Exploring VR While Lying Down With People With Physical Disability: The Relationship Between Safety, Comfort, and Experience

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Using Virtual Reality (VR) while lying down is an opportunity to increase accessibility. In our work, we explore how people with physical disability perceive and experience VR while lying down. First, we present results from an interview study with 12 participants, contextualizing existing design recommendations from the perspective of disability, showing that upper-body movement needs to be prioritized and that individual preferences regarding interaction are important. Second, we leverage these findings to design *Fruit Fisher*, a VR research game played while lying down, offering adaptable movements and supporting adjustable reclining positions. We conduct an initial expert review of the game with three persons with physical disability that explores how VR while lying down is experienced. Overall, we show that there are unique concerns related to safety and comfort, that movement accessibility varies, but that the overall experience is enjoyable and of interest to persons with physical disability.

CCS Concepts: • **Human-centered computing → Virtual reality**; **Accessibility technologies**.

Additional Key Words and Phrases: Virtual Reality, Accessibility, Lying Down, Disability

ACM Reference Format:
Anonymous Author(s). 2018. Exploring VR While Lying Down With People With Physical Disability: The Relationship Between Safety, Comfort, and Experience. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation email (Conference acronym 'XX)*. ACM, New York, NY, USA, 24 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Virtual Reality VR is a technology that allows people to immerse themselves in virtual worlds. It is typically used in either a standing/walking or sitting position [51]. A more recent interaction type for VR is using it while lying down, which has been highlighted as an opportunity to increase VR accessibility for disabled users [44]. However, existing work has thus far focused on the experiences of non-disabled persons. For example, VR while lying down has been used to relax patients by masking out external stimuli with nature videos [16], to provide pain relief [34], or for the immersive presentation of bedtime stories for children [25]. What unites these works is a strong focus on specific use cases rather than the development of generally applicable interaction paradigms for VR while lying down. Here, research has begun to analyze interaction paradigms and providing general design suggestions [44], which include suggestions like focusing on movements that work well (e.g., arm movements), adjusting movements to the presence of a bed (e.g., leaning), and replacing other movements required for using VR (e.g., ducking). Additionally, efforts have been made to examine locomotion techniques for VR while lying down, such as tapping the feet or rotating a chair in different reclining positions [27], and analyzing the problem that arises from mapping the person lying in the real world to a standing position in the virtual world [28, 29]. While those works address general interaction paradigms and provide insight into key design challenges for VR while lying down, they do not yet reflect perspectives of disabled persons. Here, previous work on VR accessibility has repeatedly highlighted the inaccessibility of general VR interaction paradigms that were not created with disabled users in mind [9, 10], an issue that is particularly pronounced in the case of physical disability [35, 47].

Thus, it is important to contextualize existing work from the perspective of persons with physical disability, critically appraising accessibility of VR while lying down. To address this research gap, we raise the following two research questions (RQs):

- **RQ1: What needs and preferences do people with physical disability have in the context of VR while lying down?**
- **RQ2: How can we design VR while lying down in a way that is accessible and enjoyable for people with physical disability?**

To answer these research questions, we engaged in a two-step research process that combined qualitative research approaches with the design and implementation of *Fruit Fisher*, an accessible VR game designed to be used while lying down. First, we carried out a semi-structured interview study that involved 12 persons with physical disability and explored perspectives on VR while lying down on the basis of Van Gemert et al. [44]'s qualitative exploration thereof. Through Qualitative Content Analysis (QCA) [50], our results highlight the need to focus on upper-body movement while allowing for diverse lying down positions (e.g., making the degree to which a person reclines adjustable). Second, we leverage key findings to develop *Fruit Fisher*, a VR fishing game that showcases key elements of VR while lying down using arm movements and small head rotations, and enabling users to adjust the reclining angle and change position during gameplay. We critically appraise *Fruit Fisher* through an initial review with three experts with different types of physical disability and previous VR experience. Results underscore the relevance of movement adaptation and adjustment of reclining position, while also highlighting the relevance of a safe physical environment when engaging with VR while lying down.

Our work makes the following main contributions: (1) We provide an empirical exploration of how people with physical disability perceive and experience VR, highlighting their needs and preferences regarding movements and lying positions, as well as the environment in which VR while lying down is used. (2) We contribute guidelines for the design of accessible VR while lying down, which are appraised through a design case study and an expert review. (3) We critically reflect on similarities and differences between our findings and Van Gemert et al. [44]'s study addressing non-disabled persons, and outline avenues for future work aiming to make VR while lying down accessible.

2 Positionality

While positionality is associated with limitations [15], we want to share information that we are comfortable with. We are a team of researchers with no physical disability with backgrounds in computer science, engineering, and psychology. The first author is a white man in his 20s and does not have a disability. He carried out data collection, the development of the research tool, and data analysis. We have comprehensive experience in VR research for disabled users, and we believe that engaging immersive experiences should be accessible for everyone.

3 Related Work

First, we discuss previous research that explored VR for use while lying down. Then, we summarize research addressing VR accessibility for people with physical disability.

3.1 Designing VR for Use While Lying Down

Here, we present systems and technologies for VR while lying down, and we give an overview of specific interaction techniques.

3.1.1 Systems and Technologies for VR While Lying Down. A significant body of research is centered on exploring specific VR use cases that either benefit from or require the user to lie down. These works are united by a strong focus on specific applications rather than on developing generally applicable interaction paradigms for VR while lying down. For example, Brown et al. [5] applied VR while lying down to enable an experience of a being buried, placing the participant into a coffin while lying down flat. However, the authors do not explore effects of using VR while lying down as such. A different perspective comes from Gerber et al. [16] who used the immersive properties of VR to mask out external stimuli such as light or noise with nature videos in a clinical environment, which resulted in a relaxing effect by observing reduced physical stress. In contrast to other case studies using standard VR, Kwon et al. [25] combined a head-mounted display (HMD) with a pillow to explore immersive bedtime stories for children, using restricted inputs only, such as looking to the side or pressing the head in the pillow. This shows how VR while lying down might require different interaction and hardware compared to standing or sitting. What unites these case studies is that they all used only very limited movements, mainly employing small rotations of the head, and not looking at more extensive upper-body movement or forms of locomotion necessary for VR usage in other settings such as games [44].

The idea that VR while lying down is only applicable to very specific use cases is also reflected in research and industry efforts addressing the use case more widely. Koeshandika et al. [23] argue that the suitability of an application for use in a lying position is determined by its complexity, such as the field of interaction, as for example the limited field of interaction (the lack of locomotion in their study) of Beat Saber [2] makes it suitable even though it has a fast-paced gameplay with a lot of interactions. Likewise, guidance for the Meta Quest 3 [39], which implemented a lying down feature, specified that it is intended for *"low intensity experiences that don't require a lot of movement"* [26]. While both perspectives narrow down the potential use cases for VR, they contradict each other in their interpretation of what is a low complexity application, i.e., whether movement intensity should be considered, and how broad the input alphabet of an application should be. In the context of accessibility research, this is an important aspect to be considered as disabled users wish to engage with the same applications as non-disabled persons (e.g., in the context of games [6]), and VR while lying down for this audience therefore needs to support applications of sufficient complexity.

3.1.2 Interaction Techniques for VR While Lying Down. Recently, research started analyzing interaction techniques of VR while lying down. Van Gemert et al. [44] explored VR while lying down on a bed from the perspective of non-disabled people through a think-aloud of popular VR games to lying down and successive semi-structured interviews with 14 participants. Their results summarize the movements the participants performed while lying down and list explicit design suggestions that are focused on movements and experiences when using VR while lying down [44]. The authors discovered that movements that would otherwise be intuitive in VR required adjustments or alternatives. For example, participants had to perform a sit-up to crouch in the virtual world, and they were restricted from turning their heads due to a pillow. Van Gemert et al. [44] also analyzed participants' experience, and highlight that comfort is central to VR while lying down, and that one should keep the illusion of standing up in the virtual world, even when not standing in the real world. While they motivate their work with accessibility benefits (e.g., they highlight *bed-bound users* [sic] as one of four use cases), they did not involve participants with physical disability [44]. Among other avenues for future work, Van Gemert et al. [44] suggest to use hip and foot movement for locomotion. This direction of research seems to have been taken up by several subsequent VR studies while lying down, exploring locomotion techniques such as calf tilting, crossing the legs or foot friction [27], or interactions similar to bicycle crunches [24]. However, it may be associated with accessibility concerns for persons with mobility disability [35].

Researchers started comparing VR while lying down to sitting in different reclining positions. Luo et al. [29] analyzed concepts such as body ownership, presence, and simulator sickness, showing that a 45° reclining angle performed worse than lying flat (90°) and that sitting up (0°) performed best. Prior paper show that remapping techniques are essential for VR while lying down, such as the remapping of lying down in the real world to standing in the virtual world [29, 44]. Further remapping techniques could be needed for accessible VR while lying down, to account for the design recommendations, as remapping techniques can improve user interaction and their experiences [28]. For example, issues such as the limited sideways rotation of the the head while lying down [44] might be compensable with head-turning redirection [28, 48]. However, remapping techniques disrupt sensory integration, which results in higher cognitive load for the user [28].

3.2 VR Accessibility for People With Physical Disability

VR often depends on the user's physical movement, such as turning the head when looking around, holding, pointing and pressing buttons on controllers, or walking when using VR standing, reducing accessibility for people with physical disability [17]. Examples of access barriers include standardized controllers, which often require users to hold them in both hands, or the required muscle strength to perform certain movements to interact with VR, making it inherently inaccessible to some people with disabilities [19]. Addressing VR accessibility on a general level, Yin et al. [49] conducted a survey with people with disabilities which indicates that the majority (three quarters) of participants have encountered barriers to enjoyment when using immersive technologies. Furthermore, Creed et al. [9] analyzed various barriers in immersive technologies, including VR. They collated barriers to physical movement, including usability issues when there are involuntary limb or eye movements, challenges in wearing the devices when the user has limited mobility, or discrimination due to disability. These findings are echoed in a literature by Dudley et al. [10]. Specifically addressing physical disability, Mott et al. [35] identified seven barriers to VR explicitly for people with limited mobility, including setting up a VR system or inaccessible controller buttons. Likewise, Wolf et al. [47] explored the accessibility of VR for physically disabled users on the physical, digital, and experiential levels. Their findings include the influence of temporal factors, such as fatigue, on accessibility and the influence of safety and comfort on presence and immersion [47]. Another example which explores the experience of VR for people with mobility disability is Franz et al. [13], who analyzed different locomotion techniques for people with upper body disabilities, demonstrating the accessibility of various techniques while also emphasizing the importance of user enjoyment, as users sometimes preferred movements that were less accessible but more enjoyable. Also, Gerling et al. [17] researched the accessibility of VR gaming for wheelchair users and demonstrated that VR is often designed without considering people with disabilities. They emphasize the need for flexible control schemes and designs that focus on the individual engaging with VR, but also that it extends to the representation within VR [17]. This further highlights multifaceted nature of VR for people with mobility disability. It includes not only access to interaction, but also takes experience into account.

4 Step 1: An Interview Study to Explore Perspectives of People With Physical Disability on VR While Lying Down

In the first part of our work, we carried out semi-structured interviews to understand the needs and preferences of people with physical disability regarding VR while lying down, and to explore how existing interaction paradigms and recommendations would need to be adapted.

4.1 Methodology

Our interview guide was structured into two parts and involved showing video material and images depicting the use of VR while lying down.

The **introductory part** of the interview covered demographic information including information on participants' type of physical disability to be able to contextualize their perspectives on VR while lying down. Additionally, participants were shown a short video of VR to introduce those not already familiar with VR to the technology.

The **main part of the interview** focused on general perspectives on using VR while lying down, current approaches to it, experiences with it, and the accessibility of movements. As an ice breaker, we engaged in a drawing activity [18, 37] in which participants were asked to describe themselves using VR while lying down, with us creating drawings based on their descriptions for further exploration. Throughout the process, we inquired how participants' bodies would feel in different positions, and which movements they envisioned to be comfortable and accessible, e.g., *"Which parts of your body do you feel are restricted by your position / you can use well in this position?"*. Afterwards, the interview guide covered participants' perspectives on specific movements, e.g., arm movements, head movements, torso movements, or leg movements, which were shown to participants on the basis of visuals provided by related work (see Figure 1). Questions on the different kinds of movements addressed interest in and ability to perform them, and potential adjustments. Overall, this part of the interview guide was developed around existing recommendations regarding movements and overall design of VR while lying down by Van Gemert et al. [44], who explored the topic with non-disabled people. Additionally, it addressed specific VR applications that participants would like to engage with while lying down, with questions such as *"If you were to use VR while lying down, what would your ideal experiences be?"*. To address other facets of experience, we explored questions around representation, i.e., whether the avatar in the virtual world should stand or lie down, and whether information on the users' position should be shared, e.g., *"What would you think about adjusting the game so that when you play lying down, the game adjusts as well?"*. The full interview guide as well as the video introducing VR are included as part of the Supplementary Material.

4.2 Participants and Procedure

Twelve people with physical disability (six men and six women, no non-binary persons) participated in the interview study. Participants were between 21 and 26 years old (μ = 24.67, σ = 1.74), and resided in Europe. All but one participant had previously tried VR while lying down, while the remaining person (P5) had experience with AR technology. Many noted using VR for entertainment or to engage with otherwise inaccessible experiences. The participants disclosed various types of physical disabilities, e.g., paralysis in one leg, leg amputation, paraplegia, or conditions such as Cerebral Palsy that affect mobility. Many participants reported engaging in some degree of exercise (n=10), e.g., strength training. Participants reported varying amounts of time spent lying down, either in bed or on the couch. Some reported lying down mainly for sleep or short periods, while most reported lying down for significant periods or most of the day.

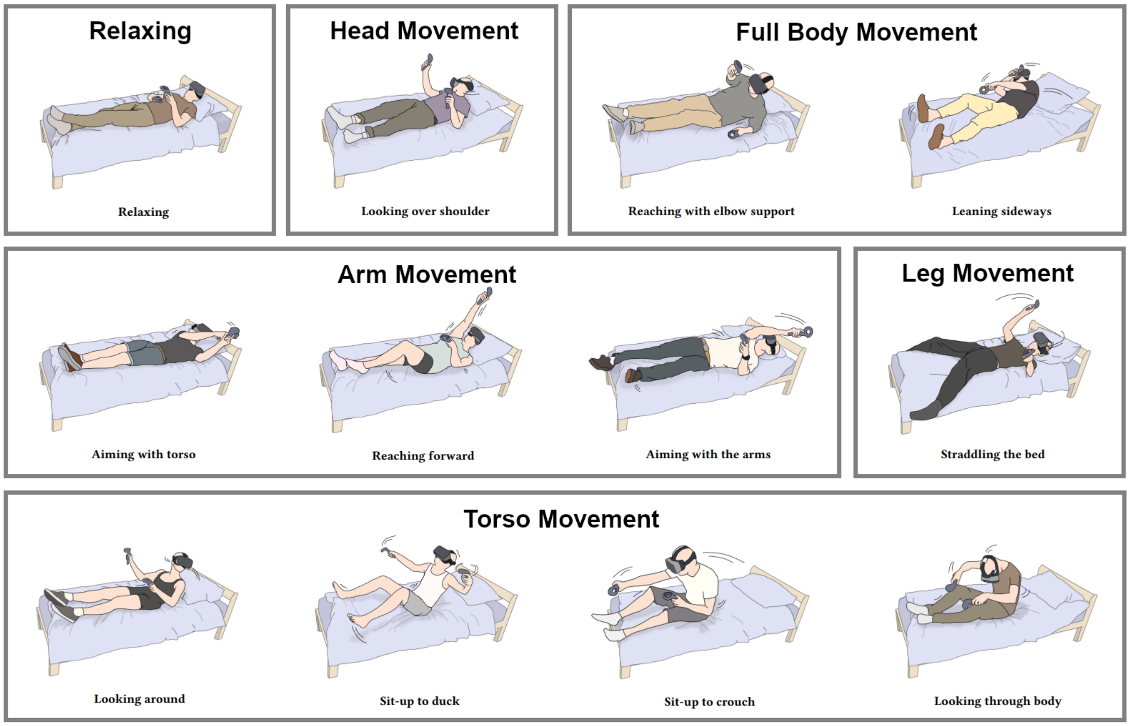


Fig. 1. Overview of our movement groups. Modified from Figure 7 included in the paper of Van Gemert et al. [44].

We recruited participants via social media, leaflets, and word-of-mouth, with recruitment continuing until we observed saturation in data [31]. Participants were given the choice of participating in person or remotely, with all participants opting for remote participation. At the beginning of the interview, participants were provided with information of the study, given room to ask questions, and provided informed consent. Afterwards, audio recording was started and the interview began (see Section 4.1), which included showing participants the short video to introduce VR as well as the drawing activity. At the end of the study, participants were thanked for their time, and given additional room to ask questions about the research. The study was approved by the <removed for review> ethics committee. Participants received a compensation of 20€.

4.3 Data Analysis

Transcripts of audio recordings were created using Buzz [45] with subsequent manual corrections. Afterwards, we analyzed the data using Qualitative Content Analysis (QCA) Zhang and Wildemuth [50]. This is a qualitative approach which requires the creation of a coding scheme within the research team, which is then applied by a single coder who engages in interpretation.

We deductively developed the initial coding scheme in line with our first research question, *RQ1: What needs and preferences do people with physical disability have in the context of VR while lying down?* To operationalize key constructs, we built on outcomes of prior work on VR while lying down (see Section 3.1) as well as VR accessibility (see Section 3.2). Our categories encompassed *Safety & Comfort*, *Usability*, and *Experience*. The coding scheme was subsequently

	Category	Definition	Examples
Safety & Comfort	*Safety*	Refers to physical or psychological safety concerns and risks.	*"So some games are somehow scary and so I have some people with me to direct me to see in case I move toward where I may fall down or I may injure myself" (P2).*
	Pain & Simulation Sickness	Refers to experiencing physical pain or simulation sickness.	*"Because you're bending to that position. I feel it's going to stress me. Bending like that"* (P8).
	Comfort	Refers to the feeling of physical comfort.	*"It is more helpful because lying down is more relaxed and compared to sitting down"* (P10).
Usability	*Effectiveness*	Refers to the *"accuracy and completeness with which users achieve specified goals"* [12]. This includes the ability to perform movements.	*"No, I'm not able to perform this. [...] The legs are completely off the bed. And they are far apart"* (P3).
	Efficiency	Refers to the *"resources used in relation to the results achieved"* [12].	*"When I'm sitting down, [...] It's more like a muscle reflex. You know, I can turn at any point, but actually lying down and doing this, it's more... Sometimes it's very difficult for me"* (P7).
	Satisfaction	Refers to the *"extent to which the user's physical, cognitive and emotional responses that result from the use of a system, product or service meet the user's needs and expectations"* [12].	*"Because it's what I, I love doing. I feel okay" (P2).*
Experience	*Immersion*	Refers to sensory immersion, which objectively describes the sensory characteristics of the VR system [42].	*"And then it also requires some little movement whereby based on what I'm visualizing on the headset. I can move my body in reaction to what I'm seeing"* (P9).
	Presence	Refers to "the subjective experience of being in one place or environment, even when one is physically situated in another" [46].	*"And it feels like I'm in that environment"* (P9).
	Embodiment	Refers to the sense of self-location, sense of agency and sense of body ownership [22]. This includes the perspective of horizon [44].	*"It was like in festivals, meetings and things like that. I think standing would be the most appropriate. So meetings, sitting might be appropriate"* (P1).

Table 1. Coding scheme for the QCA with categories aligned to safety & comfort, usability, and experience.

applied to a first subset of transcripts by the first author, after which results were discussed in the research team and small adjustments were made. Afterwards, the final coding scheme (see Table 1) was applied to all transcripts. Please note that QCA following Zhang and Wildemuth [50] does not recommend calculation of inter-coder reliability, and instead resolves ambiguity through discussion within the research team.

4.4 Results

In this section, we give an overview of the themes that we crafted, focusing on Safety & Comfort (Section 4.4.1), Usability (Section 4.4.2), and Experience (Section 4.4.3).

4.4.1 Safety & Comfort. Our results show that safety and comfort are of central importance for people with physical disability when using VR while lying down, providing the foundation for any other experience that may emerge from interaction.

Safety concerns related to participants' real-world surroundings while interacting with VR, the movements carried out within VR, and the effects of experiences made in VR. Considering the surroundings in which interaction with VR takes place, participants were concerned that interacting with VR might cause them to fall off the bed, as P5 expressed when discussing full-body movements *"I think for me to perform that movement, I might need a lot of pillows to support my sides [...]. Because if I tip over or fall off the bed, I can't stand up on my own."* Another person reflected on physical safety and space available in their home, concluding that they would *"[feel safe] if I have, you know, enough space above my head"* (P7). Concerns also extended to the environment having a potentially soothing impact that was blocked by VR hardware, with P1 commenting that *"I think there's usually an ambient sound, not a noisy one, but one that gives me rest. It gives me peace [...]"*. Despite these concerns, we note that many participants considered lying down to be a safe way of engaging with the technology, offering advantages over other ways of using VR. Here, P7 explicitly mentioned that they experienced fewer physical safety concerns when lying down, explaining that *"[Lying] down [...] causes less strain to my spine"*. Additionally, certain movements associated with VR use were a safety concern as immersion in the technology can encourage unsafe movements. For example, P6 explained how engaging in movements in VR is more dangerous for them even when lying down as they might perform movements that could cause injury, explaining that *"Like when you're not in a good position and you try to play these games, it affects the body parts [...] while trying to move yourself or to, you know, to defeat the enemy, it may affect your body, leading to some pains and some damages in your body"*. Finally, being visible to others as a VR user who is lying down was considered a safety concern as participants considered this information to be private, and did not want to disclose it freely, e.g., *"But I'll not just go and tell that, okay, I'm lying down or I'm disabled or I'm paralyzed. No, I just feel to cover my identity up."* (P6). Likewise, P4 highlighted the psychological risk of stigma, stating that *"[They] might see me as a weak person. [...] I don't want others to see me lying down while playing"*.

Closely related to the issue of safety and resulting from ongoing VR interaction, **pain was a prominent aspect in our data in relation to movements that needed to be carried out, while simulator sickness was not a concern**. Here, participants shared that certain positions and movements can cause pain, and that lying down can be a way of managing these aspects. For example, P2 explained that certain movements *"may lead to disconnection with my joint"*, and P5 stated that *"my upper body is kind of messed up due to the injury I have"*, highlighting that abrupt upper-body movement might lead to pain. This was echoed by P8, who explained in relation to the *looking through the body* movement [44] *"Because you're bending to that position. I feel it's going to stress me."*, and P7 who stated that *"I think I don't really like the idea of, you know, leaning on an elbow. So I would avoid that just to avoid muscle strains."* Here, we want to note that our data shows that which movements are unsuitable is highly individual. Finally, there was a concern that excessive movement would become painful over time, with P9 stating that *"[Too] much movement can lead to pain in my side"*. As a mitigation strategy, P5 made sure to *"take [their] time and process things and move it at the appropriate time"*. Likewise, the use of VR while lying down was seen as an opportunity to manage pain and fatigue, and was a strategy already employed by participants when playing regular games: *"I get tired of sitting. So I prefer lie* *down to engage with this particular game. So I feel...I feel I'm okay. When sitting, I get tired so quick."* Within this theme, participants expressed no exceptional concern regarding simulator sickness, however, we want to note that this was a prospective study, and not all participants may have been aware of the effects of remapping the view to standing in the virtual world (Section 3.1.2).

Being comfortable while lying down, and physical comfort being supported by the VR system was highly relevant for participants, but an experience that required exploration. Here, P4 highlighted the benefit of lying down for comfort, pointing out that *"I don't really sit a lot because I easily get tired while sitting down on my either on my chair or on my bed because I get tired easily because of my disability so I usually like them to get comfortable and also to ease my [chronic] pain too."* Reflecting on the experience of using VR while lying down, P1 recalled that *"The first time I tried it, it was totally uncomfortable, but the more times I tried it, I think I adapted quite fast."* P10 - who had also used VR while lying down before - explained how they enjoyed feeling more relaxed: *"It is more helpful because lying down is more relaxed and compared to sitting down and you being able to also perform these task you can perform while sitting down, while lying down is amazing."* In contrast, P5 noted that VR while lying down *"[...] wasn't as comfortable, I thought it would be."* For P3, this was related to the lying position, pointing out that *"I think it's more comfortable when my back is flat on the bed and not too twisted."* Here, we want to note that our data suggest that lying positions are personal and need to be adapted to each individual. Likewise, participants expressed a need to adapt their position throughout use to remain comfortable. For example, P12 suggested that *"Maybe, when I have stayed in that, my preferred position for a very long time and I want to adjust. Maybe I could just lie on my side."* Beyond lying position, comfort was also linked with the individual suitability of movements. For example, P1 stated that *"[An] ideal game where legs are not really used would be comfortable to me."*

4.4.2 Usability. The results of our study suggest that certain aspects of VR while lying down were considered more usable than others, with a core set of movements (see Table 2) that most participants in our sample expected to be able to apply effectively and efficiently.

In terms of movement effectiveness or whether participants assumed that they would be able to execute movements to interact with VR while lying down, there was a strong emphasis on upper-body movement. In particular, hand and arm movements were favored by many participants, e.g., P10 pointing out that *"I could use my upper body parts well, like my arms, my torso, my head, my neck"* while considering related movements suitable. This was echoed by many of the participants, for example, *"My arms can literally be doing anything. Going up, going down."* (P1), or *"My head is not restricted. It's moving around"* (P6). Here, we want to note that head movement needs to be applied with care particularly in the case of some disabilities like cerebral palsy. For example, P8 shared that they had restrictions in their neck: *"My neck area I feel like yeah restricted."* In this context, we want to highlight the general need to adapt upper-body movements to individual range of motion, as they might otherwise not be accessible: *"Oh, I will not be getting up to this point. I will be lower. Trying to attempt to get myself into this position, will go a long way in harming my body."* (P6). Likewise, nuance needs to be applied in the case of full-body movement. While of general interest to participants, some noted that they *"[...] can perform it, but I would want something to be at my back to relax the back"* (P11), highlighting the need for additional support to be able to engage in such movements effectively. In contrast, lower-body movement was considered ineffective by many participants due to accessibility concerns. For example, P3 commented on *straddling the bed* with their legs (also see [44] page 9), explaining that *"No, I'm not able to perform this. [...] The legs are completely off the bed. And they are far apart."* Here, we note that depending on the type of disability, some participants would not be able to engage in lower-body movement at all, while other participants who were able to move their legs preferred to apply lower-body movement to stabilize their body, improving engagement with upper-body movement rather than applying the legs as a distinct opportunity for input: *"I don't think I have to use my leg that much. I just need some basic things stabilizing myself and stuff."* (P5). Finally, the specific lying position impacted efficiency. All participants preferred either lying flat or in a reclining position compared to lying on the side or on their stomach.

Efficiency of movements was highly individual, linked with lying position, and affected by temporal aspects. Participants expressed that movement can be more difficult and less intuitive when using VR while lying down. In particular, participants reported that their disability could make movement more challenging. For example, P2 mentioned having to mitigate imbalance caused by their missing leg: *"Yeah, somehow restricted because [...] the other one is not there. So it's not well coordinated."* Likewise, P7 reported experiencing difficulties: *"When I'm sitting down, [...] It's more like a muscle reflex. You know, I can turn at any point, but actually lying down and doing this, it's more... Sometimes it's very difficult for me."* This was linked with the impact of lying down position on movement efficiency. For example, P1 reported that changing into a sitting position was easier when starting in a reclining position: *"Lifting might also require more energy, but sitting up is as if I'm already in the sat position."* Some participants commented that props like pillows could be used to improve efficiency. Finally, many participants pointed out that they expected movement efficiency to change over time. For example, P4 explained that *"To make things easy for me I will prefer half stretch because once I fully stretch I can easily get tired so I actually prefer a half stretch so I don't really stress my hand like that okay."*, which is related to reductions in comfort during prolonged interaction that we discuss in Section 4.4.1.

Finally, we want to note that **some participants made a link between using VR while lying down and being satisfied with interactions**. For example, P4 explained their preference for interaction while reclining or lying down, *"Because one of the advantage while using it while lying down I think is more satisfying to me [...] and more comfortable to me."* In contrast, other participants reflected on restrictions on movement introduced by lying down, with P8 commenting that *"[The] only challenge I get is that it kind of limits my movements, you know. [...] And then sometimes finding the right position can be a little bit difficult"*, highlighting the interplay between the different aspects of using VR while lying down. Likewise, P4 stated that *"you can't really get the most out of it while lying down because you are not using virtually all parts of your body"*, raising the challenge of integrating a sufficient amount of movements to provide an engaging experience, which we discuss in more detail in the following section.

4.4.3 Experience. Our data highlight the relevance of experience and the need to contextualize it from the perspective of people with mobility disability when using VR while lying down. Overall, we observe a strong link between considerations of safety and comfort (see Section 4.4.1) as a basis from which experience can emerge.

In terms of **sensory immersion in the virtual world**, we note participants' safety concerns as a result of a reduced connection with the real world. At the same time, some participants expressed worry that using VR while lying down would have negative implications for their ability to achieve immersion on a basic level because of interference with hardware. Here, P6 pointed out that *"[...] your face is fully covered by the headset. So moving your neck around makes the device, the headset, hit or the headset may remove from your face."* However, this experience was not shared by all participants, e.g., *"[...] my devices are actually working well"* (P2).

Despite these issues, **many participants reported a sense of presence while using VR while lying down**. For example, P9 commented that *"[...] it feels like I'm in that environment"*, and P12 described the feeling of being in a different world: *"It makes you, you know, to experience a different world altogether, yes. It's just like being here and you are in another place."* Here, we note that some participants considered a match between real-world lying position and avatar position in VR beneficial for presence, e.g., P10 explaining that *"This is because it makes it more real."* Yet, this may create a conflict with the affordances of the VR environment, with P1 commenting that *"It was like in festivals, meetings and things like that. I think standing would be the most appropriate. So meetings, sitting might be appropriate. But when it comes to probably just talking, connecting with a friend, I think lying down would be fine."* Thus, there exists a tension between supporting the sense of being in the virtual environment by matching the virtual position with the real-world position, while at the same time ensuring that a realistic experience is maintained in the virtual world.

This was linked with detailed **reflections on the implications of user embodiment in VR while lying down**. Here, participants strongly emphasized their desire to have agency in the virtual world, pointing out that neither their lying down position nor their avatar and available interaction paradigms should limit their ability to engage with the virtual world. For example, P4 explained that *"[...] if my virtual character is kind of lying down, it won't actually perform what I actually want the character to perform. So that's a no. So lying down will not actually do what I actually want."* This was echoed by other participants, who valued VR and games for the sake of escapism. For example, P7 commented that *"[Physically] I am disabled, but while playing these games, it just makes me feel like I am whole. I am whole. You know, I am a whole new person and I can actually use all these features that I couldn't use"*, and P3 highlighted that *"I guess it's better for me to, you know ... virtually imagine myself walking or standing up. Things I can't do in real."*, echoing previous findings on VR for people with mobility disability [47].

4.5 Initial Recommendations for the Design of VR While Lying Down for People With Physical Disability

Leveraging the interview findings, we revisited key themes in our data, while addressing similarities and differences in perspectives on VR while lying down in our data and previous work. On this basis, we compiled three initial recommendations for VR while lying down for people with physical disability.

4.5.1 Recommendation 1: Use movements that are appropriate for VR while lying down. Forcing disabled users to perform uncomfortable movements can lead to harm to their body (see Section 4.4.1). While specific movements that can be performed while lying down vary from person to person, there were some movements that were considered generally accessible (see Section 4.4.2). In particular, VR while lying down should focus on comfortable arm and small head movements. Designers need to be aware that some users might be able to use lower body movements only for stabilizing their own body, or not at all, and that movements that require use of the entire body can cause strain for specific groups of people with physical disability, rendering a share of movements suggested for non-disabled persons [44] inaccessible. Thus, **we recommend that VR applications designed for usage while lying down should be mindful of the core set of movements that is comfortable for a large group of people with physical disability** (see Section 4.4.2), incorporating other movements in an optional way or giving users the possibility to replace or adapt inaccessible movements when first entering VR.

4.5.2 Recommendation 2: Allow users to dynamically adjust movements and lying position during interaction. A central theme in our work was the connection between movement accessibility and lying position, with switching between different positions being highly relevant for users with physical disability (see Section 4.4.2). Here, we observed a range of preferences for lying positions, as well as the desire to adapt them throughout, e.g., to return to a more relaxing resting position (see Section 4.4.1). Likewise, for persons with fluctuating physical abilities or who experienced fatigue, general movement adaptation was perceived as a means of increasing accessibility (see 4.4.2). Therefore, **we recommend that VR while lying down for people with physical disability supports adaptation of movements and lying position**. Designers should offer real-time adaptation of range of motion and movement intensity for certain

Movement Group	Evaluation
Relaxing	Most participants considered relaxing, i.e., lying down without moving much and resting body parts, to be accessible and comfortable. Some participants noted the need for adjustments, e.g., not crossing the legs or going into a more reclining position.
Head movements	Most participants were able to perform head movements, but only wanted to carry out small rotations and doing so at low frequency. Some participants were concerned about discomfort potential strain.
Arm movements	Many participants reported being able to perform simple arm movements such as reaching. However, several participants noted not being able to engage in movement that extended to the torso, e.g., involving lifting or angling. Some people may only be able to move one arm well; persons with tetraplegia will not be able to engage in arm movements at all.
Torso movements	Many participants reported that intense torso movements, such as sit-up to duck and looking through body, were inaccessible to them. For people who would be able to engage in the movements, there was a need for adaptation, e.g., to reduce intensity.
Full-body movements	Full-body movements were not considered accessible. Reasons included the intense pressure that these movements puts on certain body parts for those participants who would be able to perform them.
Leg movements	Leg movements were associated with accessibility concerns, with many participants not being able to engage them, or not preferring to move their legs due to discomfort. Participants that were interested in leg movements would need adaptations, e.g., only using one leg, or not performing such movements for a long period.

Table 2. The evaluation of the movement groups introduced in Section 4.1

movements to accommodate fluctuating user abilities (e.g., movement amplification [8, 48]), or support alternative interaction paradigms. Likewise, VR systems should allow users to change their body position throughout interaction, which requires functionality to adapt how user input is translated in VR.

4.5.3 Recommendation 3: Do not automatically match the position of the virtual body to the position of the real body. Although lying down in the real world, some participants preferred to be represented by a standing avatar and interact with the virtual world as though they were standing up, with a smaller number of persons wanting to lie down in the real world and in VR (see Section 4.4.3). Likewise, lying down was perceived as a personal, vulnerable real-world state given that interacting while standing up was perceived as the norm (see Section 4.4.3), which has implications for user privacy, such as when communicating this information to other users (see Section 4.4.1). Given that a lying state of the avatar may have implications for interactions in the virtual world, **we recommend to be intentional about whether the avatar position is matched with users' real-world position in the virtual world**. This applies to the first-person view, where not all users may wish to see themselves and interact in a way reflective of lying down. Likewise, to protect privacy, sharing real-world user position via avatar position should not be a default setting in multi-user VR.

5 Step 2: Design of Fruit Fisher - A Research Game to Study VR While Lying Down

In this section, we present *Fruit Fisher*, a VR fishing game that we created to further validate our recommendations for design and explore how people with physical disability access and experience VR while lying down using this research game. Additionally, we present an expert review of the game.

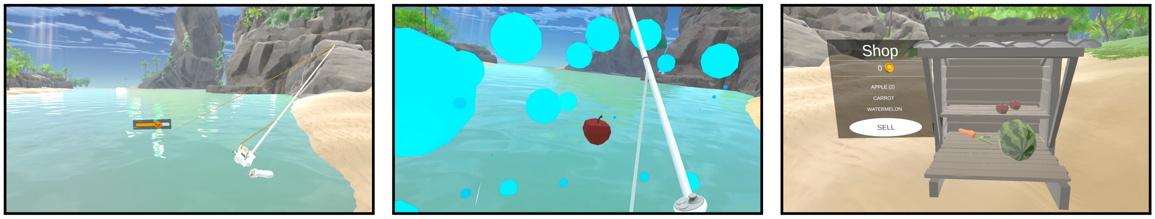
5.1 Design Rationale

The goal of our design process was the creation of an accessible VR research prototype to study how people with physical disability experience VR while lying down.

Given that many participants in Step 1 expressed their desire to use VR while lying down for gaming (see Section 4.2), we opted to implement a VR game as research prototype. After discussion within the research team, we decided on a fishing game because the genre facilitates slow-paced gameplay and allows for meaningful interaction with a relatively small input alphabet. Likewise, fishing games represent an activity related to comfort. We worked with existing games such as Bait! [14] and Ultimate Fishing Simulator [36] as reference. For example, in Bait!, the player is stationary and usually does not have to look down or move their head much, which we deemed a safe set of user interactions for initial exploration of VR while lying down. We designed the game in accordance with our initial recommendations for the design of VR while lying down for people with physical disability (see Section 4.5). Here, a fishing game was well-suited to enable flexible real-world and virtual user positions (i.e., fishing is an activity that is possible while standing up, sitting down and reclining, or lying down; see Recommendation 3, see Section 4.5.3). Likewise, the activity of fishing is strongly involving upper-body movement, while lower body movements are scarcely involved, mapping well onto the preferred set of movements identified in Step 1 (see Section 4) that are reflected in Recommendation 1 (see Section 4.5.1). In this context, we also opted to create alternative movements and button input as a way of enabling user flexibility throughout engagement with the game, aligning with Recommendation 2 (see Section 4.5.2). Finally, we made the decision to not include fish in our game, but instead make fishing for fruit the goal of the game (see Figure 3b). We opted for this less realistic scenario to avoid negative participant responses to having to hurt virtual animals.

Fruit Fisher was implemented in Unity [43] for the Meta Quest 3 [39] headset, which is one of the most popular options [11, 20] and comes with head straps that are suitable for using VR while resting the head on a backrest or pillow (see Figure 2).

Fig. 2. The Meta Quest 3 headset used in the study [39]



(a) Catch Hooked (b) Reel Fruit In (c) Shop To Sell The Catch

Fig. 3. Gameplay Screenshots: hooking the catch, catching fruit, and selling fruit in the shop

5.2 Gameplay

Fruit Fisher aims to engage the player in a relaxing fishing experience. Therefore, the player is located on a sunny beach and interacts with the game using a fishing rod as part of the core gameplay loop (Figure 3a). First, players have to throw the bobber into the sea. Once the player has done so, they have to wait between four to nine seconds for fruit to start biting and pulling. This is signaled to the player visually with an exclamation mark, as well as a sound effect and controller vibration. Then, the player needs to start reeling within a five seconds reaction window to hook the catch. When hooked, the player has to reel in while maintaining adequate line strain displayed via a slider above the moving bobber (Figure 3a); otherwise, the catch breaks free. Once reeled in (Figure 3b), the catch is placed on a produce stand to the right of the player. The player can optionally sell their catch using a user interface next to the stand after each round (Figure 3c), and the next round of fishing is only triggered once the player has made a decision, allowing for small breaks in gameplay. Overall, players are tasked with reeling in five pieces of fruit. Afterwards, they can sell their catch at the produce stand, and the session ends.

5.3 User Interactions

Here, we give an overview of the movements implemented in Fruit Fisher, including direct interaction with game mechanics and overall position adjustment.

5.3.1 In-game Interaction. Here, we describe how key player interactions map onto specific movements, relating them to the initial recommendations for design (see Section 4.5), and discussing further accessibility considerations where relevant. Generally, game mechanics can be interacted with using movement-based input only, using only the right controller for sedentary input, or a combination of both options. The supplementary video figure illustrates a non-disabled person (for data protection reasons) interacting with the game.

Throwing the bobber (basic) is performed with a swing motion of the right arm when the rod is pointed toward the sea. To increase accessibility, the movement is implemented in a way that requires a smaller range of motion than its real-life equivalent. However, the movement is also recognized if the user wants to perform a larger or sideways swing to accommodate different preferences. Alternatively, throws can be performed by pointing a ray at the target location and and pressing the trigger button. An indicator appears at the aiming point to communicate valid target positions (Figure 5a). The alternative throwing method, can be activated by pressing the trigger and grip buttons on the right controller simultaneously. *This implementation builds upon Recommendation 1 (see Section 4.5.1) and Recommendation 2 (see Section 4.5.2).*

Throwing the bobber (advanced) is an interaction that players can engage in after two successful catches. Here, two round sections appear on the water surface, one to the left and one to the right of the player (Figure 4b), which can be targeted by performing more complex movements involving torso and arms. Fishing in these sections is optional, as only enables different types of fruit to be caught, which does not affect progress within the demo. *We implemented this option to allow users to engage in optional advanced movements, reflecting Guideline 1 (see Section 4.5.1).*

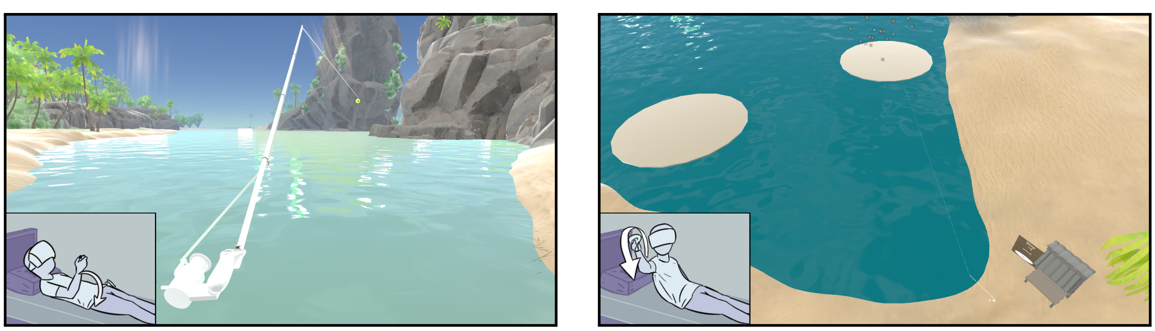
Reeling in the catch is done by a left-hand spinning movement, quickly moving the gray sphere around the white extruded axis of the spool (Figure 5b). The gray sphere moves relative to the top of the left controller. Depending on the user's preference, this can be done with small circular wrist movements or larger arm movements. As an alternative reeling interaction, it can be achieved by pressing the A (reel in) or B (cast out) buttons on the controller. *We leverage Recommendation 1 (see Section 4.5.1) and Recommendation 2 (see Section 4.5.2).*

Observing the fishing process is possible via small head movements: When a catch is hooked, players can watch the bobber move around in the sea using small head rotations. The main gameplay area is shaped in a cone similar to the player's field of view (Figure 4b), reducing the need for head movement unless desired. Once the player has made a catch, the bobber slowly moves around the player in a sideway arc, changing directions in a way that only requires slight adjustment of head position. Alternative input to adjust the view allows players to adjust their perspective in 90 degree increments using the right controller stick. *Thereby, we build upon Recommendation 1 (see Section 4.5.1).*

Selling the catch takes place in the shop, which is placed in a 90° rotation from the sea. Here, users can press the "Sell" button in the UI using controller buttons to trigger the action, increasing the money shown in the UI, and removing the fruit from the inventory.

5.3.2 Adjustment of Player Position. Player position can be adjusted before the start of the game and throughout interaction. Instead of using the lying-down feature built into the Meta Quest 3 [33], we implemented our own position adjustment screen. This gave us more control in the research process, first letting users get comfortable in the virtual world, and it enabled the provision of visual feedback on the selected position (see Figure 6).

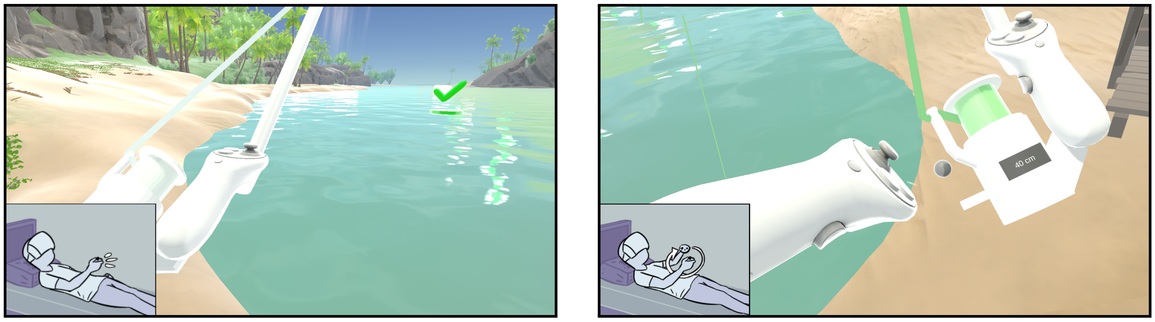
Adjustment of the reclining position is possible via the settings menu (Figure 6). Here, the player can configure three presents for reclining positions, and make a selection at the bottom of the screen. Once the player presses the *confirm button* in the UI, the position adjustment is applied. From a technical perspective, this adjustment is achieved by changing the position and rotation of the parent object of the camera, which applies the transformation seamlessly



(a) Throwing The Bobber

(b) Round Sections On The Water That Have Different Fruit

Fig. 4. Two user interactions: throwing using a pointing motion and sections that require sideways motion



(a) Alternative Throw: Pointing Directly To The Target Position

(b) Reeling The Gray Sphere Around The White Axis

Fig. 5. Two user interactions: Throwing the bobber using a swing like motion input and reeling using circular hand or arm rotations.

to the regular VR camera. Here, the final rotation is the sum of the head and body rotations; the position offset is computed by comparing the sitting position with the selected reclining position. *Thereby, we leverage Recommendation 3 (see Section 4.5.3).*

Adjustment of height of user view is likewise possible via the settings menu (Figure 6). This option was included to account for different representation preferences in the virtual world, i.e., whether users want to experience the game from a reclining position or while standing up, reflecting previous research that addressed the need to adjust the height of the user view in the context of wheelchair use [17]. *This likewise reflects Recommendation 3 (see Section 4.5.3).*

5.4 Expert Review

We carried out an initial expert review of *Fruit Fisher* with three people with VR expertise and physical disability to better understand the accessibility of and experience provided by the game, as well as the practicalities of using VR while lying down. We opted to work with a small number of people familiar with VR to receive in-depth feedback on the game, and to manage the risk of a highly exploratory technology.

5.4.1 Method. The expert review was carried out as a semi-structured interview with a hands-on exploration of VR.

Semi-structured interview: As part of the semi-structured interview, we obtained demographic information from participants, including age and gender, previous experience with VR, and experiences lying down. Additionally, the

Fig. 6. UI to adjust the virtual position within the research tool.

interview focused on the experience of engaging with *Fruit Fisher*, with the focus on their general experience with the game (e.g., *"Can you tell me about your experience with the demo and what it was like to use VR while lying down?"*) and perspectives on the design thereof, as well as a critical appraisal of the guidelines (see Section 4.5) and their implementation (e.g., *"which movements do you consider suitable for VR while lying down?"*). The full interview guide is included in the supplementary material.

Hands-on VR session: The hands-on session was structured into two parts. The first part consisted of an exploration of comfortable lying down positions, using the setup in our research lab (see Figure 7) that offered different options (e.g., lying down flat vs. reclining on a sofa) and supports (e.g., pillows). The second part included playing *Fruit Fisher*. The first step focused on familiarization with the controls; the second step included playing the game. Throughout, experts were invited to engage in a think-aloud protocol [21], verbalizing their observations and experiences throughout their engagement with the game, allowing us to understand their perspectives on accessibility and experience provided by the game in a step-by-step manner.

5.4.2 Participants and Procedure. Three experts (age range 20 to 30, one woman and two men) who were familiar with VR from a research perspective and/or had previous experience using the technology participated in the study. All participants had a mobility disability; one person is a wheelchair user, and one person uses crutches. Experts were offered a reimbursement of 50€. At the beginning of the review, experts were given information about project, and given room to ask questions. Afterwards, they provided informed consent. In the first step of the session, which lasted about 15 minutes, experts provided demographic information. Afterwards, they were invited to take part in the hands-on exploration of VR while lying down. First, they were given opportunity to explore comfortable lying down positions, then they were invited to engage with the game. Throughout, experts remained in conversation with the researcher, following a think-aloud protocol. This phase lasted about 40-75 minutes. The review session closed with a semi-structured interview exploring the experience with the game, lasting about 45 minutes. At the end of the session, participants could ask questions, and were thanked for their time. All sessions were audio recorded. The research was approved by the <removed for review> ethics board.

5.4.3 Data Analysis. Audio recordings were transcribed using [45] with manual corrections by the main researcher. Video material was likewise reviewed by the main researcher, who took notes of relevant in-game events. Subsequently, data were analyzed following an inductive thematic analysis approach [4]. Therefore, the first researcher familiarized himself with the data, coded it inductively, and crafted hierarchical themes based on the codes, which was accompanied by regular meetings with the other authors. On this basis, we crafted three main themes from the data, which we present in the following section.

5.4.4 Results. Here, we give an overview of the main themes of the expert review, contrasting the views of different experts while summarizing key aspects of their feedback on accessibility and experience of VR while lying down.

Theme 1: VR While Lying Down Is Associated with Increased Safety and Comfort, Giving Room to Positive Experiences. Expert feedback showed that using VR while lying down significantly contributed to safety and comfort, alleviating concerns that resulted from using VR while standing up. For example, E1 pointed out that *"Because like I felt like [using VR while standing up] is kind of affecting my balance since I don't see anything first and then it's heavy and it's then kind of harder for me to maintain my balance. That's why I remember that I felt unsafe with that position but when lying down I think I didn't have the same feeling."* All experts reported feeling comfortable when lying on the sofa or the mattress *"So like based on where I was sitting and lying like the mattress, the couch, that was comfortable."*

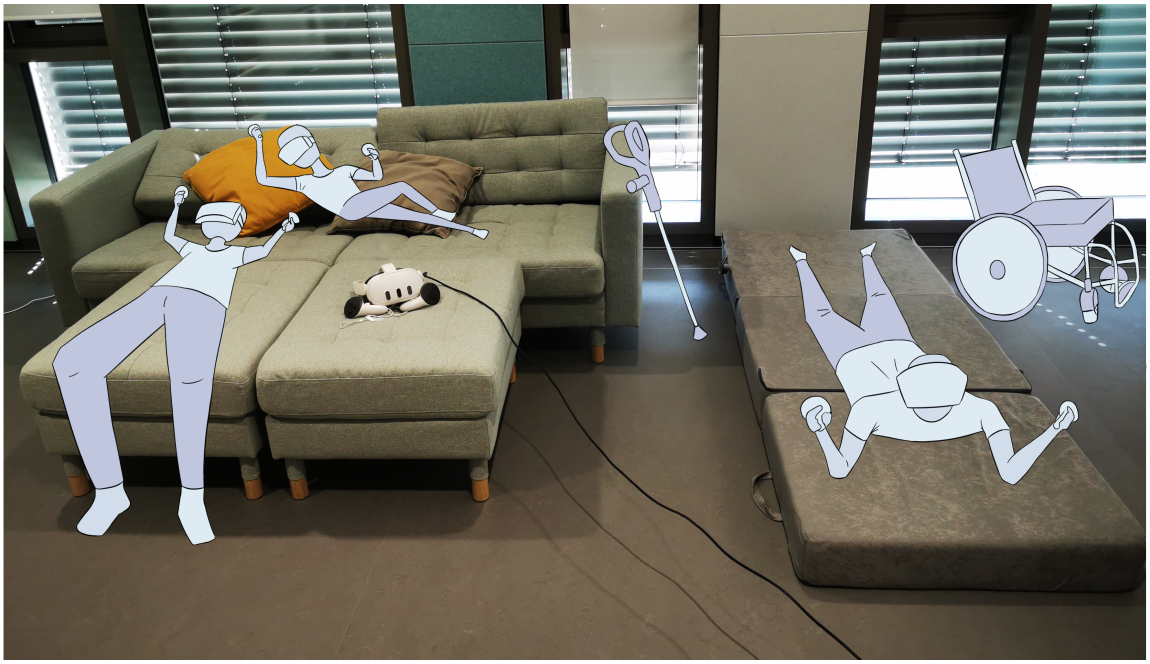


Fig. 7. The expert study setting with the different positions that the expert used is drawn in. Only one expert used the tool at a time.

(E3), but that the environment would need to be cleared of nearby objects (e.g., not keeping a glass of water on the table) and generally accounted for, e.g., *"[...] there's a wall right next to my bed and you don't have much room to the right with your arm"* (E2). Comfort gave way to a positive experience with the game. For example, E1 explained that *"I think it was really fun. I liked the experience overall. And I just realized that I haven't really thought about there might be alternative ways of using VR in different positions. [...] I always considered it as inaccessible because people generally use it while standing and moving around. So I think it was eye opening for me in that sense."*, further commenting that *"[...] the view [in the demo] was nice and relaxing."* In contrast, while E2 considered the general experience pleasant, they were concerned about the impact of the unfamiliar position and slow pace of the game on their experience of presence, stating that *"Probably because it's an unfamiliar position lying down. I would say that. And secondly, I think it's also because the game wasn't really the kind of thing that invites you to really immerse yourself in it, at least not for me."*. Finally, there was agreement among experts that full immersion in VR and the subsequent reduced focus on the physical environment might interfere with safety. For example, E3 was surprised how close to the ground they were after removing their headset, and E1 commented that *"[...] if I wanted to add a cushion that I know is lying somewhere, then I can't see where it is and then put it down properly, that might be a bit more annoying."*

Theme 2: Movements and Lying Down Position Need to Support User Agency. Adaptability of movements and lying down position were viewed as strong contributors to a positive experience by experts, with user agency being a central theme, e.g., E2 pointing out that *"[...] I want to be independent, especially as an individual. And that also means that I can play VR on my own."*. In terms of movement accessibility, the expert review echoes findings from the initial interview study (see Section 4.4.2), with leg movements being perceived as less accessible. For example, E1 commented that *"For me, like basic leg movements might work, but I wouldn't like to rely on them."* This was even more pronounced for E2, who pointed out that *"[...] it's also not technically supported and that's kind of practical for me, where legs or something are out as far as operation is concerned."* E3 indicated an interest in more exhaustive movements, but less frequently: *"[...] I guess I feel comfortable, like, rotating the torso, maybe not the legs. So that could be motion, but you don't want to, like, rotate it all the time."* Across all experts, upper-body movement was preferred. For example, E2 commented that *"So I'll say everything that takes place in front of the upper body [is accessible]."* Additionally, the option to change between movement-based and sedentary input in real-time was valued, e.g., *"And what I liked also there was an option to not do the motion input. So I could decide."* (E3), and contributed to perceived agency. This also applied to the option to adjust lying down position, where E1 pointed out that it was a relevant accessibility feature: *"Because like at least for my body it's not always good to like stay in the same position for too long."* Here, participants managed to adjust the position to their desired position, except for the sideways head tilt, which our research tool did not account for, but E1 wanted to use to rest their head. This shows the need for further research on position adjustment technology designed to fit different individuals' needs. Finally, not all experts were convinced that a fixed lying position would contribute to immersion, and highlighted that the appeal of the approach was highly dependent on the content that would be offered. Likewise, we observed challenges caused by the lying down position mirroring those identified in work addressing non-disabled users Van Gemert et al. [44], e.g., *"[Looking] a little to the left, a little to the right, no problem. Looking backwards is more difficult. And looking downwards, I think you somehow end up in such an uncomfortable position if you have to angle your chin so sharply"* (E3).

Theme 3: VR While Lying Down is Associated With Old and New Accessibility Issues. Our results show that the experts encountered accessibility issues, some of which have already been reported in previous studies, and others being unique to using VR while lying down. Among the accessibility issues echoing those identified by previous work, our results show that the HMD was a barrier. For example, E1 commented that it was too big and heavy, *[...] maybe it was also a bit, I don't know, maybe it's a bit too big for my head too. So I felt like it's a bit heavy and like it's not properly actually fitting with my, I don't know, face and head.* Likewise, E3 commented that the combination of headset and glasses was difficult, stating that *"At that moment I didn't feel like it's comfortable wearing the glasses and the headset."* Additionally, controller size was an issue, *[...] maybe for some buttons that are a bit more far away to each other that I need to press at the same time it might be problematic. [...] maybe like, I don't know a smaller controller, it probably would be easier for me"* (E1). These issues provide further evidence by findings by Mott et al. [35], Creed et al. [9] and Wolf et al. [47]. Issues unique to VR while lying down focus on the interactions between a lying or reclining position and HMD use. E1 wanted to rest their head on the pillow, and reported that this resulted in pressure on their nose, *"[The HMD is] not very uncomfortable but it's just pressing to my nose"*. E2 commented on a similar issue, *"But what I notice when I look up, in that context, is that it really slides up. And I hadn't noticed that before because of the movement. That the movement of my head also causes the strap of the glasses to shift."*

6 Discussion

In this section, we answer our research questions and we discuss challenges and opportunities for the design of VR while lying down for disabled users.

6.1 RQ1: What needs and preferences do people with physical disability have in the context of VR while lying down?

The results of our interview study (see Section 4.4.2) show that people with physical disability have distinct movement preferences when using VR while lying down (see Table 2). In particular, arm movements were considered accessible if not associated with torso or lower-body movement, and when adjusted to the range of motion of an individual user. Likewise, small head movements were viewed favorably, however, extensively moving the head was considered a safety risk. Finally, the accessibility of torso movements, full-body movements and leg-movements was more problematic, and associated with individual types of disability (e.g., whether participants had the ability to move their legs). Overall, adaptability of movements was highly relevant to reflect the diversity of people with physical disability. We further explore this consideration in Section 6.3.1. Additionally, our work shows that people with physical disability interpret the context of VR while lying down more broadly, with an interest in using VR in different reclining positions and on different surfaces, e.g., on the sofa (also see Section 6.3.2 for further discussion). Here, our findings highlight the relevance of safety and comfort, an issue that has been highlighted by previous research on VR accessibility [10, 47], and which we examine in more detail in Section 6.3.3. Finally, in terms of VR experience, our work shows that participants were interested in VR while lying down as engaging leisure (see Section 4.2), and that experiencing presence was one of their goals when engaging with the technology.

6.2 RQ2: How can we design VR while lying down in a way that is accessible and enjoyable for people with physical disability?

The design and expert review of *Fruit Fisher* (see Section 5) highlights a number of challenges and opportunities for the design of VR while lying down for people with physical disability. On a basic level, we demonstrated that it is possible to design VR experiences for use while lying down that are accessible and enjoyable. Here, carefully designed upper-body movement that focuses on a close range in front of the body while involving the hands facilitated access, and alternative movements and the option to adjust reclining position contributed to user agency. Overall, this step of our research provides support for our initial recommendations for the design of accessible VR while lying down (see Section 4.5). Additionally, the expert review offers further context, highlighting that researchers and designers need to be aware that regular accessibility concerns such as the weight of the HMD [9, 35, 47] remain relevant (see Section 5.4.4), but may be exacerbated by the lying position, something that was also noted by Van Gemert et al. [44]. Likewise, we want to note that *Fruit Fisher* offered a slow-paced experience in a setting sympathetic to using VR while lying down. As noted within the expert review, such a relaxed experience may not be suitable for everyone, suggesting a need to explore more vigorous applications of VR while lying down for disabled users.

6.3 Re-Appraising VR While Lying Down From the Perspective of People With Physical Disability

We initially structured our exploration of VR while lying down around the work of Van Gemert et al. [44], who explored the approach with non-disabled persons. Here, we outline where our key findings add nuance, taking into account preferences and needs of people with physical disability.

6.3.1 Movement Adaptation is Crucial for Accessibility. Our work shows that what constitutes a suitable movement is highly individual, with accessibility depending on an individual's ability to move a specific body part and their range of motion (see Section 4.4.2), as well as movement intensity that results from required frequency of execution (see Section 5.4.4), where ability to carry out specific movements may change over time (see Section 4.4.2). This perspective adds nuance to the more homogeneous approach to VR movement adjustment in current research. Although research has focused on adjusting for VR while lying down, such as by implementing redirection of head rotation to address limited head movement while lying down, the approaches that have been implemented rely on hard-coded values that are independent of the individual's needs [28, 48]. This is also echoed by the results from Van Gemert et al. [44], who report no need to adapt movements to individual users, but rather focus on generalizable issues and movements (e.g., replacing crouching or ducking). Here, our work rejects their suggestion that *"future designs for VR while lying down should leverage the legs"*, which was identified as a major access barrier for many people with physical disability (see Section 4.4.2 and Section 5.4.4). Overall, we conclude that future work addressing VR while lying down for people with physical disability should explore real-time movement adaptation, and offer ways of remapping inaccessible movements, for example aligning with Van Gemert et al. [44]'s suggestion to replace strenuous movements with partial automation, something which Cimolino et al. [7] previously highlighted as an opportunity to increase accessibility.

6.3.2 Lying Positions are Dynamic, Varied, and Should Be Private. Lying down positions preferred by the people with physical disability who participated in our work were varied, ranging from flat lying positions to reclining positions (see Section 4.4.1), picking up on a thread for future work identified by Van Gemert et al. [44], who recommended to explore VR while lying down beyond lying down on a bed. Here, our work confirms their assumption that characteristics of furniture (e.g., back of the sofa) affect movement suitability. In addition, our work highlights the relevance of adjusting one's position throughout interaction, e.g., needing to adjust one's body position regularly to avoid discomfort and pain that would be caused by remaining in the same position for too long. To account for this, our recommendations include the adjustment during gameplay (see Section 4.5.2), which we also implemented in the research tool and which our experts viewed positively (see Section 5.4.4). However, we note that research must explore additional adjustments based on individual preferences. For instance, adjustments could be made to various movements, and positions other than reclining, such as sideways tilts, should be considered in future work. Finally, we want to highlight that being represented as a VR user lying down was controversial (see Section 4.4.1), which has implications for avatar design for VR while lying down that should not force users to disclose their position, while at the same time supporting the sense of embodiment.

6.3.3 Safety and Comfort are Foundations for an Enjoyable Experience. While Van Gemert et al. [44] already emphasize the relevance of comfort for VR while lying down as a result of participants associating the bed with a comfortable experience, our work shows that comfort has even higher relevance for persons with physical disability, implying an experience that is free from pain and limits the risk of injury (see Section 4.4.1). Thus, there is a shift in interpretation of comfort, which Van Gemert et al. [44] associate with *relaxing* experiences, whereas our work shows that for people with physical disability, comfortable experiences are those that are *safe*, providing physical and psychological comfort. In particular, movement suitability was directly linked with safety and comfort, and so was engaging with VR while lying down in an environment with privacy and low risk of collision. Here, concerns were associated with reduced awareness of surroundings as a consequence of full immersion in VR (see Section 5.4.4), which has previously been discussed in accessibility research [47]. Here, we want to note that safety and comfort provide the foundation on which people with physical disability have experiences with VR while lying down; in particular, future work should explore how to facilitate a desirable degree of immersion, and how to create sets of movements and lying down positions that are safe and comfortable for individual users.

7 Limitations and Future Work

There are a few limitations that need to be considered when interpreting our findings. Our first study had a relatively small sample, although in line with other qualitative accessibility research (e.g., see [30, 32, 40]), and no non-binary people took part. Here, future work could explore key findings through an online survey with a broader reach. Considering our research game, we want to note that we intentionally implemented a slow-paced experience for initial exploration.

However, the review suggests that this may not have appealed to all experts, and future work should explore different types of games and VR applications designed for use while lying down. Likewise, there is room to further explore user representation for VR while lying down, expanding on previous efforts in the HCI accessibility community that addressed representation of disability in VR [1]. Our expert review only included a small number of participants, and future work should follow up with a broader user study, reflecting on diversity within the group of people with physical disability. In particular, we recommend exploring this approach to VR with individuals who spend the majority of their day lying down, given that the technology may have large potential to facilitate enriching experiences for this demographic.

8 Conclusion

By exploring VR while lying down in the context of physical disability, our work adds nuance to the efforts of Van Gemert et al. [44], who examined VR while lying down for non-disabled persons. Our work shows that a core body of movements was also relevant in the context of physical disability. Yet, the general design of VR while lying down needs to be approached with additional care, addressing the need for adaptation of movements and lying position, and acknowledging the importance of safety and comfort as a basis on which users with physical disability can have positive experiences with VR while lying down. Beyond our contributions to VR accessibility, our work highlights how post-hoc contextualization of research originally addressing non-disabled audiences can serve as a tool for accessibility research. However, our findings also show that if research focuses on non-disabled perspectives first, these will guide the narrative [38, 41], and thus, shifting key focus points for technology design may be more difficult than when engaging in bottom-up design that directly accounts for preferences and needs of disabled persons [3].

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Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009