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Towards a Bedder Future: A Study of Using Virtual Reality while Lying Down

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ABSTRACT

Most contemporary Virtual Reality (VR) experiences are made for standing users. However, when a user is lying down—either by choice or necessity—it is unclear how they can walk around, dodge obstacles, or grab distant objects. We rotate the virtual coordinate space to study the movement requirements and user experience of using VR while lying down. Fourteen experienced VR users engaged with various popular VR applications for 40 minutes in a study using a think-aloud protocol and semi-structured interviews. Thematic analysis of captured videos and interviews reveals that using VR while lying down is comfortable and usable and that the virtual perspective produces a potent illusion of standing up. However, commonplace movements in VR are surprisingly difficult when lying down, and using alternative interactions is fatiguing and hampers performance. To conclude, we discuss design opportunities to tackle the most significant challenges and to create new experiences.

Figure 1: Three examples of our participants using Virtual Reality (VR) while lying down: The top row shows their VR view and the bottom row their movement in the moment. On the left, a participant relaxes in bed while traveling through the mountains. In the middle, another is sitting up to dodge a wall in a rhythm game. On the right, a participant is leaning to aim a catapult.

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CCS CONCEPTS
• Human-centered computing → Virtual reality; Empirical studies in HCI.

KEYWORDS
virtual reality, supine, bed, room-scale, lying down, movement, user experience

ACM Reference Format:

1 INTRODUCTION
In the majority of Virtual Reality (VR) applications, the user is in either a standing or seated position. More often than not, the user is not just standing still but is using natural movement to move through the virtual environment. In fact, eight of the top ten best-selling VR titles on Steam\(^1\) allow the user to interact by ducking under an obstacle, stepping around a corner, leaning to aim a weapon, or reaching for and grabbing an object. In research, too, there is an increasing interest in how we move through the physical space while in VR, for example, by dancing in VR [39], using walking-based locomotion (e.g., [37, 49]), or accidentally moving out of the tracking space [6]. Even when sitting, users can still leverage their torso and arms to lean, reach for buttons, or grab things off the ground. However, it is unclear how we can use VR while lying down.

We spend much of our time lying in bed or on the sofa, using up to four hours a day for entertainment [16, 42]. While lying down, VR can be used to watch movies on a virtual ceiling (e.g., through Netflix VR or Bigscreen VR), enjoy guided relaxation or meditation (e.g., [12, 28]), watch 360-degree videos, or even sleep (e.g., [46, 54]). Outside of popular use, VR is gaining traction in areas where a user typically lies down. In medicine and rehabilitation, VR improves therapy [3] and offers pain relief [35, 45]. In neuroscience, VR has been used in studies using MRI or EEG [29]. However, these virtual reality experiences are often limited by rotation-only tracking, design for stationary use, or a constraining environment.

Simply donning a VR headset and getting into bed or lying on the sofa presents numerous challenges. First, when a user lies down, they will be staring at the ceiling or sky—typically not the most exciting part of the environment. Second, the virtual perspective can be rotated to let the user look forward virtually, but this breaks the mapping between their body’s pose in the real and virtual worlds. Third, the surface the user lies on likely imposes significant movement restrictions compared to standing freely. These are some of the open questions we address: How do users move around? How do they want to interact? How do they feel when using virtual reality while lying down?

We investigate the user experience and movement requirements of popular VR applications when lying down. We developed a custom driver for SteamVR to transform the virtual coordinate space; this allows the user to look virtually forward while physically lying down. We then conducted a qualitative study using a relaxed think-aloud protocol with 14 experienced VR users. The participants used six of the most popular VR applications on Steam, selected for a variety of genres and movement requirements, for approximately 40 minutes. Finally, we conducted a semi-structured interview to address more general questions related to pragmatic and hedonic qualities.

Using thematic analysis, we identified three themes related to using VR in bed. First, we describe how everyday movements become tricky when lying down; this requires users to devise new ways to move and interact, which are strenuous and uncomfortable. Second, despite the additional strain, users can use the applications while lying down comfortably. Third, we discuss how the illusion of virtually standing up can lead to embodiment—when the virtual torso is aligned with respect to the physical head—and disorientation—when the virtual horizon is misaligned with respect to the physical body. We conclude this work by suggesting design opportunities to create new experiences and future directions to tackle the current challenges of using VR while lying down.

2 BACKGROUND
In this section, we show that a need for using VR while lying down exists and that many applications demonstrate that VR is useful while lying down. However, we know remarkably little about the challenges of using VR in bed or designing VR experiences for use in bed. To conclude, we present an overview of applications and research related to using VR while lying down, and we discuss previous efforts to understand the experience and tackle the obstacles of using VR in bed.

2.1 Why Should VR Be Used While Lying Down?
People may want to use VR while lying down out of necessity or by choice. The WSC’s XR Accessibility User Requirements state that “the user should not have to be in a particular physical position such as standing or sitting to play a game or perform some action.” [23] This suggests that VR should be usable while lying down, but in practice, this is not yet the case: Amongst recent discussions of accessibility of VR, Gerling and Spiel [15] argue that current VR systems and software are an “inherently ableist” technology that requires a whole, average body to use. Many applications require bodily motion controls without providing alternatives. HCI researchers have echoed the need for accessible VR in the context of wheelchair users [14], system use [36], and software (e.g., WalkinVR\(^2\)). Some recent forum posts show that bed-bound users want to use VR while lying down in bed (e.g., [22, 48]) and that this need has not yet been satisfied.

Outside of VR, people spend about 4 hours a week watching TV in bed [42]. The idea of using virtual reality in bed appears to be well-established in popular culture: A Google Images search for “virtual reality in bed” produces a plethora of stock images and videos of people wearing VR headsets in bed—sleeping, relaxing, or excitedly reaching out to something in the virtual environment. Other examples come from fiction, such as the anime series “Sword

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\(^{1}\)The largest video game digital distribution platform for PC; https://store.steampowered.com

\(^{2}\)https://www.walkinvrdriver.com
Art Online” or the movies “The Incredible Doctor” and “The Matrix,” in which people are completely immobile in the physical world.

Together, these works suggest that 1) there is an imminent need for using VR in bed, 2) current work on accessibility in VR does not cover the use of VR while lying down in bed, and 3) there is an imagined future where VR can be used in bed when desired.

2.2 Why Has VR Been Used While Lying Down?
VR has been applied in contexts where the user already needs to lie down, such as pain relief for bed-bound patients (e.g., [35, 38] and Figure 2b), VR-augmented therapy (e.g., [3, 29, 30]), and creating conditions for magnetic resonance imaging (MRI) or other neuropsychological assessments (e.g., [17, 29, 44]).
When lying down by choice, VR has been used to improve sleep quality (e.g., [28, 43, 54]) or to provide guided meditation (e.g., [12]).
When consuming entertainment, VR users may want to lie down for comfort. For example, apps like Netflix for VR and Bigscreen VR already allow users to watch movies in a virtual environment by placing the TV on a virtual ceiling. Research papers have discussed the potential of immersive applications for VR pornography [11, 53]. Some users of the popular VR app “VRChat” are already sleeping in virtual environments. YouTube creator “The Virtual Reality Show” presents an interview with such users [46]. The mentioned benefits include the ability to sleep in wondrous, often natural, locations (e.g., camping in the mountains) or social sleeping with physically distant friends or family. These examples show that VR can benefit many applications where people need or want to lie down. However, they reveal little about the challenges in doing so.

2.3 What Are the Obstacles for Using VR While Lying Down?
Both academic and commercial works have designed hardware systems to enable VR while lying down. One of the first examples of using an immersive system for pain relief and entertainment in bed was published in 1998 by Ohmura et al. [38]. Their “Bedside Wellness System” used a large mechanical arm to hold displays above the user’s head and foot pedals to allow the user to locomote through a virtual environment. More recently, Kwon et al. [26] presented a VR system for viewing immersive bedtime stories in bed while minimizing movements. They present a custom pillow with lenses wherein a smartphone can be embedded and a back-of-the-head pressure sensing system to provide interface control through head rotations. The ergonomics of virtual reality use have been investigated (e.g., [5, 7, 52]), and interaction techniques have been proposed to improve standing and sitting VR use (e.g., [34, 31]). However, apart from anecdotal reports regarding the comfort of the hardware while lying down (e.g., [43]), the ergonomics of using VR while lying down remain unclear.

On the commercial side, Figure 2a shows the proposed HalfDive VR system that was designed specifically for use in bed [9, 10]. The system comprises a platform under the head and an HMD that surrounds the user’s head. The hardware platform supports head rotations, input through foot controllers, and force feedback on the hand controllers. The Kickstarter page says the HalfDive aims to “complete life in-bed” for working and playing in bed. However, the project was canceled in 2022. The creators noted that contrary to the project’s direction, their potential users were more interested in interaction techniques for working in bed than the video system. Figure 2b shows a different VR system that relies on specialized software to allow its use while lying down. Due to the lack of positional tracking and its proprietary nature, it is unclear a user’s movement in VR is supported.

These works suggest that enabling the user’s movement for interactive VR while lying down is important, but the possible challenges of moving while using VR in bed remain uncharted.
2.4 How Do People Experience VR While Lying Down?

Since lying down physically and looking forward virtually creates a mismatch between the perceived virtual and physical direction of gravity, some authors have hypothesized that this can induce VR sickness. Marengo et al. [32] created a custom “Pac-Man” game with a rotated coordinate space and joystick locomotion and measured VR sickness between seated and lying-down users. Their 25% dropout rate and high reported SSQ scores suggest that supine users are more susceptible to VR sickness. Another study by Tian et al. [47] compared supine users between a Body-Vertical / Real Vertical and Static / Dynamic game. The study does not report a significant difference in SSQ scores. However, the SSQ-Disorientation score was always higher when the direction of gravity was body-aligned (i.e., using a rotated virtual coordinate space). Although the assumptions in these studies was that the source of the sickness was the mismatch in the perceived direction of “up,” they did not measure how participants perceived the direction of gravity. Kawai et al. [25] studied this perception and found that the perceived horizontal plane depends mainly on the proprioceptive sensation of the upper body angle, not on the physical direction of gravity.

These studies suggest that the experience of using VR while lying down differs from that of standing, at least in the discomfort of VR sickness. However, the overall experience, including a positive aspect that could inform the design of VR while lying down, remains unclear.

3 STUDY

This study aims to identify the movement requirements and user experience of VR while lying in bed. To do so, we develop a custom driver for SteamVR to transform the virtual coordinate space and select six applications to represent contemporary VR. We use a relaxed think-aloud protocol (RTA) [20, 21] to collect rich verbalization of the participant’s experience as they were engaging with the applications. We used a relaxed think-aloud protocol because it allows us to prompt the participant to elaborate when they move or interact in an interesting way but do not verbalize why they do so. Furthermore, it allows us to communicate with the participant and provide instructions where needed to limit the influence of unfamiliarity with the application or the controls themselves. We recorded a video of the participant lying in bed and captured a video of their application view. We simultaneously recorded audio from the participant, observer, and application. The observer was positioned so that they could observe the participant and the application view simultaneously, take notes, and communicate with the participant.

After the RTA part, we conducted a semi-structured interview (SSI) outside of VR to ask more general questions about the experience of using VR while lying in bed. The SSI focused on three topics. First, the quality of the interaction with the virtual environment (Gameplay), which is characterized by usability, utility, and emotional impact. Second, the context of the user (Context), which is characterized by the user’s previous experience, physical position, and physical abilities. Third, a higher-level reflection (Reflection) on the utility and appeal of the VR experience when lying down. For each of these topics, we constructed a starting question that focused on how participants use the system (pragmatic quality, P) and how participants feel while using the system (hedonic quality, H) [19]:

(1) How did it feel to use these VR applications in bed? (Gameplay, H)
(2) Were you able to do what you wanted to do in the application? (Gameplay, P)
(3) How does the experience compare to other times you’ve used VR? (Context, H)
(4) How does lying down influence the way you move? (Context, P)
(5) Why do you think people would want to use VR while lying down? (Reflection, H)
(6) What would you want to be improved about the system to make it perfect? (Reflection, P)

3.2 Applications

VR games represent one of the most popular forms of VR applications for consumers. To have a representative sample of contemporary VR experiences, we selected the six games from the “Top Seller” list of VR titles on Steam. Within the most popular titles, we selected different movement requirements, locomotion techniques, and genres. Each application could be played for a maximum of 15 minutes or less if the participant finished the task early.

In the study, each participant was assigned a unique order of applications, and each application was played at least six times in total. Based on a pilot study, the nature of the applications, and the physical setting, we expected some issues to be similar across games and participants. So, a relatively small number of participants will suffice to identify the most prominent challenges and benefits. Simultaneously, we wanted to consider individual preferences, experiences, and differences between the applications, so we opted for at least six samples per application.

Figure 3 shows a screenshot of typical gameplay for each of the six applications. Below, we describe the type of application and their typical movement and interaction requirements. All of the applications, except for VTOL VR, support a room-scale play area, which means the user can move around in-game by physically moving. We describe the selected applications and their different genres ([1, 13]) below. We also describe typical movements in these applications in standing or seated VR.

3.2.1 Beatsaber (Figure 3a). A Music/Rhythm application3 that requires the participant to hit oncoming blocks using two light sabers. The participant plays the first three songs — “$100 Bills,” “Balearic Pumping,” and “Beat Saber” — at a self-selected difficulty. The walls are enabled by default but may be disabled if the participant fails to dodge them. The interaction area is primarily in front of the

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3Steam ID: 620980
participant. The participant uses their arms and hands to swing the sabers in time, either in front of them or to the sides. Furthermore, they use their whole body to lean left and right and duck to dodge oncoming walls.

3.2.2 Pavlov VR (Figure 3b). A Shooter application with a wide variety of guns and a full-body avatar with inverse kinematics. The participant plays the tutorial. The interaction area is all-around (shooting targets) but primarily on/near the body (weapon handling). The application features a lot of object manipulation in handling, customizing, and aiming the weapons. Navigation is done through natural motion (walking) or joystick locomotion and snap-turning.

3.2.3 VTOL VR (Figure 3c). A Flight application where the user controls a military aircraft with a high degree of realism. The participant plays the first two tutorial missions that teach them how to operate the aircraft, take off, and land. The participant is virtually seated in the aircraft, and the interaction area is in front of the participant and at waist height (controls). The application requires precise hand-eye coordination to control the various switches, buttons, and joysticks.

3.2.4 Blade and Sorcery. (Figure 3d) A medieval-style Fighter application with realistic physics, various melee weapons, and a full-body avatar with inverse kinematics. The participant’s task is to play “Recruit” training in the “Arena” map and kill ten enemies. The interaction area is all-around. The participant can navigate through natural motion or joystick locomotion and snap-turning. Dueling the enemies requires full-body maneuvering and fast and precise arm movements to handle the weapon with one or two controllers.

3.2.5 The Lab: Slingshot (Figure 3e). A Puzzle/Action application that is part of The Lab. The user needs to shoot a ball at towers of stacked boxes using a large slingshot. The task is to play the application for three rounds. The interaction area is primarily in front of the participant (the slingshot). Due to the size of the slingshot, the participant needs to maneuver around in a 3x3m virtual space to aim the slingshot using precise hand-eye coordination. Locomotion is also supported through teleportation and snap-turning.

3.2.6 The Lab: Postcards (Figure 3f). A Simulation application that is part of The Lab. In Postcards, the participant explores four real environments that have been photo-realistically re-created. The majority of interaction is active viewing. The participant can use natural motion to navigate or teleport between fixed locations and rotate using snap-turning. The participant can also pick up sticks off the ground to play fetch with the robodog.

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3Steam ID: 555160
4Steam ID: 867970
5Steam ID: 829930
6Steam ID: 450390
7Steam ID: 450390
3.3 Participants

We invited 14 experienced VR users to participate in the study. We selected experienced participants because participants with little to no experience may be distracted by the new experience of VR itself and its controls instead of the experience of using VR in bed. We recruited participants in the local area through an internal mailing list, word-of-mouth advertisement, social media posts, and by reaching out to VR companies and research groups. Overall, our participants were very experienced: eight participants regularly use VR in a professional setting; the other six regularly use VR for games or entertainment. Most participants had played Beat Saber before, and two could comfortably play at the highest Expert+ level. The participants had little experience with the other games in our repertoire, but most participants had at least heard of them and had played similar games. The participants were eleven males and three females. The mean age was 31.8 ± 5.9 years old. The mean time participants spent in VR in this study was 00:37:56 ± 00:03:46.

3.4 Rotating the Virtual Coordinate Space

To enable users to use existing VR applications while lying down, we need to rotate the standing forward direction (by approximately 90 degrees) so that the participant looks forward in the virtual world while physically lying down. The desired effect is illustrated in Figure 4. To accomplish this, we modified OpenVR Motion Compensation\(^9\) (OVRMC), a custom piece of software for SteamVR that hooks into the OpenVR drivers to modify the pose of a tracked device. Our version of OVRMC tracks the pose of a reference device (e.g., an HTC Vive tracker) and applies the inverse pose to both the HMD and controllers. This means that the virtual environment moves with the tracked device. We use this to rotate the virtual environment by rotating the reference device while the HMD and controllers maintain their true pose with respect to the user’s body. Furthermore, we implemented software offsets to align the center of the tracking space with the participant’s feet. Because this approach works at the driver level, it allows us to transform the virtual coordinate space for any SteamVR title. The code is available in the supplementary material\(^10\).

3.3.1 Aligning the virtual coordinate space. Figure 5 shows the rotation between the physical and virtual coordinate spaces. The procedure to rotate the virtual coordinate space is as follows: We ensure that the bed is aligned parallel to the virtual forward direction (perpendicular to the solid green line in Figure 5), so we can rotate the tracker 80–90 degrees around the world lateral axis, changing \(\alpha\). The virtual forward direction is now aligned with the physical up direction. We then translate the center of the tracking space to align it with the user’s feet so that they are virtually standing in the center of the tracking space, looking forward. When the user rests their head on a pillow, \(\beta\) indicates the angle between the head-forward and virtual vertical axis. We used a simple Unity application to manually check and calibrate \(\alpha\) and \(\beta\), the code is provided in the supplementary material.

3.5 Apparatus

Figure 6a shows the physical setup of the study. The bed is an Ikea Neiden (90x200cm) with an Ikea Vestmarka mattress and Ikea Sköldblad pillow. Perpendicular to the bed was a desk with a laptop for note-taking and three monitors to display the in-game view, an on-screen clock, and the OBS recording window. The laptop was positioned so that the observer was facing the participant as well as the in-game view and clock.

\(^9\)https://ovrmc.dschadu.de/

\(^10\)https://github.com/tvangemert/ovrmc-BedderFuture
Figure 5: We have rotated the virtual coordinate space so that line (A) is the virtual vertical axis. The angle $\alpha$ is the degree of rotation between the physical vertical axis (B) and the virtual vertical axis (A). $\alpha$ is controlled by physically rotating the HTC Vive tracker. The angle $\beta$ between the head vertical axis (C) and the virtual vertical axis (A) is controlled by the user’s position in the bed and the pillow ($\beta$ is exaggerated in the figure for illustrative purposes). Line (D) through the user’s head is the virtual head-forward axis.

The VR system comprised an HTC Vive Pro headset with a modified head-strap (see Figure 6b), two HTC Vive Pro controllers, and four SteamVR 2.0 lighthouses. The reference tracker was an HTC Vive Tracker mounted on a tripod and connected via an additional HTC USB radio. The headset cable was suspended from the ceiling above the participant’s head. The HTC Vive Pro, by default, has a rigid head-strap with a buckle at the back of the head. To improve comfort while lying down, we created custom mounting hardware to attach an HTC Vive (original) head strap to the HTC Vive Pro (see Figure 6b). The head-strap for the original Vive is flat and does not impair the head while lying down. The models for 3D printing and instructions for the conversion are available in the supplementary material.

We used SteamVR version 1.23.7 on Windows 10. To rotate the tracking space, we used our modified version of OVRMC (see subsection 3.4) which was based on version 3.6.0. The tracking space was set up to be approximately 2.5 by 2.5 meters. We rotated the virtual coordinate space to $\alpha = 86.06 \pm 1.42$ degrees on average. With the pillow, $\beta = 14.64 \pm 7.93$ degrees on average. The latter varied based on the participant’s preference and pose in the bed; some participants removed the pillow during the study, and several re-adjusted their head position during the study by moving around in bed.

A video camera was pointed at the bed. We used OBS Studio to record the in-game footage from both eyes using SteamVR’s built-in “VR View.” An on-screen clock was included in the PC recording and video camera recording to synchronize the videos in post-production. The computer to drive the VR system was a powerful workstation with an AMD Ryzen 7 5800X CPU and an Nvidia GeForce RTX 3080 GPU. We used the HTC Vive Pro’s built-in microphone to record the participant audio and a Blue Yeti microphone to communicate with the participant during the study and to record the interview. MaxQDA 2022 was used for coding and analysis.

3.6 Procedure

Before the study, the observer set up the bed, VR hardware, computers, and peripherals. They then rotated the virtual coordinate space and aligned the tracking space origin with the observer’s feet as they were lying in bed. At the start of the study, the observer welcomed the participant and explained the purpose and procedure of the study: that we are interested in the user experience of using VR while lying down with a “rotated world, so you will be looking forward in VR” and that we wanted to know “what works well and what does not.” Within that context, the participant was free to comment on anything, from feelings to usability issues. After obtaining informed consent (and optionally, permission to use their images in the figures), the participants conducted two warming-up exercises for the think-aloud protocol: verbally solving a math problem and brainstorming improvements for a household device.

When the participant was confident they understood the protocol, the VR system, and the procedure, the observer asked them to lie down and put on the headset. OVRMC and the calibration application were already running, so the participants would immediately be in the transformed coordinate space. We provided a pillow and used the application to set the floor-HMD height and record $\alpha$ and $\beta$. Then, the observer asked the participant to put in the earpieces, started SteamVR Home, started the video and audio recordings, and instructed the participant to start thinking out loud.

When the participant acknowledged that they were ready and had no further questions, the observer asked them to start the first application from the SteamVR Home menu. Once the game had started, the observer gave the participant instructions on the controls for the game and the task they were to complete. If the participant got stuck in the application and could not figure out how to proceed, the observer provided additional instructions. In some games, the observer provided tips to ensure that all participants used the games in roughly the same way (e.g., trying to use a sword in Blade and Sorcery). When the task was completed or the time limit was up, the participant was instructed to return to SteamVR Home and start the next game.

During the entire VR session, from calibration up to the interview, the participant was in VR. After the last application had finished, the observer instructed the participant to take off the headset and take a seat on the bed next to the desk. The observer then proceeded with the semi-structured interview for approximately 10 minutes. Afterward, the study ended, and the participant was thanked with a gift worth $20.

3.7 Analysis

To analyze our data, we drew upon the thematic analysis framework as explained by Braun and Clarke [4]. We use a primarily inductive approach: this allows us to stay close to the participant’s experience of using VR applications in bed. This experience was expressed through their utterances during the think-aloud study and interview, as well as their movements and interactions that were recorded on video. We have no existing frameworks or guidelines to analyze the user experience, movements, or interactions of using VR while lying down, so a bottom-up approach is the most appropriate.
The first two phases of thematic analysis are data familiarization and initial coding. One of the authors was also the observer during the studies and was thus intimately familiar with the data. To streamline the first two phases with multiple coders, we coded the first two participants together in a simultaneous session where interesting segments and codes were determined collectively through discussion and analysis of the data.

What to code was determined by what the authors agreed to be interesting with respect to how the participants used VR while lying down: This could be a movement, an utterance, a design limitation, or a way to interact with the virtual environment. We used descriptive codes and memos to detail interpretation, context information, or assumptions. Following Braun and Clarke [4]'s recommendation, we erred on the side of inclusion during initial coding. Irrelevant codes were dropped during theme construction. We used the following research questions to guide our analysis:

1. What is the user experience of using VR while lying in bed?
2. How do users move, or want to move, when using VR in bed?
3. How can users interact with the virtual environment (e.g., locomotion, object manipulation)?

After the two simultaneous coding sessions, we created an initial loose grouping of codes to serve as an initial code system for coding the rest of the participants. In further sessions, authors individually coded three participants each by adding their codes to the existing code system. Finally, we held three 2-hour collective sessions to search for, construct, and review potential themes. During these sessions, we created a more detailed grouping and hierarchy of the codes and then merged and split codes as needed into the constructed themes. The themes were further refined during writing. Both the detailed grouping and the final themes with their codes are available in the supplementary material.

4 RESULTS

During the study, we observed how participants experienced VR while lying down for the first time: some were highly active and engaged, whereas others preferred to lie mostly still and relax. At the start of the in-VR session, most participants remarked something about the strange virtual perspective that resulted from transforming the virtual coordinate space. While performing the task, the participants spoke about what they were doing, how it felt to do things in VR while lying down, or about the implications of lying down for their behaviour. In moments of high concentration (e.g., a fast section in Beat Saber or landing the airplane in VTOL VR), it was difficult for the participants to think aloud and play at the same time. Sometimes, we reminded them to “keep talking”. Other times, we asked them about an unfinished thought they had spoken about or something they were doing without commenting on it.

The participant’s speech and movements in bed provided rich data about how they could and wanted to move while lying down and how it felt to use VR while lying down. We provide a 5-minute video in the supplementary material that summarizes the results.
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(a) Relaxing

(b) Aiming with torso

(c) Looking around

(d) Looking over shoulder

(e) Reaching forward

(f) Reaching with elbow support

(g) Aiming with the arms

(h) Sit-up to duck

(i) Sit-up to crouch

(j) Leaning sideways

(k) Straddling the bed

(l) Looking through body

Figure 7: This figure shows a selection of movements that the participants in the study performed while using VR applications in bed. The figures are directly based on the video data and thus accurately represent the participant’s pose mid-action.

and shows footage from the study. In the following, we present the results from our thematic analysis of this varied and fascinating data set.

4.1 “It’s just a lot of ab work!” — Common Movements are Surprisingly Hard in Bed.

Many VR applications require relatively small, precise, and localized full-body movements that we call “maneuvering” [27]. In standing VR, interactions like grabbing a cup from the other end of the table, looking around a corner, or ducking under an obstacle are straightforward and effortless. However, using VR while lying down highlights how frequently maneuvering is needed and yet how hard it is to do.

4.1.1 Leaning. While P12 is playing Beatsaber, they describe a lack of maneuverability: “I can’t really move to the sides that much. I’m supposed to move to either left or right when there’s a wall coming towards me, but that is difficult when you’re lying in bed.” The participants also lean to aim (Figure 7j and Figure 7b), which is slow...
and difficult: “Ok, so I’m trying to aim at the hidden barrels there, but this is very awkward for me here” (P2).

A user can lean in bed by engaging the abdominal muscles to lift the torso slightly off the bed to get enough clearance to tilt the torso left or right. The required ab crunch demands significant physical effort, which was highlighted by P8’s already sore muscles: “Leaning to the side is quite uncomfortable. But again, I already [had] a bit of an ab workout ... yesterday.” Some participants used their legs as a counterweight or as an anchor for additional balance and support: For example, P1 straddled the bed to improve their “ability to dance [in Beastsaber]” (see Figure 7k).

4.1.2 Reaching. When lying down, reaching (Figure 7e) for something “[is] a workout when things are not right in front of you” (P9); due to the rotated coordinate space, users also need to pitch their head backwards to maintain a forward perspective. This movement was “weird” (P6), or as P9 put it: “Just not natural, at least. But it was doable. ... I could still play the game.”

Compared to leaning, reaching forward is more strenuous if the user has to hold the position for a moment. While P2 is controlling a switchboard in front of them, they do an ab crunch to reach forward and remark: “Especially these kinds of interactions where you lean in, and you have to do multiple things while holding your abs, is pretty tiring.” Two participants figured out a solution by supporting themselves on one elbow while reaching forward (Figure 7f).

4.1.3 Crouching. The participants often found their object of interest to be lying on the ground (due to game design or after being dropped). This required them to crouch down virtually and grab the object. In Beastsaber, two of the songs included an overhead wall that needed to be dodged by moving down and under it. The applications in the study did not have the option to move down vertically other than through physical movement. So, the participants used a sit-up (i.e., the fitness exercise) to virtually move down to duck (“ducking”, see Figure 7h) or to reach the ground to manipulate objects (“crouching”, see Figure 7i and Figure 9). Like reaching forward, ducking requires the participant to maintain sight of the target by pitching their head back, which does not feel natural.

Most participants were acutely aware of the need to crouch, but it took them a while to figure out that they could use a sit-up. For ducking, as in Beastsaber, the time pressure showed how a sit-up is not intuitive even if the participant had used crouching before: “Heading head-first into a barrier. Aaand I failed. Because I cannot duck, in a bed” (P14). Other unsuccessful responses were leaning hard to a side (P14), dragging themselves lower in the bed (P1), or leaning back into the bed, pressing their head into the pillow (P6). On the other hand, P10 had used a sit-up to crouch before and managed to duck just in time:

“Oh no! You have to duck for this!! [Does a sit-up to dodge, lies back down.] Oh, we’re bringing sit-ups into this. ... Kind of counter-intuitive to have to sit up to duck. It’s interesting.”

Most sit-ups were paired with grunting and comments on it being an “ab workout”. P5 describes it as “grabbing something off the floor is [not exhausting, but] obviously way harder” (P5). P4 figured out an alternative to sitting up: they preferred “being lazy” in bed, and so when they see their weapon lying on the ground in Blade and Sorcery, they decide that “[it] is unreachable” and instead use the kicking mechanic to attack the enemy.

However, a sit-up can be less strenuous compared to leaning and reaching because the physical effort is minimal once sitting up. We regularly saw participants sit up for a moment before lying back down. Some participants enjoyed the physical effort required by ducking: “The walls are really fun! ... There’s something really satisfying about having to account for that” (P3). Although sit-ups can “[disrupt] the flow of Beastsaber”, some participants enjoyed how it “brings back some of the ‘physicality’ you normally have in Beastsaber” (P1) and that “[its] good exercise” (P2).

4.1.4 Looking around. Virtually looking down is a common movement that is required to observe interaction at waist-height and on-body or to aim the teleportation (see Figure 8). However, an ab crunch is needed to move the chin towards the chest to look down. P4 said that “looking down is so fatiguing” and the physical effort appears to hamper task performance: “The constant neck strain from looking at the controls makes it hard to follow [the instructions]” (P5, VTOL VR). However, the participants were able to virtually look down, contrary to looking up, which was physically blocked by the bed.

Ironically, the limited field-of-view (FoV) of the headset means that more head rotations are needed: When standing, eye movements that are used to look around can be substituted for head movements with relative ease to account for the limited FoV. The headset is also specifically designed to maintain the “clear spot” of the lenses in an upright pose. When using VR lying down, the sub-optimal headset design and the pillow cause the headset to move around on the user’s head, making it difficult to maintain a clear image. At the same time, because of the difficulty of moving the head when lying down, it is difficult to look around outside of the limited FoV.

In order to look around, most participants lifted their head or torso off the pillow (see Figure 7c and Figure 7d) to enable a greater range of head movement at the cost of physical effort. This makes looking around take more time and require more energy than when standing, which affects task performance and enjoyment. Participants were comfortable lying down and did not want to move their heads (P3, VTOL VR):

“... because your head is so comfy in the pillow, you don’t look around as much. And so I’m assuming [that] if I was sitting or standing ... I would have looked over my shoulders a lot more.”

4.1.5 Translating. The locomotion techniques in the applications, like joystick locomotion, teleportation, and snap-turning, were not precise enough to be used as an alternative for taking a physical step. All of these were difficult to control to move small distances, especially while simultaneously using the controllers to aim (Pavlov VR and Slingshot) or swing a weapon (Blade and Sorcery). P5 commented that “It put a lot more cognitive stress on me in a certain way, because I had to map the navigation to my hands. And at the same time ... the games also put a lot of different actions on different hands.”

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11Some applications, such as Afterlife VR, allow crouching by button press when playing in “Seated VR” mode.
However, when participants got used to the combination of controller-based locomotion and arm interaction while lying down, even the intense applications became usable: “Pavlov was okay; you could move around. And then [Blade and Sorcery], I think, was completely fine. I don’t know if I adjusted to it maybe, but I didn’t feel the difference so much” (P11).

Even when successful, using the locomotion techniques did not completely relieve the need for ab work: Turning around by button press (snap-turning) typically rotates the virtual view ~45 degrees, which then requires additional head rotations to get the desired perspective, and aiming to teleport requires an ab crunch to look down or to the sides. Teleporting backward is particularly difficult. P11 preferred an ab crunch in Slingshot over the awkward aiming of the teleportation: “I’m too lazy to teleport, so I have to reach out.”

4.2 “If you’re moving so much, why not get up?” — The Challenge of Benefiting from Lying Down

Intense applications, such as Blade and Sorcery, and applications that require crouching, were overall regarded as being uncomfortable and difficult. When asked about their ability to play the games, P13 responded: “I could do the mechanics, but I was like, if I’m rolling around in bed, why am I not getting up?”

However, when you can take a break, lie back, and just use the controllers, then VR while lying down is very comfortable. Slower applications, such as Slingshot, Postcards, or VTOL VR worked well for this. Moreover, despite the additional physical effort, participants were surprisingly capable of using the applications.

4.2.1 Relaxing and being comfortable. Being comfortable or being able to relax were the most common positive experiences mentioned for VR while lying down. For example, P1 summarizes his experience as “surprisingly not weird. I was gonna say surprisingly comfortable.” Figure 7a shows P13 relaxing and taking in the scenery in Postcards. When the movement requirements are low and the participant can relax, “it’s so chill, doing something like this lying down” (P3, VTOL VR). P8 explains this nicely:

“I think for the most part, it felt good. But as soon as I had to perform ... movements that are unnatural in bed like sitting up or, especially in Beatsaber in the end with leaning to the side, it got quite uncomfortable. But ... when I was able to do the interactions, where I was lying and resting my elbows, and ... the movement was constrained within that space, it actually felt totally fine and all.”

Some participants were eager to put in a lot of physical effort, but others considered a trade-off between staying comfortable (lying down) and having to move to interact: “It’s like nah, now, I’m lying in bed, I don’t want to do some exercises. ... But yeah, it’s comfortable” (P4).

Among the more intense experiences, participants returned to a comfortable pose whenever possible. While lying down, P3 in Beatsaber “[puts their arms] down on the bed as soon as [they] get a chance.” Similarly, participants enjoyed playing with the elbows on the bed. P14 exclaims in Beatsaber: “Ah, nice blocks! Now I can just stay in the middle, which is relaxing” and P10 “… realized that I can rest my arms, I don’t have to hold them up all the time.”

4.2.2 Using the arms to interact. Overall, interacting within arm’s reach “without having to get up” (P8) worked well: “Everything that is really close, in this area [signals area in front of torso], is comfortable” (P4).

The participants also held their arms up in the air regularly for improved freedom of movement (e.g., Figure 7g or Figure 7k). For example, in Beatsaber for faster or wider movements, or in VTOL VR during moments that require high concentration (e.g., landing the airplane). Keeping the arms up for a prolonged duration is fatiguing, as explained by P10: “Well, I guess it’s more tiring. Because you’re fighting gravity with your arms.” Fast arm movements were difficult because the bed was too “bouncy”. P14 explains this nicely:
“... When doing the rapid movements, everything felt sort of laggy and oscillating. ... My response time has gone down significantly when lying down, and I feel the bed shaking when I move too fast.”

Despite the arms having relatively much freedom of movement while lying down, some movements remain challenging: The bed blocks the elbows (P3), which hampers performance in Beat Saber and Blade and Sorcery, where you need to swing your arms: “I miss the ability to do proper swings [demonstrates elbows hitting bed]” (P8). In Slingshot, many participants wanted to pull the catapult backward, which was blocked an elbow or controller hitting the bed or their own body. “I’m a little annoyed that my arm movement is restricted and [that] I have to use teleportation and look around a lot” (P6).

4.2.3 Expectations of movement. The participants associated a bed with comfort, relaxation, and rest. Sometimes they did not think about moving or did not want to move because of these assumptions of what a bed does: “When I’m lying down, I feel like I should not sit up” (P8). P1 explains how being aware of the fact that you’re lying in bed can control your movement:

“I mean, you know, the first impulse is to step. You don’t actually physically step and then realize, oh, no, I can’t do that. You kind of stop yourself before you make the movement.”

For many participants, the bed implied a certain level of comfort or relaxation. This study challenges this implication because the applications often required physical effort to be used. However, this was not always a bad thing: It “brings back some of the physicality ... that you normally get while playing Beat Saber” (P1). Once you learn that you can move in bed it makes a large difference, which is explained well by P3:

“But then later on, ... I just kind of realized that well, actually, you can just move around quite a lot more. Which is weird for a bed. But it’s not weird for a game.”

4.2.4 Avoiding VR sickness. The bed may relieve VR sickness by providing physical support. P11 explains this as a benefit similar to sitting down for VR: “I have quite strong nausea from moving games: Sometimes it helps when I sit down for games like this.”

P2 and P3 expected the experience to cause VR sickness, but neither experienced it after using joystick locomotion and purposefully performing crazy flying maneuvers: “Surprisingly, not nauseating!” (P3). Similarly, P10 experienced less vertigo than normal:

“Because of being confined to a certain space, being locked into a bed, so to speak, I didn’t have the fear of falling. I find often when flying, if I’m standing up, I will tilt my body ... and I might almost fall over. ... That doesn’t happen when you’re lying down. So it’s sort of more comforting, in a way, though also more difficult in a different way.”

Two participants did report significant VR sickness, but it is unclear what the cause was: P13 exposed themselves to a lot of mismatching visual motion by maintaining odd physical poses in bed (e.g., lying diagonally, looking upside-down). P12 appears to have been exceptionally sensitive to the mismatching visual perspective because they complained about it more often and more strongly than other participants. Both had to use joystick-based locomotion as well. P13 thinks the bed contributed to their VR sickness: “Because this is a very springy bed it’s creating a wobbly sensation, which I couldn’t deal with very well.”

4.3 “I forgot that I’m lying down” — Embodiment and the Illusion of Standing Up

Surprisingly, the illusion of standing up in VR works, even when in reality the user is lying down. Regardless of the haptic feedback of the bed pressing against the back instead of having the feet on the ground, and despite gravity informing the vestibular and proprioceptive senses of the orientation of the body in the world, it works. As P3 put it: “You do forget that you’re ... lying down.
And it just feels like you’re playing ... kind of up against a wall in a weirdly constrained way.

One illusion of standing up is about the alignment between the physical and virtual body (e.g., legs straight or bent for sitting), and another is about the alignment between head movements and the view of the horizon (e.g., rotating the head rotates the view in unexpected ways).

4.3.1 Embodiment. Some participants mentioned embodiment and other body-based illusions. P13 commented that “I don’t care about body orientations, it kind of just works” and that “I don’t feel I’m in a wrong orientation ever. I feel like I’m just playing a game.” However, the lack of movement can limit embodiment. For example, one of the most active players, P10, mentioned that the experience “is less immersive because I wasn’t able to move like in real life.” P3 said it’s a “less embodied experience because the head is anchored.”

Yet, the embodiment seems to work even if only the torso and hands are aligned with respect to the head. For example: in VTOL VR P7 and P14 looked down at the virtual chair and without a pause or prompt agreed that they are indeed sitting in a chair. P1 tested how they might feel about such a (mis)alignment in the body by pulling their legs up into a 90-degree angle, like sitting on a chair, and added in the interview: “No, the mismatch with the body wasn’t that bad. And it certainly wasn’t noticeable 90% of the time.” P13 in Blade and Sorcery exclaims “Oh, I have a body now!” — as they notice the virtual full-body avatar.

4.3.2 Perception of the horizon. In connection with the illusion of standing, the participants talked about the horizon in the VR scenes and about feelings of gravity. When there is a clear horizon, and the user is looking forward in VR while lying down, the illusion of standing works very well, to the point where people do not question it. P10 commented that “it’s interesting that you don’t think about lying down or being upright. It feels natural.” When the illusion broke, the participants regained it after a moment. P10 said that “I feel like my brain naturally compensates very quickly for not having gravity in the direction that it would usually have.”

The participants had differing experiences regarding the effects of sitting up on the illusion. P12 commented that “sitting up breaks the illusion” as the floor looks vertical. P2 said, “the shift in the direction of gravity kind of ... reminded me that I’m not in the same orientation to the game.” For some, the illusion remained when sitting up to duck, as long as they kept their head straight forward with respect to their torso. P13 thinks aloud while testing the illusion:

“It works if I’m looking down [sits up to duck, looks at the virtual ground]; it works when I lean back and look forward [lays back on the bed]; but if I look [to the side], the world is getting tilted [demonstrates looking to the side].”

Looking to the side when sitting up or when lying down “makes the horizon seem tilted” (P12) and typically broke the illusion. But, in Postcards, when P13 is looking out over the mountains, they comment that because the world is round, they can imagine the horizon tilting when rotating to the side, so it does not ruin their illusion. P13 experimented a lot with the virtual perspective (e.g., looking upside-down, Figure 7) and also managed to retain the illusion when rotating around completely on their belly to look backward (see Figure 10): “… Somehow having the gravity be on my chest rather than on my back matched the image better. I actually really liked that. It was a little bit like scuba diving.”

The illusion of standing up is precarious when there is no clear horizon. In the cave scene in Postcards, the ground slopes up to a hole in cave ceiling with a view of the sky. P10 commented that “This whole space seems to be slanted. It’s a little bit disorienting that I can feel gravitationally that I’m lying down.” P13 remembered that “[In the cave scene] it was harder to rationalize my body position.” In Beat saber, P12 describes that an unrealistic scenery could actually strengthen the illusion: “It felt more natural in Beat saber. Because I was in some kind of zero gravity space, or in space, or in some non-real location.”
5 DISCUSSION
Based on our results, we have identified a number of implications for the design and future research of VR while lying down. We discuss those here in line with the three themes of section 4. Finally, we discuss use cases based on a user’s ability and desire to move while lying down. We show some more implications in Table 1.

5.1 Implications of Movement for Research and Design
Our results show that maneuvering is one of the most significant limitations of using VR while lying down: To maneuver, users need to exert much physical effort to use alternative movements like sitting up. Some related work exists to improve the accessibility of VR (e.g., WalkinVR) or to design VR hardware specifically for use in bed (e.g., [9, 26]). However, more work is needed in the following directions to enable movement-rich interactions while lying down.

We need interaction techniques to replace maneuvering when lying down. However, this is not a trivial task. Consider the difference between virtually crouching to grab or duck: The former requires physical effort, but the user can rest at the top of the sit-up, and the illusion of their position in the visual world can remain intact. Ducking under an obstacle, however, requires fast reaction time and sight of the target (the object to be dodged). Some proposed hardware solutions enable VR use while lying down (see section 2), but these only allow left-right head rotations and maintain the body in a stationary supine pose (see Figure 2). VR applications demand more than that, so researchers and designers need to create new interaction techniques to enable maneuvering, avoid maneuvering, or make users think they are maneuvering.

Future designs for VR while lying down should leverage the legs. For example: by using the hips for rotation control, the feet for locomotion, or the whole legs in a walking-in-place locomotion technique. Participants complained that the existing locomotion controls were difficult to use because they were on the same controller that needed to be swung at an enemy or aimed at a target. By offloading the locomotion controls to the legs, this problem can be solved. In real life, crouching, ducking, and side-stepping rely on the legs to move the user and maintain balance. Legs were used in our study to provide additional balance and support, but not directly to interact. Although our applications did not support leg-based interaction, there is ample previous work on foot-based interaction (see [50] for an overview) to kick-start new interaction techniques for VR while lying down.

Physical head rotations should be supported and augmented. We need the ability to use head rotations to effectively interact with VR applications and benefit from the immersion of VR. Looking around while lying down was difficult enough, physically straining enough, that users would rather not move and stay comfortable. So, the ability to turn the head left or right and especially up or down should be better supported. Several aspects should be considered in future work to better support head rotations. First, the ergonomics of the headset: Currently, the HMD interferes with head rotations left and right and it moves too freely on the face, causing the clear view through the lenses to shift. Improvements to the field-of-view of the HMD could allow the user to more easily look around with their eyes before requiring head rotations. Second, physical head rotations could be supported by hardware solutions (e.g., [9]), but also need to consider up and down rotations. Third, novel interaction techniques should be designed to let the user vary how much they look up or down dynamically, with only minimal physical head movements.

Strenuous physical movements can be replaced with game mechanics. Rather than using alternative physical movements to interact while lying down, we can integrate new interaction techniques into the experience. An example of this was demonstrated by a participant, who decided at some point during the session that they did not want to do a sit-up to grab a weapon off the floor. Instead, they used an existing mechanic, kicking, to attack the enemy, which meant they could remain lying down and comfortable. A similar idea exists in the popular VR application Half-Life: Alyx, where the protagonist can pull faraway objects closer using their “gravity gloves.” Both of these techniques have the added benefit that they stay true to the application’s universe while greatly improving users’ ability to interact. Many techniques for object interaction at a distance exist [2] as well as for locomotion [8]. The challenge for future work is to determine which of these are most suitable for use in VR while lying down.

We need locomotion techniques for small, not just medium, distances. It was surprising to see how difficult popular VR applications become when maneuvering is not an option, and the only choices are typical locomotion techniques or ab crunches. At first sight, locomotion techniques are an obvious alternative to maneuvering, as they are in seated VR. However, the more restricted freedom of movement while lying down makes locomotion techniques like joystick control, teleportation, or snap-turning not precise enough for maneuvering. Normally, they do not need to be, as they are designed for use with the more common standing VR experiences. In section 2, we discussed how the field of accessibility of VR has some overlap with VR while lying down, and the lack of good interaction techniques for users with limited movement (by choice or necessity) is a prime example. We need locomotion techniques to allow users to maneuver while lying down. We suggest that VR designers consider how, for example, a supine user could compete for a top-3 score in Beastsaber.

5.2 Implications of the Bed for Research and Design
Apart from the challenges of maneuvering, we found many aspects of lying in bed to work well for VR. Being comfortable is the main benefit, and applications with low movement requirements (e.g., VTOL VR and Postcards) work quite well without additional improvements. Other low-intensity VR applications, such as watching a movie, browsing the web, or doing office work, can be readily adapted to lying-down use. However, several issues will remain, such as limited head rotation, arm fatigue after prolonged use, and limited maneuvering (e.g., when grabbing an object). Here, we discuss some opportunities to leverage the benefits of lying down.

### Footnote
[12]https://store.steampowered.com/app/546560
Table 1: We have identified several design suggestions and directions for future work based on our results and related work. We discuss the main ones in the text, and this table provides additional concrete opportunities. Each of the three groups of rows relates to the subsections in the Discussion, respectively. Each of the three columns lists the topic, our findings, and our suggestion, respectively.

<table>
<thead>
<tr>
<th>Movements in VR</th>
<th>Main Finding for VR while Lying Down</th>
<th>Suggestions for Design and Future Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaning</td>
<td>Leaning is restricted by the bed.</td>
<td>Support physical leaning through devices.</td>
</tr>
<tr>
<td>Reaching</td>
<td>Holding an ab crunch to lift torso is fatiguing.</td>
<td>Replace small sideways movements with an interaction technique.</td>
</tr>
<tr>
<td>Crouching</td>
<td>Crouching to grab requires a sit-up.</td>
<td>Let user interact just outside of arm’s reach without moving closer.</td>
</tr>
<tr>
<td>Looking around</td>
<td>Head is “anchored” in the pillow.</td>
<td>Interaction technique to look down and move down easily in VR.</td>
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<tr>
<td>Translating &amp; Turning</td>
<td>Locomotion is not precise enough.</td>
<td>Replace physical ducking with an interaction technique.</td>
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If you're moving so much, why not get up? — The Challenge of Benefiting from Lying Down.

<table>
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<th>Main Finding for VR while Lying Down</th>
<th>Suggestions for Design and Future Work</th>
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<tr>
<td>Being comfortable</td>
<td>Movement is physically straining.</td>
<td>Limit full-body movements and head rotations in bed.</td>
</tr>
<tr>
<td>Arm interaction</td>
<td>Interacting within arm’s reach works well.</td>
<td>Calibrate head pitch angle to provide illusion of standing up.</td>
</tr>
<tr>
<td>Expectations</td>
<td>It is difficult to “see what you’re doing.”</td>
<td>Allow user to go back to resting position (elbows on bed) often.</td>
</tr>
<tr>
<td>VR Sickness</td>
<td>A bed is too “bouncy” for fast movements.</td>
<td>Provide main interaction in front of the user, at chest or head height.</td>
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</table>

I forgot that I'm lying down — Embodiment and the Illusion of Standing Up.

<table>
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<tr>
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<th>Main Finding for VR while Lying Down</th>
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</thead>
<tbody>
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<td>Embodiment</td>
<td>Embodiment despite the rotated VE.</td>
<td>How does awareness of the rotated VE influence embodiment?</td>
</tr>
<tr>
<td>Perception of Horizon</td>
<td>Illusion of standing up is precarious.</td>
<td>How does haptic feedback of lying down influence embodiment?</td>
</tr>
</tbody>
</table>

Manage expectation of comfort versus effort. For most users, a bed comes with the expectation of being comfortable. We saw this in how users did not want to or did not know to move while lying down. Having to move to interact (e.g., the infamous ab crunch) causes discomfort and thus frustration. However, just lying in bed is very comfortable, and the participants enjoyed VR experiences with low spatial and temporal movement requirements, such as VTOL VR, Postcards without crouching, or Beat saber at low difficulty. However, designing relaxing experiences that integrate a small amount of movement is a good opportunity to create engaging VR experiences. We expect that small maneuvers like leaning, reaching, or turning on a side are acceptable, but managing the user’s expectations is crucial: a relaxing experience for use in bed should not require physical effort, but an exercise application for the sofa could.

Expand the usable area of interaction for the arms. The bed provides a stable basis of support, which supports comfortable interaction with the arms and relieves VR sickness. Using the arms with the elbows on the bed was considered to be very pleasant and offers an interesting design opportunity for VR when lying down. Applications like Beat saber, VTOL VR, and Postcards could all be enjoyed while keeping the arms comfortably supported by the bed. On the other hand, the bed also blocked some arm movements at the elbow or hand. There is a relatively small space where arm interaction is easy, between the arm’s reach and the “wall” of the bed. Future work should investigate how we can (virtually) extend the area where arm interaction is easy and comfortable. For example, existing work on improving the ergonomics of VR interaction through hand redirection may be extended to lying down VR [34].
Explore the use of VR for reclining and lying on other surfaces. In this study, the participants all used the same single bed. However, there are many more surfaces where a user could be supine: double beds, softer or harder surfaces, sofas, recliners, and even the floor. We found that the bounciness of the bed can hamper performance for expert users who need fast movements. Furthermore, the pillow did not work as well for everyone. Small differences in the results may be observed for different supine surfaces. For example: lying on the floor may improve performance at the cost of comfort.

Another obvious use case of VR for comfort would be to sit or recline on a sofa or chair. The VR hardware and the software we used to rotate the coordinate space can easily be adapted to different non-vertical poses. We speculate, however, that the experience of these different poses and surfaces will vary slightly from our observed results. For one, the illusion of standing up may be more powerful when supine, and so a different reclining angle may be less effective [24, 25]. Second, some movement restrictions will be alleviated depending on the surfaces (e.g., head rotation on a chair), but others will change or remain (e.g., the back of the sofa may prevent elbow movement when seated or whole arm movements when lying down). Third, a user may be more likely to change pose when not in bed, for example: going from lying down to leaning to sitting upright on a sofa. Currently, our system does not dynamically adapt to these changes. Exploring the impacts of updating the transformed coordinate space during changes in pose remains an exciting avenue for future work.

Use locomotion techniques that do not cause VR sickness.
Future work should investigate the effect of lying down on VR sickness in a controlled lab study, as our work provided conflicting results. Some participants suggested that the bed may relieve VR sickness — likely by improving balance. However, previous work suggests that VR while lying down causes VR sickness [32], and two participants reported VR sickness. Considering the limitations of previous work, the exceptional movement of our participants, and participants’ comments on VR sickness relief, it is impossible to conclude the effect of lying down on VR sickness.

5.3 How Do Haptic and Vestibular Sensations Influence Embodiment?
Proprioception is known to influence embodiment [18, 41]. In our study, the visual and proprioceptive cues were congruent: when looking down or holding the hands in front of their face, the participant could see the parts of their virtual body being collocated with and moving like their physical body. However, the visual feedback of standing was incongruent with both the haptic and the vestibular sensations of lying down. The backside of the body pressing against the bed provides a haptic sensation of lying down, and gravity pulling on the horizontal body provides a vestibular sensation of lying down. Regardless of the conflict between these two sensory perceptions and visual perceptions, our participants experienced embodiment.

Vestibular and haptic information contribute to the experience of embodiment through multisensory integration: congruency increases the illusory effect of body ownership and embodiment (e.g., [31, 40]), and incongruity severely hampers it. Research in neuroscience shows that without vestibular sensations (e.g., in microgravity), the sense of disembodiment is not severe. But, both the neural measures [31] and subjective perceptions [40] indicate significant reductions in body ownership when the sensations conflict.

Nevertheless, our results suggest that people experience embodiment when using VR while lying down. This has two implications for future work. First, investigating how the components of embodiment, such as body ownership and self-location are perceived while lying down could help in understanding why, and when, the illusion of standing can be created. Second, when understanding how the illusion of standing can be induced, the visual-vestibular mismatch can be employed in applications to improve body ownership or provide even stronger experiences, such as allowing bed-bound patients to experience the freedom of walking.

5.4 Use Cases of VR when Lying Down

Table 2: We can distinguish four types of use cases for VR when lying down, based on whether the user can move (Ability) while lying down and whether they want to (Desire). In this table, we show an example use case for each scenario. The scenarios where a user can move (italics) are the most promising.

<table>
<thead>
<tr>
<th>Desire</th>
<th>Ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Exercise Bed-bound</td>
</tr>
<tr>
<td>No</td>
<td>Travel MRI</td>
</tr>
</tbody>
</table>

“I don’t want to use VR while lying down if I don’t have to” summarizes what many participants felt after the study. A bed is comfortable, but much of the comfort comes from the lack of physical effort. When using VR in bed, our participants had to use a lot of physical effort to be able to interact with the applications. This negates the expected benefits of lying in bed and leads to frustration and little motivation to use VR while lying down. Based on the related work and our results, we can distinguish two high-level ways by which users may use VR while lying down: by choice or out of necessity. Based on this, Table 2 provides an overview of use cases for VR while lying down.

**You can, but do not want to move.** By choice, a user may lie down for comfort (e.g., on a bed or sofa) or because lying down holds a benefit. For comfort, movement should be limited and the focus should be on relaxation and immersion. Immersive animations, movies, or travel experiences are examples of suitable applications according to our participants. Still, these experiences can benefit from hand-based interaction and easy head rotations.

**You cannot move, but want to.** Out of necessity, on the other hand, a user may lie down because they cannot do otherwise (bed-bound users with chronic ailments, hospital patients, etc.) or because it is required by the application. For bed-bound users who are in hospitals, undergoing therapy or rehabilitation, or have to
lie down due to chronic ailments, VR can offer a welcome distraction or improved treatment. Several recent forum posts show that bed-bound users have a need for using VR while lying down in bed (e.g., [22, 48]) that has not been satisfied yet. Furthermore, in section 2, we discussed the increasing popularity of VR for pain relief (e.g., [35]), which could be further improved with movement-based interaction. In these scenarios the users may not have full use of their body, so use cases in this scenario will be bound by the ability of the user and the goal of the application.

You can and you want to move. If the surface to lie on is not a bed, there may not be an expectation of comfort. Furthermore, different surfaces can have different benefits for applications where users can—and want to—move. For example, a military stretcher provides more freedom of movement for exercise, while lying prone in an underwater rig supports the haptic experience of being underwater in VR. Or, perhaps the bed is simply used for VR sickness relief while playing an intense game. While most users found the abdominal crunch uncomfortable and needlessly fatiguing, some users commented that it brings back some of the “physicality” of standing use of the application (e.g., Beatsaber). In any case, the user may want to move as much as possible, and the limit depends on the application.

You cannot move and do not want to. Finally, in some use cases, the user may be lying down and not want to move. For example, while lying in an MRI scanner or lying down in a dentist’s chair while wearing a VR headset to relieve anxiety. In some cases, the user has been sitting upright while using VR in bed (e.g., SyncVR Medical and other hospital applications), but our work shows that lying down with a transformed coordinate space is a pleasant experience. In any of these cases, an interesting direction for future work is the illusions embodiment and standing up, specifically while the user is stationary and lying down. It may be possible to design an interaction technique that makes the user believe they are moving to interact based on illusions and minimal physical input.

6 CONCLUSIONS

In this work, we conducted a study to find out how users experience virtual reality (VR) while lying down and how they move around physically and virtually. We discussed how VR has been used when users are lying down, but we found that the use of contemporary, movement-rich applications has not been considered yet. So, in a qualitative study with 14 experienced VR users and six popular VR applications, we investigated how users move, how they want to interact, and how they feel while using virtual reality in bed. Our results show that the lack of maneuvering while lying down is a significant challenge for interacting with VR applications. However, using VR in bed also has many benefits (e.g., comfort), and the transformed virtual coordinate space produces embodiment and a potent illusion of standing up in the virtual environment. We have discussed the key implications of our themes on future research and design. In addition, we have provided a discussion of use cases for VR while lying down and a table of concrete suggestions. In conclusion, our work shows that using VR while lying down has great potential, regardless of whether the user aims for comfort, exercise, new experiences, or entertainment.

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