and addressing them through design, we align with Gerling and Spiel [26] and engage in a bottom-up design process that examined how to tailor solutions to their individual bodies and VR use cases.

3.2 Research Approach

We employed an RtD approach similar to the accessibility focused work of, e.g., Ellis et al. [17] and Nevsky et al. [43] (see also Section 2.2) to contextualize and describe the case studies separately. Each was done with one person with physical disability, to whom we will refer in the following via pseudonyms or as experts in their respective case study. They were not involved in each other's cases.

3.2.1 Research and Design Process. Both case studies spanned 10 months and were divided into four core phases focused on ideation, implementation, feedback, and reflection: (1) *Ideation* phase. In initial meetings we got acquainted with each of the experts, talked about typical interactions in the real world, their requirements for VR, and discussed possible concepts for bespoke input devices and/or interaction paradigms. This could also include discussions about virtual environments in which the bespoke artifacts could be tested. As part of this phase, we developed initial sketches, considered hardware and system requirements, and used paper prototypes and/or drawings to create a shared understanding between researchers and experts. (2) *Implementation* phase. Here, we created or revised functional controller and/or VR environment artifacts based on the previous discussions. This included the hardware and software design and implementation, as well as the construction of necessary housing and tangible elements. We used 3D printing as well as manual processes such as soldering or sewing. VR environments were implemented using the Unity 6 game engine. (3) *Feedback* phase. After implementing functional artifacts, we met with the experts separately again. Both tried their respective bespoke input devices and/or interaction paradigms within their bespoke VR environments or commercial applications, and shared their thoughts with us in think-aloud sessions. Then, we discussed their impressions, any challenging aspects, or future directions in a semi-structured interview format. We prepared guiding questions that let the experts talk about their subjective level of adaptiveness of the approaches to their own body (*"Do you feel that the controller is well-adapted to your body?"*), or reflect on experiential qualities such as the sense of presence based on modified prompts of the igroup presence questionnaire (IPQ) [51]. For example, we asked IPQ item 1 (*In the computer-generated world I had a sense of "being there"*) as *"In the computer-generated world, did you have a sense of "being there"?"* We added all guiding questions to the supplementary material. Based on the results of this phase, we either entered another development cycle consisting of another implementation and feedback phase or continued with the reflection phase. (4) *Reflection* phase. In the reflection phase, we collected all thoughts of both us and the experts regarding the RtD process that were expressed during the work. This could include remarks concerning the collaboration, but also the expert's perceived influence on intermediate or final artifacts.

The different phases and the involvement of researchers and experts are also depicted in Figure 1. We documented the RtD processes according to the recommendations of Bardzell et al. [4] and Oogjes and Desjardins [44] through written documents and notes, as well as with sketches and images of the artifacts to capture *transitions* between different development stages. Additionally, we audio-recorded all *encounters* between researchers and experts. We structure our reporting of the case studies by first reporting on the expert's requirements for VR usage according to our design rationale, situate the individual requirements in the literature, and detail the concepts for our work (ideation phase). Then, we describe the building processes for the artifacts within development cycles, which each consist of implementation and feedback phases. Finally, we reflect on each RtD process. The research protocol was approved by the Karlsruhe Institute of Technology ethics board (A2023-058). We reimbursed both experts with 25€ per hour spent on the project.

	Category	Definition	Example
Ideation phase	*C1.1: Real world interactions*	Everything describing interactions within the real world that can be seen as ground truth when designing virtual interactions fostering embodiment similar to the real world (see Dourish [13]), e.g., habits and modes of actual locomotion or interactions with physical devices.	*"Well, I've been driving since I was, um, seven years old, um, with an electric wheelchair with a joystick."* (P2)
	C1.2: VR expectations and previous experience	All comments regarding the expectations towards VR, as well as previous experiences, including reasons for and against engagements, for example, descriptions of barriers (e.g., similar to Mott et al. [41] or Gerling et al. [25]).	*"In my case, I am not even physically capable of holding the controller. [...] I haven't been able to do much with VR because of this usability issue."* (P2)
	C1.3: Individual requirements and preferences for VR	Statements highlighting individual requirements for VR usage and preferences for the design of bespoke input devices and interaction paradigms, for example, as a consequence of lived experience or barriers described in category C1.1.	*"It's also important to me that I can just let go [...], without having to worry about anything falling off."* (P1)
Feedback phase	*C2.1: Interplay between body and artifact*	All thoughts regarding the interplay between body and bespoke input device and/or interaction paradigm (cf. Gerling and Spiel [26]), for example, concerning how well the artifacts are designed for the individual bodies, comments regarding physical comfort or pain during usage or temporal factors such as fatigue (see Wolf et al. [60]), and ideas for future adaptations.	*"And I put my hand on it and notice, wow, there's a button under every finger."* (P2)
	C2.2: Impact on experiential qualities	Statements concerning the perceived experience while using the bespoke input device and/or interaction paradigm, for example, regarding the sense of presence [52], sensory immersion [7], or embodiment [34].	*"That kind of situation was pretty cool, [...], that makes you realise, okay, I'm kind of in there."* (P1)
Reflection	*C3.1: Reflecting on the RtD process*	Thoughts regarding the RtD process and the cooperation between researchers and experts, for example, describing individual dynamics such as coupled or decoupled interests (see also Basballe and Halskov [5]) and the reactions to individual wishes and raised issues (categories C1.3 and C2.1).	*"It was also great fun because you know that you're getting something that you can really use."* (P2)

Table 1. Coding agenda with categories aligned with our design goal and the research questions. The categories were divided into two phase-specific subsets applicable only to the data gathered during the ideation or feedback phases, and one phase-agnostic subset concerning reflections on the RtD process.

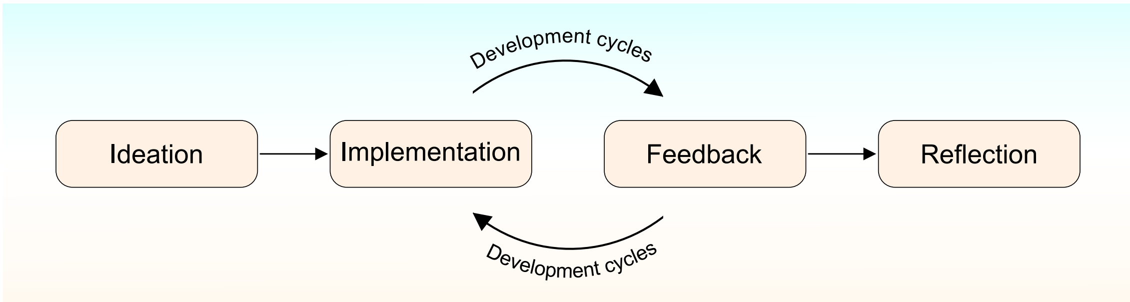

Fig. 1. Case study phases. Each case study followed the same process and can be divided into four core phases: ideation, implementation, feedback, and reflection. Implementation and feedback phases were part of repeated development cycles.

3.2.2 Data Analysis. We analyzed data gathered in the encounters between researchers and experts during the ideation and feedback phases for each case study using a directed Qualitative Content Analysis following Zhang and Wildemuth [68]. For this, all audio recordings were transcribed locally using Buzz v1.2.0[3] and manually checked for consistency and formatting. We developed a deductive coding agenda with mutually exclusive a priori categories aligned with our research questions and design rationale to allow for comparisons between phases and subjects (see Table 1). Categories were grouped into three subsets, of which two were phase-specific and only applicable to the data gathered during the ideation or feedback phases, and one phase-agnostic subset concerning reflections on the RtD process. The goal of the categories of the ideation phase subset was to set the tone for the bespoke development by gathering individual experiences with and requirements for VR while taking preferences and real-world interactions into account (categories C1.1 - C1.3). Categories of the feedback phase subset focused on the interplay between body and artifact and its perceived impact on experiential qualities such as presence or the sense of embodiment (categories C2.1 and C2.2). Finally, the reflection subset allows reflections on the RtD process itself (category C3.1). We underpinned our categories with related work on VR accessibility barriers (e.g., Mott et al. [41]), virtual avatars (e.g., Angerbauer et al. [2]), and experience-centric perspectives on VR (e.g., Slater [52], Wolf et al. [60]). To ensure inter-coder agreement, the first and second-last author applied all applicable categories to one randomly selected encounter of each case study after its data was available and discussed their results (here, we want to note that Zhang and Wildemuth [68]'s approach does not recommend calculations of inter-coder reliability scores). We performed minor adjustments to each subset category definition until both authors achieved a sufficient coding consistency. The first and second-last author then each applied the coding agenda to half of the available encounters, and the results were discussed within a subset of the research team to achieve trustworthiness [55, 68].

3.2.3 Positionality Statement. In this study, we acknowledge that our personal histories, lived experiences of disability, and our situated relationship to the research context inevitably shape the ways we gather and interpret data. Critical reflexivity regarding the possible effects of these to our research process worth mentioning [27]: Our group is a mixed-ability team, bringing together varied ethnic (western, non-western), and academic (including computer science, engineering and psychology) backgrounds, alongside diverse disability experiences (two members with physical disabilities, one member with neurodivergence and other members who identify as non-disabled). The first five authors conducted data collection, and data analysis was carried out collaboratively by two authors with differing experiences

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

of disability. Though our experiences of disability differ, we share a justice-oriented commitment to accessibility and believe society must ensure emerging technologies are designed for both disabled and non-disabled people.

4 Case Study 1: A VR Glove Controller for Nick

In this section, we present our work with Nick (name changed), which resulted in the design and development of two iterations of a VR glove controller as well as a VR basketball game to match the input device. Here, we first give an introduction to the case study, then we describe how the design was developed and implemented following our RtD process, and we report on the exploration of the artifact with Nick, sharing insights that enable us to reflect on our research questions.

4.1 Ideation Phase: Exploring Nick's case

In the ideation phase, we focused on getting to know Nick, engaging in joint ideation as a basis for concept development for this case study.

4.1.1 Getting to know Nick. Nick is a university student in his early twenties who uses a manual wheelchair due to caudal regression syndrome. He is a physically active person and enjoys playing wheelchair basketball in his free time.

Real world interactions (C1.1): Nick navigates the real world using his manual wheelchair. As an active wheelchair basketball player, he showed us how to balance on his back wheels and what fast turning in confined spaces looks like. Discussing typical interactions with his wheelchair, he elaborated and depicted how to use different push types in everyday life, for example, *"If you're going really fast, you do two short pushes and then a long one, and there you'll reach down considerably."* Additionally, Nick demonstrated how he positions his hand on his wooden hand rims, but told us that these grasp types differ from person to person. As he uses gloves occasionally outdoors, Nick also reflected on propelling his wheelchair with them, and concluded that almost anything situated at the hands slightly impacted grip quality, explaining that *"You can't grip as well as you can without it."*

VR expectations and previous experience (C1.2): Although Nick did not consider himself a gamer and only occasionally used a PlayStation console at home, he was interested in VR due to the possibility of fully immersing himself in virtual worlds. He shared with us various instances where he previously tested VR, for example, during a museum exhibition or in a shopping center. As part of these engagements, he played the game Beat Saber[4], a fast-paced rhythm game, and tried out different controllers that ranged from conventional VR controllers to small, smartphone VR controllers and gamepads. During his past VR experiences he also encountered access barriers. For example, he recalled that *"When I have the controllers in my hand, controlling the wheelchair is a challenge"*, which significantly impacted his natural VR locomotion experience, and aligns with previous research on VR accessibility for people with physical disability [41, 60].

Individual requirements and preferences for VR (C1.3): Commenting on his individual requirements and preferences for VR use, Nick recalled his previous frustration with handheld devices and expressed a desire for a controller that would not interfere with wheelchair interactions and could, for example, be used to play a VR wheelchair basketball game. However, such a controller would need to come with proper fixation or in wearable form, as Nick explained that *"It's also important to me that I can just let go [...], without having to worry about anything falling off [...]"*. Besides his wish for natural wheelchair locomotion (*"[...] it just feels more natural, in the moment"*), Nick also highlighted his preference for intuitive button-based input, although their spacing needs to be *"[...] ergonomic, so that you can easily*

[4]Beat Games (2019): https://beatsaber.com/

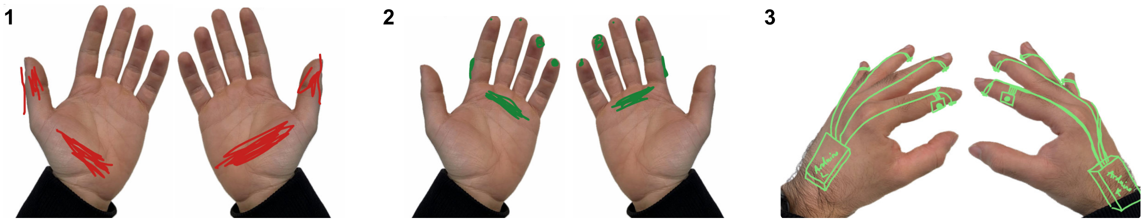

Fig. 2. Sketches accompanying the design of the glove controller for Nick. **1** Hand sketch with bad candidate areas that should be left free to not impair manual wheelchair control. **2** Hand sketch with good candidate areas for button or thumbstick positioning. **3** Glove controller input concept sketch. Four buttons at the fingertips and one thumbstick at the side of the index finger as input components for a microcontroller.

reach all the buttons and so on." As long as there would be no unnatural or especially fine actions necessary, e.g., due to buttons requiring complex pinky or ring finger movements, he was confident that this would allow him to *"[...] don't [need to] look to see whether I'm pressing an upper or lower button, [...], which means you can react quickly."* Finally, he also reminded us to be mindful of hardware or material placements in combination with his wheelchair, as *"[...] if I don't pay special attention to them, they would come into contact with the hand rims, and I think that would cause a lot of wear and tear"*, reaffirming the importance of Gerling et al. [25]'s call to consider wheelchair characteristics during development.

On this basis, we decided with Nick that the **design goal of this case study** would be to create a controller that supports button- and movement-based VR interactions, but that does not interfere with wheelchair use.

4.1.2 Concept development. Based on our encounter with Nick, we translated our design goal into technical requirements, i.e., the creation of an *unobtrusive controller with high DoF for simultaneous use of VR and a manual wheelchair*. Here, a key requirement was to replace the commercially available handheld controllers with a wearable alternative that would allow Nick to use his hands for wheelchair propulsion. To keep his hands free, we decided to co-design a pair of gloves augmented with buttons that provide the same input options as handheld controllers. To tailor the gloves to Nick, we first created a shared understanding of where the placement of buttons on a hand would be preferable by letting Nick identify relevant areas in a sketch (see Figure 2: 1 and 2). For example, while Nick wanted to use buttons at the fingertips and marked the corresponding areas as possible candidate areas, we learned that he often relied on the thumb as well as the base of the thumb to control his wheelchair, and thus disqualified these areas. Consequently, we then *envisioned a controller pair (left and right), each with four buttons located on the inner side of the fingertips that could be pressed with the thumbs, as well as thumbsticks sitting on the side of the index fingers* (see Figure 2: 3). Another consideration was that of material that would be suitable for such a glove. Here, we aimed for thin gloves of elastic fabric that still provide grip for locomotion through a plastic coating on the inside, a feature common to many gardening gloves.

From a technical perspective, this approach requires a combination of hand tracking and button input (see Section 4.2.1). This translated into a **second design challenge**, because commercially available applications require users to either opt for hand tracking or for controller-based input. Thus, our design goal was associated with the requirement to develop a *virtual environment in which Nick could test interacting with the glove controller while operating his wheelchair*. Drawing on his wish for a wheelchair basketball game, we jointly developed a concept for a single-player VR wheelchair basketball court scene that would leverage the full functionality of the glove controller.

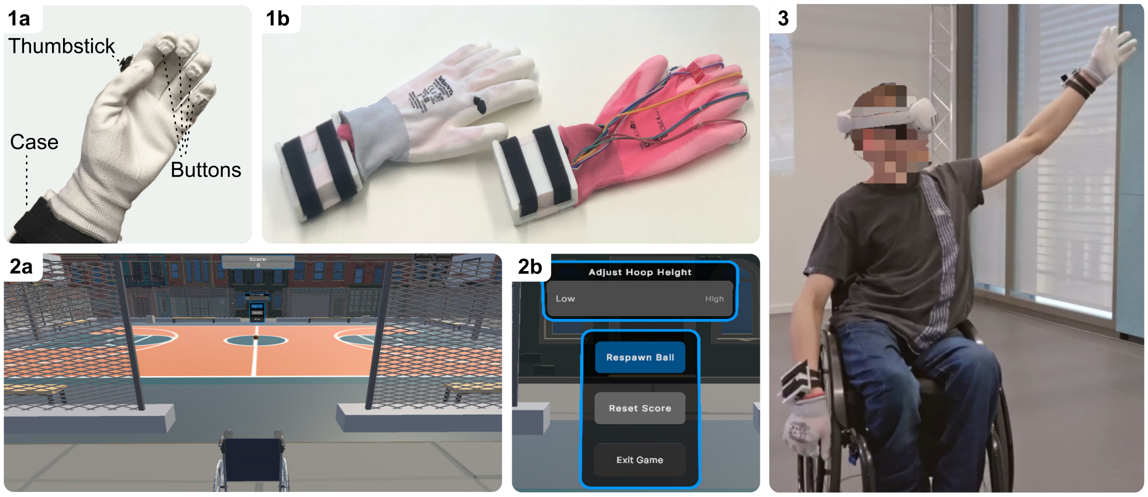

Fig. 3. First iteration of Nick's case study. **1** Initial glove controller design: **a** Each controller consists of two glove layers, here shown with the white outer layer and the pink inner layer. **b** Interactions are possible using a thumbstick and buttons. A case on the wrist holds the microcontroller and a battery to allow wireless control. **2** First version of the virtual wheelchair basketball environment: **a** Side view of the court with the player's wheelchair in front. **b** Floating game UI. **3** Nick during his exploration.

4.2 First Iteration: Implementation Phase and Feedback Phase

Based on the design concept, we initiated the first iteration of our RtD process, which involved creating an initial implementation of the controller and VR game, followed by a round of feedback with Nick.

4.2.1 Building the glove controller. When building the first version of the glove controller (see Figures 3.1a and 3.1b), we focused on the identification of suitable gloves and materials, and an initial electronic design that included buttons, wiring, and housing for the necessary microcontroller.

As one of our design goals was to create an unobstrusive device, we opted for two portable microcontrollers (Arduino Nano 3.3V BLE). Each microcontroller managed one glove and had four small Omron B3FS-1002 tactile buttons and one small two-axis SparkFun Thumb Slide Joystick connected to its pins. We deliberately chose these components to keep the glove controller as compact as possible. Each microcontroller was powered by a 3.7V Lithium-Ion battery that was governed by an Adafruit PowerBoost 500 Charger board, which also allowed us to switch the power state using a small tactile switch. We encapsulated most hardware components in custom 3D-printed parts we devised with Computer-Aided Design (CAD). While the microcontroller, charger board, and battery were packed together into one housing that featured recesses for velcro fasteners, buttons each got individual enclosures with space for cable strain relief. We only created base plates for the thumbsticks. All housings of the buttons and the base plates of the thumbsticks featured small holes that we later used to sew and glue these individual components onto gardening gloves in Nick's size (L). To leverage the glove as an input device, events from the buttons and thumbsticks were then read out by interpreting their respective digital or analog signals in a loop. These events were gathered wirelessly at the microcontroller of the right hand and communicated further as the right microcontroller advertised itself as Human Interface Device (HID) to any Bluetooth Low Energy (BLE) capable devices. For location tracking, we tried out the hand tracking capabilities of different VR systems (Meta Quest 3, Meta Quest Pro, PICO 4, and Vive XR Elite) in conjunction with the glove controller. Here, our preliminary tests revealed that the cables we used to connect the individual components that ran along the back of the hands interfered with hand tracking. As a fix, the first controller iteration needed to be worn with an additional outside glove (size: XL) that covered the artifact and re-enabled tracking.

4.2.2 Creating the VR wheelchair basketball game. To complement the glove controller, we developed a VR scene in Unity in which key functionality could be tested (see Figures 3.2a and 3.2b). This environment included a low-poly styled basketball court with two hoops, where players collect points by scoring with a basketball. The player avatar matches the theme and consists of a wheelchair and floating hands. We added a user interface to the side of the basketball court, which allows the player to control the loop height and to view and reset the score.

Within the scene, players can interact with elements by pointing at them and pressing any button on the glove controller. Interaction with the basketball requires holding the pressed button for pick up as well as continuous grasp in the right hand, Throwing requires releasing the pressed button while performing a hurling motion, which propels the basketball along a trajectory according to the hand velocity and direction. For locomotion, the player can either rely on natural wheelchair movements or use the thumbsticks on the gloves.

4.2.3 Exploring the prototype controller and game with Nick. Once finished, we explored the prototype controller and VR scene with Nick (see Figure 3.3), focusing on his initial impressions, specifically on how the glove connected with his body and wheelchair, and what the experience was like. For this, Nick tested the glove controller in our VR lab using a Meta Quest 3 for 45 minutes.

Interplay between body and artifact (C2.1): Generally, Nick was able to interact with the glove controller in the virtual environment. Comparing the controller to his previous experiences, Nick had a positive look on the first bespoke iteration: *"In itself, of course, it's better suited than a classic controller, because it reflects the hands more."* Commenting on the fit between the controller and his hands, Nick pointed out that the two layers of gloves resulted in a fit that was too tight, which complicated putting on the controller independently and decreased haptic feedback during button and thumbstick interactions. Here, Nick also called attention to the position of the left thumbstick, which was a bit too close to his thumb for comfortable interaction. He also pointed out a conflict between the controller and his body, as the microcontroller housing needed to be fixated too close to his wrist, which impacted his movements and even resulted in a collision with the hand rims of his wheelchair once. However, locomotion with the wheelchair (i.e., propelling and turning the wheelchair while wearing the gloves) worked well. When performing basketball throws, he also noted that the required hurling motion while holding a button did not match the natural motions he was used to from sports, which was further impacted by the need to keep his hands in the visible area of the headset cameras for the hand tracking to work. Finally, Nick pointed out that the first version of the game uses a right-handed throw by default, which clashed with his own handedness: *"Perhaps it's also because I'm left-handed and prefer to reach for the ball with my left hand."*

Impact on experiential qualities (C2.2): While Nick enjoyed the game and we observed indicators of presence, e.g., *"That kind of situation was pretty cool, [...], that makes you realise, okay, I'm kind of in there"*, there were a lot of irritations Nick had to deal with. For instance, tracking issues negatively impacted his experience along with the difficulty in scoring due to the throwing mechanism. Over time, Nick attempted to adapt his strategies, for example, by using a reverse layup instead of a standard throw, and commented: *"It's also really funny to think about, okay, how do I throw if it doesn't work like that."* Reflecting on his bodily representation, he appreciated being able to view his own hands as well as the wheelchair, although the model in the scene was a general sports wheelchair rather than one

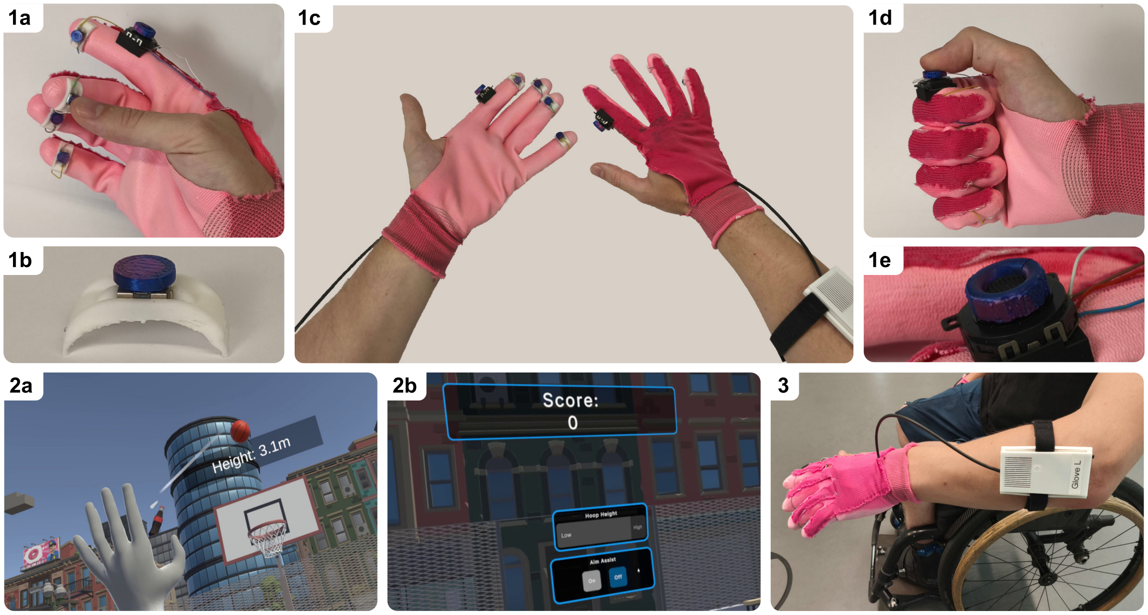

Fig. 4. Final iteration of Nick's case study. **1** Glove controller: **a**, **b** The new button design is curved and overall smaller. **c** The gloves leave the thumbs free, and a long cable runs in a sewn-on sleeve on the back of the hand to the microcontroller box. **d**, **e** The thumbsticks feature a 3D-printed ring with a recess for better haptics and control. **2** Virtual wheelchair basketball environment: **a** View of a scoring throw with visible loop height. **b** Simplified game UI floating at the side of the court. **3** Nick with the glove controller during his exploration.

specifically designed for basketball: *"Finally a game where a wheelchair at least appears, [...], and that outweighs the fact that 'it's not the ideal wheelchair'."*

4.3 Final Iteration: Adaptation Phase and Feedback Phase

After exploring the first iteration of the glove controller with Nick, we adapted the controller and game design according to Nick's feedback.

4.3.1 Adapting the glove controller. Our second iteration of the glove controller (see Figures 4.1a - 4.1e) incorporated the feedback we got from Nick during the exploration phase. As one of the key takeaways of the session was that the double-layered gloves were responsible for multiple challenges, we now opted for a single-layered design: A sewn-on sleeve on the back of the hand would take on the task of the outer glove layer and hide the cables from view. To further increase the haptic quality of buttons and thumbsticks, we cut the thumb free and added a 3D-printed ring to the thumbstick that created a recess for the thumb on the otherwise flat top. We also revisited our button case design, adjusting its form and size to be smaller and less obtrusive, and slightly moved the left thumbstick further away from the thumb. As Nick had also pointed out that the microcontroller casing was too close to his wrist, we extended the cable between the case and the glove. Additionally, we decreased the respective enclosure size by using cuboid instead of cylindrical 3.7V Lithium-Ion batteries and added longer velcro straps to ease setup and avoid collision with the wheelchair. When testing, we noted minor communication issues stemming from our own HID device implementation, and switched to Arduino Nano ESP32 microcontrollers. While this did not affect the general architecture, it allowed us to use a reliable third-party library for self-made BLE HID devices[5].

4.3.2 Adapting the game. We also adapted the wheelchair basketball game according to Nick's feedback (see Figures 4.2a and 4.2b). This mainly included changes to the game mechanics: We added a 'stickiness' mechanic to the player's hands that only allows a basketball to be thrown when an over 100 ms averaged velocity threshold of 1.2 m/s is reached. Thus, for a throw, the respective motion needs to be performed within the camera view of the VR system, but button presses are no longer needed to release the ball. We also reassigned the remaining actions triggered by buttons according to their position so that they are mirrored between the left and right glove: (1) Index finger: Summoning the basketball into the respective hand, (2) middle finger: increasing the hoop height, (3) ring finger: decreasing the hoop height, and (4) pinky: toggling on/off an aim assist mode. When using aim assist mode, a thrown basketball gradually experiences a small force to adjust its trajectory towards the nearest hoop. Additionally, we added visual indicators displaying the hoop height upon adjustments and the points won upon scoring (e.g., '+3' for a shot from beyond the three-point line).

4.3.3 Exploring the final controller and game with Nick. After iterating on the design of the controller and the game, we met again with Nick (see Figure 4.3) to explore how the changes impacted the interplay of the controller and his body, as well as his experience in VR.

Interplay between body and artifact (C2.1): Overall, Nick found that the revised controller design provided a better fit to his body and wheelchair: *" [...] my [hand] mobility was much better than when I wore two pairs of gloves. [...] [The new design] improved the experience."* In particular, he stressed that the new glove design enabled him to put on the glove more independently, commenting that *"I think the glove was relatively easy to put on, even by myself."* While he still noticed that the glove controller slightly reduced his grip on the hand rims, he positively noted that they did not interfere with the wheelchair interaction: *"So, I'm not accidentally pressing anything at the moment. My fingertips are slightly less sensitive than usual, but I can still drive fine."* Further, the new positioning of the buttons and the revised joystick enabled smoother interaction, making it *"easier to steer."* Still, Nick saw further potential in making them *"even more subtle"*, as long as they would provide *"[...] good feedback"* and *"[...] work well and [were] really easy to control."*

Impact on experiential qualities (C2.2): Despite technical difficulties with the VR system in the beginning, Nick's overall VR experience was improved. Over time, he got used to the interactions provided by the controller, and thus became more immersed, explaining that *"[the interaction with the controller] became very automatic, [...] And that helps [immersion], I would say. You no longer had to think about how to interact."* While he liked the new stickiness mechanic with the ball, he still found that the new throw interaction did not accurately reflect real basketball movements due to the need to keep within the hand tracking volume. This impacted his sense of presence to some extent, as the game was not *"totally realistic."* However, he saw the gloves as one of the key aspects of improving immersion: *"Unlike in other games, you don't have to hold anything in your hands here, so you can move them freely without anything falling down when you let go. I think that, when you really get into the tunnel, the gloves are very powerful."* For an even more embodied gaming experience, Nick saw great potential in adding sensors for wrist and hand tracking to the gloves, since *" [...] if you can actually detect what's moving there, then you can make a lot of natural movements in the game. For example, the throwing motion where I flick my wrist — I see more potential in the gloves than in conventional controllers."*

Ultimately, this feedback round revealed that the bespoke glove controller worked well for Nick within the bespoke virtual environment. As the improvement suggestions would primarily require addressing the current limitations of VR

[5] Mystfit, ESP32-BLE-CompositeHID v0.3.1, (2025), GitHub repository, https://github.com/Mystfit/ESP32-BLE-CompositeHID

systems, particularly by enhancing hand tracking precision and its tracking volume, we decided with Nick that our RtD process had come to an end.

4.4 Reflection Phase: Appraisal of the RtD Process

Because the RtD process spanned a longer period of time, we managed to build a mutually meaningful and friendly relationship with Nick, with his perspective contributing valuable insights based on lived experience, such as an ergonomic and non-interfering button placement, which would have been overlooked without the design and development iterations. Reflecting on the RtD process (C3.1), Nick appreciated the bottom-up and bespoke approach, commenting that *"It's also [nice] to realize that this glove is being made just for you!"* He was surprised by the quality of the hardware artifact, although he pointed out that the representation of assistive devices, e.g., the sports wheelchair in the game environment, would require more attention to detail if developing a commercial product: *"If I don't know, EA or someone releases it, then I would be annoyed by it and not feel represented by it, but in this context, I don't really care."*, highlighting the challenge when engaging in prototyping rather than developing fully finished designs.

5 Case Study 2: A VR Gamepad for Simon

In this section, we present our work with Simon (name changed), where we designed and developed three iterations of a bespoke VR gamepad.

5.1 Ideation Phase: Exploring Simon's case

In the ideation phase, we focused on getting to know Simon and engaged in joint ideation discussions as a basis for concept development.

5.1.1 Getting to know Simon. Simon is in his early thirties. He manages accessibility concerns for a city administration, and is a musician. He describes himself as of short stature, and uses an electric wheelchair in his daily life.

Real world interactions (C1.1): Simon has developed flexibility when interacting with real-world objects because his disability affects reaching and grasping. Depending on the object and/or task, he adopted strategies ranging from using voice control or a joystick-driven robotic arm for placing objects in his vicinity. Once reachable, Simon shared that he was very confident in his fine motor skills, having numerous years of experience with joystick controls for wheelchair control and driving: *"Well, I've been driving since I was, um, seven years old, um, with an electric wheelchair with a joystick, and I've been driving my car with a joystick for eleven years. [...] When it comes to fine motor skills, I have no problems whatsoever. My friends have been amazed when we've played Formula 1 racing games, for example."* However, Simon also expressed his frustration with most game controllers, as he *"[...] can't reach the rear buttons, the shoulder buttons, L and R."* For locomotion, Simon uses a highly customized electric wheelchair adapted to his needs, which supports, for example, the attachment of a table and robotic arm, and also serves as a car seat.

VR expectations and previous experience (C1.2): Simon has an interest in VR and had previously tested social VR with friends, using a Meta Quest 2. This experience fell short due to hardware-related access barriers, with Simon explaining that *"In my case, I am not even physically capable of holding the controller. [...] I haven't been able to do much with VR because of this usability issue"*, a concern shared by other people with physical disability when contemplating VR use [41, 60]. Hand tracking did not provide a solution as his hands were either not visible or not recognized correctly by the cameras.

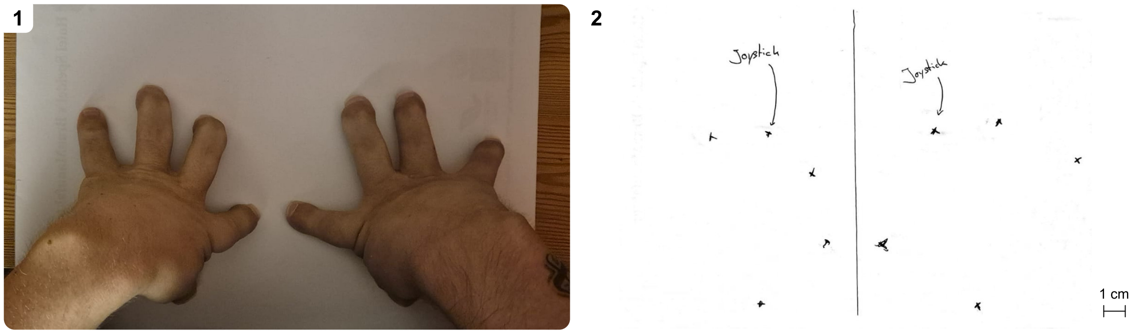

Fig. 5. Button positioning for the gamepad controller of Simon. **1** Simon's hands on a white DIN A4 paper sheet. **2** Scan of the annotated paper. Marked spots locate the natural position of each finger, and arrows indicate the preferred joystick positions.

Individual requirements and preferences for VR (C1.3): Simon highlighted the challenge of holding and operating handheld controllers. Based on his experience with stationary input devices such as PlayStation or Xbox controllers, he expressed his desire to *"[...] use practically all my fingers. Mhm. [...]. That there's a button under practically every finger"*, an approach that would allow close tailoring of the input device to his body. To enable locomotion, he suggested complementing the buttons with a joystick, a mode of interaction well-familiar to him.

After careful consideration of technical constraints of VR, we decided with Simon that the **design goal of this case study** would be to create a stationary controller that could be placed on a tray mounted on his wheelchair.

5.1.2 Concept development. We translated the design goal of creating a *stationary VR controller* Simon into technical requirements, with the main goal being the creation of a bespoke controller layout that would allow Simon to fully utilize all fingers without repositioning his hands. We decided to embed this in a stationary gamepad where the buttons and joysticks were all positioned on a single plane. To facilitate a higher degree of embodiment, head-tracking will be used in addition to controller input to facilitate 3D interaction wherever possible. To create the layout, Simon provided us with photos of his fingers and indications for button and joystick placement aligned with his preference (see Figure 5). Considering different materials, we found 3D-printed plastic to be most suitable, as it would allow us to iterate rapidly. Together with Simon, we decided that for this case study, the goal would be to *ensure that the controller can be integrated into commercially available VR games.* As an intermediate step, we decided to develop concepts of small VR environments where Simon could familiarize himself with the button layout, use his head direction for ray-pointing selection, or observe the controller in VR. For later iterations, Simon expressed his desire to test commercial VR applications.

5.2 First Iteration: Implementation Phase and Feedback Phase

Based on the design concept, we initiated the first iteration of our RtD process, where we created an initial prototype of the gamepad controller and implemented auxiliary VR environments for Simon to explore.

5.2.1 Building the gamepad controller. In the first iteration (see Figure 6.1), we focused on translating Simon's bespoke button layout into a gamepad controller. This included an initial electronics design with buttons and joysticks in a stationary enclosure.

We created the enclosure using CAD and 3D printing and manufactured two parts, a bottom part and a top lid, which could be screwed together. In addition to buttons at the positions marked by Simon, we also added extra buttons along

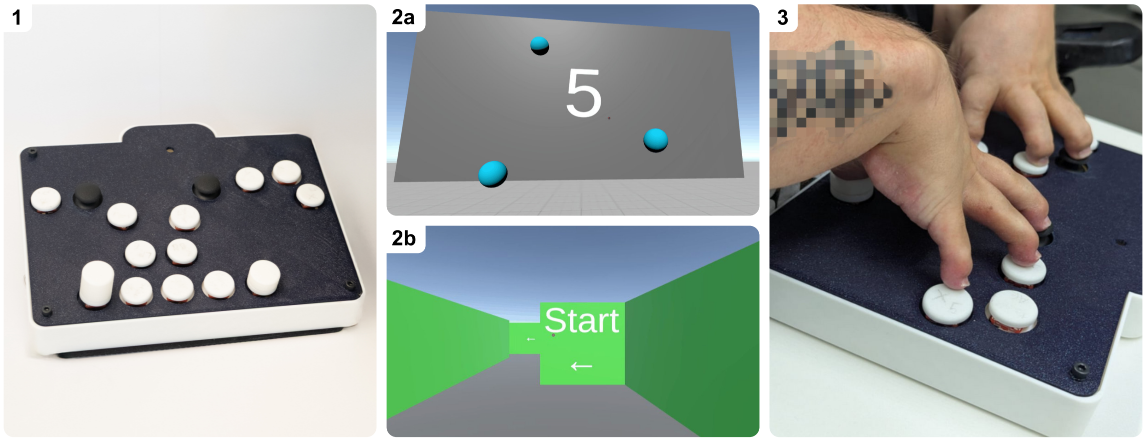

Fig. 6. First iteration of Simon's case study. **1** VR gamepad controller with 13 buttons (white) and two joysticks (black) in a bespoke layout. **2** VR environments for the gamepad controller: **a** Blue balloons must be destroyed by selecting them with a head-based raycast and pressing a button. **b** A labyrinth must be navigated using joystick-based continuous or wheelchair movements, or head-based raycast teleportation locomotion. **3** Simon testing the first iteration of the gamepad controller.

the provided curvatures to incorporate sufficient input possibilities for VR control. All buttons were fixed right below the top cover of the enclosure, and we 3D-printed stackable button caps to allow for adjustments matching Simon's finger heights. The controller had a total of 13 Kailh Low Profile V1 tactile buttons, as well as two KY-023 analog joysticks, which were screwed into the bottom part of the enclosure. Here, we also installed an Arduino Nano 3.3V BLE microcontroller, a 3.7V Lithium-Ion battery, and an Adafruit PowerBoost 500 Charger board for communication and power control. The microcontroller read all button and joystick events by interpreting their respective digital or analog signals in a loop and communicated them to BLE-capable devices by advertising itself as HID.

5.2.2 Creating VR test environments. We created two VR environments in Unity that complement the gamepad controller to test key functionality. The first environment focused on pointing and selecting, featuring a wall with blue balloons spawning in front of it, which had to be destroyed to collect points (see Figure 6.2a). This can be achieved by using a head-based raycast to point at a sphere and clicking a button while remaining stationary. In the second environment that focused on locomotion, players navigate a labyrinth (see Figure 6.2b) using either joystick or wheelchair locomotion, or head-based teleportation.

5.2.3 Exploring the prototype controller and environments with Simon. After concluding the first iteration of the prototype and implementing the auxiliary VR environments, we invited Simon for a feedback session (see Figure 6.3). Here, we were interested in his initial impressions of how well the controller fits his body and wheelchair, as well as how he perceived the experience of interacting with the controller in VR.

Interplay between body and artifact (C2.1): Simon was very satisfied with how the initial prototype fit his body: *"And I put my hand on it and notice, wow, there's a button under every finger. [...] I'm not used [to things directly fitting me]. I think it's really nice when that happens."* While the current button design allowed for small height adjustments, exploration of the artifact revealed that Simon required more variable button cap heights for a few buttons, as well as easier-to-press buttons. In terms of material characteristics, he remarked that the joysticks could provide more grip and suggested a recess, an *"upside-down thimble"*, which would fit his finger tip.

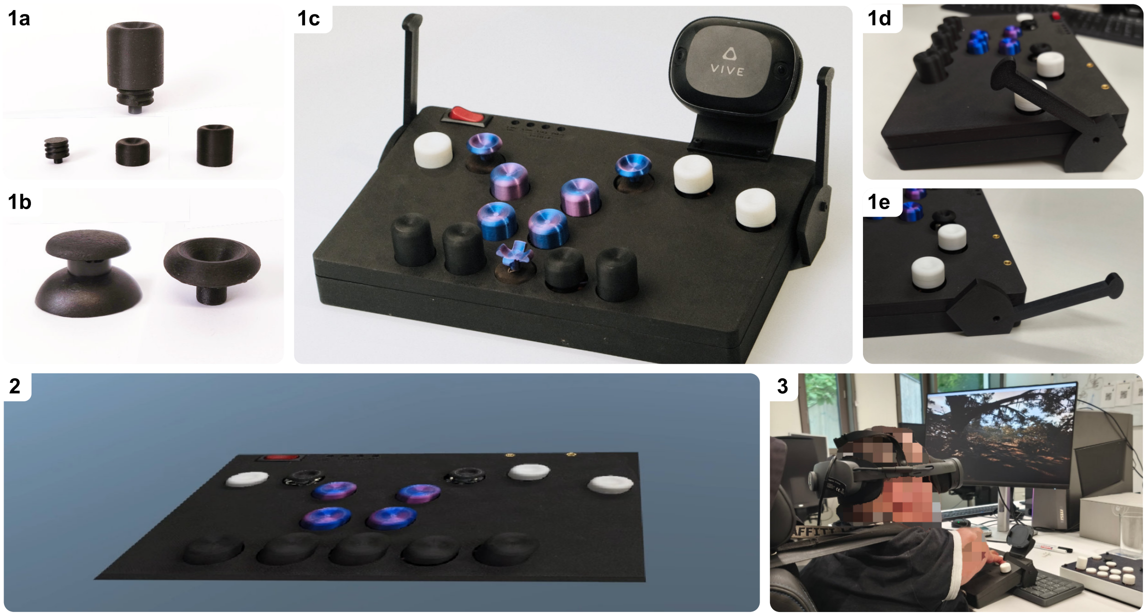

Fig. 7. Second iteration of Simon's case study. **1** VR gamepad controller with new features: **a** Height-adjustable buttons in two sizes with a screwing mechanism. **b** A comparison of old (left) and new (right) joystick caps. **c** VR gampad controller with attached HTC Vive Ultimate Tracker. **d**, **e** Handles can change the controller tilt. **2** Virtal replica of the gamepad as seen in VR based on tracking data of the HTC Vive Ultimate Tracker. **3** Simon playing Resident Evil 7: Biohazard with the second iteration of the gamepad controller.

Considering interaction paradigms within VR, he found the head-based selection methods intuitive, but noted that he *"had to tilt the wheelchair down quite a long way, because otherwise my head... My head couldn't go any further down"*, especially when targeting locations on or near the floor. Likewise, the flat positioning of the controller was not ideal for Simon, suggesting the need for an option to tilt the controller. For locomotion, he enjoyed testing teleporting and steering his wheelchair with one hand while the other continued to play; however, in the end, he preferred joystick-based locomotion due to its simplicity.

Impact on experiential qualities (C2.2): While playing, Simon was primarily focused on the controller, explaining that *"I didn't pay much attention to [how I felt in the virtual world]"*. However, reflecting on his overall experience, Simon found the controller to be a positive influence and suggested tests with commercial games in the next iteration to produce more detailed insights.

5.3 Second Iteration: Implementation Phase and Feedback Phase

Based on Simon's feedback, we revised the gamepad controller and created an additional VR scene in which he could explore the artifact tracked and depicted in VR. Additionally, we prepared the exploration of a commercial VR game.

5.3.1 Adapting the gamepad controller. For the second iteration (see Figure 7.1a - 7.1e), we addressed three main concerns Simon had previously identified. First, we replaced our buttons with Cherry MX2A-81NN keyboard buttons to reduce the force and distance required for button presses. We created an adapter with a screwing mechanism and 3D-printed button caps with two different heights (13 and 23 mm) that could be screwed onto the adapter for height adjustments. Second, we designed new thumbstick caps with a recess in the middle to increase their grip and haptic quality, and added a third thumbstick with directional output (up/down/left/right) for menu navigation. Third, we adapted the enclosure and added handles on the sides that change the controller tilt depending on their position by raising the back 10 or 20 mm. The new enclosure also featured an adapter for an HTC Vive Ultimate Tracker. In this case study, we also switched to an Arduino Nano ESP32 microcontroller to avoid BLE communication issues.

5.3.2 Creating a third test VR environment. We added VR tracking in this iteration by creating an environment in Unity where the controller would be visible in VR based on its real-world location (see Figure 7.2). We used an HTC Vive Ultimate Tracker for tracking and added a visual depiction of the controller, mirroring the real artifact.

5.3.3 Exploring the prototype controller, environment, and Resident Evil 7: Biohazard with Simon. In our second feedback session, Simon explored the new iteration of the gamepad controller, the VR environment showcasing the tracking capabilities, as well as the commercially available game Resident Evil 7: Biohazard[6] (see Figure 7.3), which was made VR accessible by the mod REFramework v1.5.9.1[7] that also allows playing the game without tracked handheld controllers.

Interplay between body and artifact (C2.1): Simon described the interactions with the controller as comfortable, but not yet perfectly matched with his body. The center components worked well, and he found the new joysticks *"[...] definitely much more comfortable with the recess, my fingers no longer slip off."* However, after extended play time, Simon noticed that he would prefer to control the left joystick with another finger, and that pressing the joysticks for interactions was challenging. Here, he proposed the addition of two buttons that could be pressed with the palms of his hands. Simon was very fond of the mechanism for button height adaptation (*"This screwing is really cool, because you can adjust them really precisely"*). Still, for him, it was often *"[...] a matter of millimetres"* that prevented a perfect fit. However, Simon found the maximum controller tilt insufficient, and we had to elevate it further during gameplay. Reflecting on his preferences, he changed his mind about the need for dynamic adaptation: *"Once you've found the right angle, it's actually enough if it's static."* Finally, Simon proposed adding an adhesive material to the corners of the controller to prevent it from slipping.

Impact on experiential qualities (C2.2): Simon enjoyed both the VR environment where he could see the tracked controller (*"It's really crazy!"*) as well using the controller to play Resident Evil 7. He noted being more immersed than in screen-based games, although talking with us while using VR somewhat reduced presence. Likewise, he found that the stationary interactions with the gamepad controller felt as though coming from outside the virtual world in comparison to the imagined experience with handheld controllers: *"I think it's different when you hold the controllers in each hand and actually move your hands. Because my hands stay in one place, it doesn't become so... interactive."* Still, he experienced body ownership in the virtual world, e.g., commenting *"Wow, it's crazy that it feels like I'm walking"*. Here, he also explained that the avatar was him, but with a different body than he is used to in reality: *"The fact that [the avatar] stands on its own, so it's quite high up, was a bit of an adjustment for me, because normally when I'm in my wheelchair, I'm not sitting that high up. So that was quite a change. And just the act of walking was different for me than rolling, which is what I'm used to."* However, he attributed the changes in height and walking mainly to experiencing the game through a VR headset rather than to the controller.

[6]CAPCOM Co., Ltd. (2017): https://store.steampowered.com/app/418370/Resident_Evil_7_Biohazard/
[7]Praydog (2025), https://github.com/praydog/REFramework

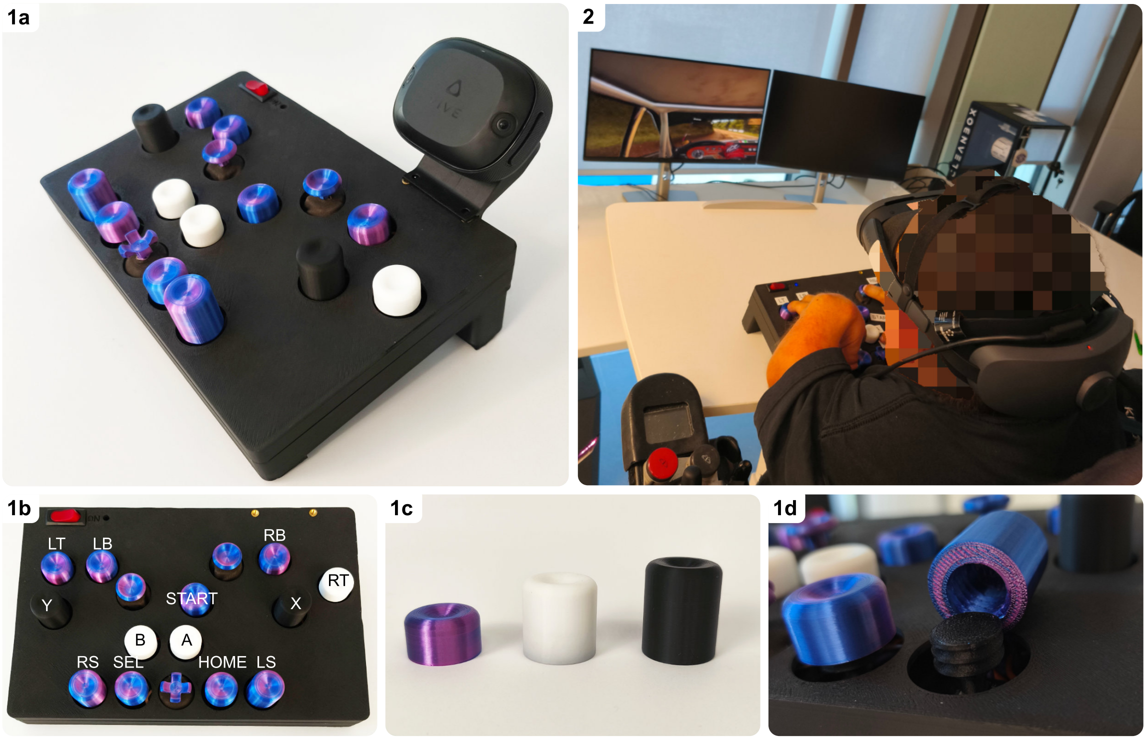

Fig. 8. Final iteration of Simon's case study. **1** The VR gamepad controller for Simon. **a** The controller has a static tilt and an interface for an HTC Vive Ultimate Tracker. **b** Controller layout with button mapping. **c**, **d** Height-adjustable buttons with screwing mechanism in different colors and sizes. **2** Simon playing Dirt Rally 2.0 with the final gamepad controller.

5.4 Final Iteration: Implementation Phase and Feedback Phase

After exploring the second iteration of the gamepad controller with Simon, we adapted the controller based on his feedback and prepared another VR exploration of a different commercial game.

5.4.1 Adapting the gamepad controller. In our final iteration of the gamepad controller (see Figure 8.1a - 8.1d), we addressed the points raised by Simon during the second exploration phase. For this, we swapped the left joystick position with one button, added two new buttons to the gamepad that can be pressed with the palms, and modified the button mapping together with Simon to match the new design. We also 3D-printed a static tilting support based on Simon's preferred tilt angle that can be screwed into place below the controller, and extended the set of screwable button caps with new heights and screw limits. Finally, we added cutouts of an adhesive mat to the corners of the controller to prevent slipping.

5.4.2 Exploring the final controller with Simon. We met again with Simon to assess the impact on the interplay between the controller and the body, as well as his experience with VR. For this, Simon played the VR racing game Dirt Rally 2.0[8] (see Figure 8.2).

[8]Codemasters, Electronic Arts Inc. (2019): https://dirtrally2.dirtgame.com/

Interplay between body and artifact (C2.1): Simon was very fond of the fit between the controller and his body: *"I no longer had to strain myself to reach a button. [...] it was really pleasant because it was really adapted to me. And the [button] heights matched [me], even though, yes, for me it's millimeters that make the difference."* With button functionalities he remapped in-game, he could handle the controller intuitively and noted that he could easily interact with all components. He also appreciated the static tilt and adhesive corners, and was able to rearrange the controller to his liking. Reflecting on the final result, Simon shared that *"I don't know what else needs to be changed at the moment. [...] I'm absolutely thrilled."*

Impact on experiential qualities (C2.2): Playing the racing game was very enjoyable for Simon. Although he was still aware of his environment due to the think-aloud protocol, he experienced presence within the game: *"I definitely feel right now as if I were sitting in the driver's seat of a car."* He attributed this not only to the game, but also to the controller as *"The way it was now set up, my right hand felt as if I were operating an accelerator pedal, only with my right hand."* Additionally, he positively noted that he no longer had to focus on the controller during playing: *"Before, I was very busy with the controller, and that divided my attention between the game and the controller, so to speak. Now that I can operate the controller very comfortably, the game gets more attention and the controller less, which is how it should be."*

Overall, the feedback session with Simon supported the notion that the bespoke gamepad controller was a good fit for his body. Since no future adaptations were necessary, we jointly decided to conclude our RtD process.

5.5 Reflection Phase: Appraisal of the RtD Process

We were able to establish a productive and enjoyable working relationship with Simon, who was a very involved design partner. Reflecting on the RtD process (C3.1), Simon shared that he was impressed with the development work: *"Totally cool. [...] Everything I imagined has been implemented. Even for the smallest millimetre decisions, which play a significant role for me."* In reflection, he highlighted the importance of being able to access bespoke devices and designs, explaining that *"[...] there's nothing off the shelf that you can just buy in a shop. [...] It was just cool to know from the outset that something customized was being designed."*

6 Discussion

In this section, we first answer our research questions. Then, we discuss the relevance of bespoke VR controllers for VR experience and implications for their design. We close with critical reflection on the complexity of VR and scalability of bespoke design in the context of accessibility research.

6.1 RQ1: How can Research through Design be leveraged in a technical accessibility project to tailor VR input devices and interaction paradigms to the bodies of people with physical disability?

The results of our work demonstrate the potential of RtD to support the design of personalized, bespoke VR input devices and interaction paradigms. In particular, the two case studies demonstrate how a bottom-up approach that is rooted in users' preferences and real-world interactions and respects bodily difference can guide VR controller design and result in distinct controller characteristics: While the wearable glove controller developed with Nick highlights the potential of enabling large-scale movement while facilitating propulsion of a manual wheelchair (see Section 4), the gamepad controller developed with Simon revealed the potential of stationary VR controllers that rely upon small-scale movement (see Section 5). Although both Nick and Simon are wheelchair users, they had different individual requirements and preferences for VR use (see Sections 4.1.1 and 5.1.1), which directly impacted the scope of the individual case studies and required us to be flexible in our RtD approaches. For example, when working with Nick, we discovered the need to create a complex VR environment relatively early, as current VR applications lack input flexibility and redundancy [1, 14, 65], which is a barrier to the integration of novel VR hardware [60]. In contrast, we could primarily focus on hardware adaptations to enhance functionality and comfort with Simon, as his preferred type of controller could be integrated into basic custom or commercial, non-motion-based VR environments. As consequence of their personal requirements, we must also acknowledge that the two case studies resulted in two highly personalized artifacts and approaches to VR interaction. While Nick and Simon appreciated how the controllers were tailored to their bodies, this raises the question of the scalability of bespoke design, which we further discuss in Section 6.3. Reflecting on the overall RtD processes, we found it beneficial to engage in and document according to pre-structured phases and analysis schemes, following the recommendations of Bardzell et al. [4] (see also Section 2.2). This allowed us to contextualize and justify design decisions for each artifact based on individual encounters. Furthermore, we observed that the iterative approach left room for testing and careful adaptation required for body-centric technologies. Overall, our research demonstrates the potential of RtD for technical VR accessibility research.

6.2 RQ2: What is the impact of bespoke VR input devices and interaction paradigms on disabled users' access to the experiential qualities of VR, i.e., immersion, presence, and the sense of embodiment?

Our work highlights the immense potential of bespoke design to facilitate access to VR, removing a key barrier repeatedly reported in previous work (see Section 2.1), enabling people with physical disability to engage with VR at the experiential level [60]. Regarding the key constructs of VR experience, our results show that VR controllers that are tailored to disabled users' bodies had positive effects: With respect to immersion, the first case study showed that accurate tailoring of the VR controller to Nick's body and wheelchair gradually reduced friction that resulted from initial collisions between glove controller and wheelchair (see Section 4). In terms of immersion of Simon, the RtD process offered the opportunity to fine-tune the gamepad controller to his body for a comfortable experience (see Section 5). Likewise, there are indications that the controllers and associated interaction paradigms supported the experience of presence. In the case of Nick, the glove controller supported the sense of being part of a basketball match (see Section 4.3.3); for Simon, the controller supported presence particularly in the case of the racing game (see Section 5.4.2). This aligns with prior work on game controllers for non-disabled persons, which has highlighted that a good mapping between input devices, interaction paradigms, and game content contributes to a positive experience [23]. Furthermore, our work demonstrates that the sense of embodiment is closely tied to meeting individual requirements regarding hardware and interaction paradigms, as well as aligning with real-world interactions, which supports the *sense of agency* subcomponent [34] in particular. Here, Nick's interactions with the glove controller within his bespoke VR environment were closely linked with his lived experience as a wheelchair basketball player and matched familiar activities in his peripersonal space (cf. Rizzolatti et al. [49]). Likewise, Simon's interactions with the bespoke gamepad controller utilized his peripersonal space to facilitate interactions that required a comparable degree of physical interaction as his real-world interactions, suggesting that what constitutes successful embodied interaction [13] is in fact highly individual. Finally, we found effects of the *sense of self-location* subcomponent [34], for instance, Simon needed time adjusting to being represented by the main character of Resident Evil: 7 due to a mismatch in camera movement and head direction, camera height, and head shakes when walking (see Section 5.3.3). This suggests that to achieve a sense of embodiment, accessible VR needs to bridge the gap between hardware design, suitable interaction paradigms, and accessible VR avatars (see [2, 67]).

6.3 Moving Beyond the Individual: The Challenge of Achieving Scalable Bespoke VR

A question raised in the context of bespoke design is that of scalability. Although the bottom-up design process recommended to create truly accessible VR [26] was successful and the artifacts are already a situated empowerment for Nick and Simon (cf. Huffman et al. [31]), the question remains how broader groups of people with physical disability can benefit from the approach: For example, we are reasonably optimistic that the concept of the glove controller would be a suitable input device for other manual wheelchair users with minor adjustments. However, in the case of the bespoke gamepad controller, we must acknowledge that extensive effort is required to adapt the controller to other users. A viable strategy would be a tracked modular system in which users can position components to their liking on a build plate, extending current strategies for accessible game control, such as the Xbox Adaptive controller, to a finer scale. However, the question remains whether such solutions can achieve the fine degree of tailoring experienced by our participants. Building on Mankoff et al. [38]'s call to engage Disability Studies as a source for technology design, we turn to Disability Studies for possibilities of achieving scalable bespoke VR. Ravneberg [48] note that the design of (assistive) technologies is an important aspect of shaping selves and self-identities that shouldn't be 'reduced' to a fixed essentialist category of disability, e.g., wheelchair users. This becomes even more relevant in the case of emerging technologies, where expert knowledge is required to craft designs, hardware components may be expensive, and access to production methods (e.g., 3D printing) are not available to broad audiences. This leaves us with the question of how highly individualized solutions can be scaled up without reinforcing inequalities. Beyond accessible co-design methods [21], we argue that this requires justice-oriented, inclusive policy structures [48] and investment in technologies that empower low-effort crafting by end-users with a lower access barrier than current DIY approaches (see also Vandenberghe et al. [56]) to achieve scalability and access while maintaining bespoke customization.

6.4 Implications for the Design of Bespoke VR Input Devices and Interaction Paradigms that Support Experiential Accessibility

Our work has implications for the design of bespoke VR input devices and interaction paradigms, particularly with respect to VR experience of users with physical disability. Here, we summarize key implications for design.

6.4.1 Everyday interactions and people's bodies are a suitable starting point for design.

Implication for design: In order to root bespoke design of VR hardware in disabled users' movement habits and preferences, close attention needs to be paid to users' bodies and their everyday interactions with objects and the environment (e.g., with assistive devices or technologies such as computers). This then offers relevant insights into how to design VR interactions that are accessible and intuitive, which supports the familiarity aspect proposed by Cossovich et al. [10] for the design of accessible input.

Example from our work: One of the first challenges when designing the glove controller for Nick was to consider how he interacted with his wheelchair, specifically which parts of his hand he used to propel himself, as this informed the placement of our components on the gloves (Section 4.1). Similarly, Simon's bespoke button layout, adjustable button heights, and controller tilt were the result of analyzing hand shape and interaction preferences (see Section 5).

6.4.2 Embodiment is highly individual and can be supported by different types of hardware within the peripersonal space.

Implication for design: A sense of embodiment is not necessarily linked with large-scale movement, but with appropriate use of an individual's range of motion, which can be supported by wearable and stationary VR input devices alike. Likewise, the restriction to the peripersonal space supports calls to adopt a broader, more inclusive perspective on what constitutes embodied interactions in technology [54] beyond corporeal standards.

Example from our work: While we designed completely different hardware for Nick and Simon, both noted a sense of embodiment as their devices utilized their peripersonal spaces, e.g., during basketball throws that incorporated large upper-body movements (Nick's case study, see Section 4.3.3), or joystick interactions during Simon's exploration of the racing game (see Section 5.4.2).

6.4.3 Iteration is necessary to reduce friction that negatively impacts VR experience.

Implication for design: Due to the relevance of unobtrusive hardware that seamlessly connects with users bodies' to support sensory immersion (see Section 3.1), it is important to engage in iterative design that gradually adapts VR hardware to users' bodies while continuously probing impact on VR experience.
Example from our work: Only an extended gameplay session in the second iteration revealed the optimal joystick position for Simon's left hand (see Section 5.3.3), and Nick only noticed comfort issues with the microcontroller box after trying out new movements that we had not anticipated during development (Section 4.2.3).

Finally, our work shows that suitability of VR hardware and interaction paradigms are linked with the type and content of VR application, supporting previous findings on VR accessibility [60].

7 Limitations and Future Work

In this section, we consider the limitations of our work and discuss potential avenues for future research. In the context of our research approach, we must note that we employed a qualitative content analysis following Zhang and Wildemuth [68], but used it for encounters with only individual participants. While we saw success with our approach in generating structured evaluations, there may be more suitable analysis methods for RtD accessibility work. We also utilized think-aloud sessions for exploration, which had a negative impact on experiential factors such as presence and immersion for both participants and should not be reconsidered in the future. Reflecting on the conclusion of our case study with Simon, we must acknowledge that the bespoke controller is unable to provide access to all VR experiences. Here, future work should ensure input redundancy [14], as an accessible controller still requires accessible applications. Likewise, we see benefit in including assessments of the peripersonal space into work on accessible VR embodiment. Finally, as previously discussed, there is a potential for future work in exploring VR accessibility with other individuals (e.g., women or non-binary people), and adapting our bespoke results to a broader audience beyond wheelchair use, also addressing other types of mobility disability.

8 Conclusion

VR hardware and interaction paradigms are body-centric and pose access barriers for people with physical disability. In our work, we address this issue through complementary RtD case studies. We designed bespoke versions of unobtrusive VR glove controllers that allow for simultaneous manual wheelchair use, as well as a VR gamepad controller as an alternative to handheld devices for a powered wheelchair user. Our work demonstrates the promise of bespoke design of accessible VR, successfully addressing a key barrier repeatedly reported by VR accessibility research, and enabling the further study of how people with physical disability experience VR. Furthermore, we critically reflect on the scalability of bespoke results in accessibility research, provide implications for the design of bespoke VR input devices and interaction paradigms that support experiential accessibility, and we contribute to the small but growing body of literature that applies RtD to accessibility research.

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