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LEANING-BASED CONTROL OF AN IMMERSIVE TELEPRESENCE ROBOT

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ABSTRACT

This thesis presents an implementation of a leaning-based control method which allows using the body to drive a telepresence robot. The implementation consisted of a control mapping to drive a differential drive telepresence robot using a Nintendo Wii Balance Board (Wiiboard). The motivation for using a balance board as a control device was to reduce Virtual Reality (VR) sickness by using small movements of your own body matching the motions seen on the screen; matching the body movement to the motion seen on the screen could mitigate sensory conflict between visual and vestibular organs which is generally held as one of the main causes for VR sickness. A user study (N=32) was conducted to compare the balance board to joysticks, in which the participants drove a simulated telepresence robot in a Virtual Environment (VE) along a marked path using both control methods. The results showed that the joystick did not cause any more VR sickness on the participants than the balance board, and the board proved to be statistically significantly more difficult to use, both subjectively and objectively. The balance board was unfamiliar to the participants and it was reported as hard to control. Analyzing the open-ended questions revealed a potential relationship between perceived difficulty and VR sickness, meaning that difficulty possibly affects sickness. The balance board's potential to reduce VR sickness was held back by the difficulty to use it, thus making the board easier to use is the key to enabling its potential. A few suggestions were presented to achieve this goal.

Keywords: Telepresence robot, leaning, balance board, virtual reality sickness

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TIIVISTELMÄ

Tämä diplomityö esittelee nojautumiseen perustuvan ohjausmenetelmän toteutuksen, joka mahdollistaa etäläsnäolorobotin ohjaamisen käyttämällä kehoa. toteutus koostui ohjauskartoituksesta tasauspyörästö vetoisen etäläsnäolorobotin ohjaamiseksi Nintendo Wii Balance Board -tasapainolaudan avulla. Motivaatio tasapainolaudan käyttämiseen ohjauslaitteena oli vähentää virtuaalitodellisuus pahoinvointia käyttämällä pieniä oman kehon liikkeitä, jotka vastaavat näytöllä näkyviä liikkeitä; kehon liikkeen sovittaminen yhteen näytöllä nähtyyn liikkeeseen voi lieventää näkö- ja tasapainoelinten välistä aistiristiriitaa, jota pidetään yleisesti yhtenä pääsyistä virtuaalitodellisuus pahoinvointiin. Tasapainolautaa verrattiin ohjaussauvoihin käyttäjätutkimus (N=32), jossa osallistuja ajoivat simuloitua etäläsnäolorobottia virtuaaliympäristössä merkittyä reittiä pitkin käyttämällä molemmilla ohjausmenetelmiä. Tulokset osoittivat, että ohjaussauvat ei aiheuttanut osallistujille enempää virtuaalitodellisuus pahoinvointia kuin tasapainolauta, ja lauta osoittautui tilastollisesti merkitsevästi vaikeammaksi käyttää sekä subjektiivisesti että objektiivisesti. Tasapainolauta oli osallistujille tuntematon, ja sen ilmoitettiin olevan vaikeasti hallittava. Avointen kysymysten analysointi paljasti mahdollisen yhteyden koetun vaikeuden ja virtuaalitodellisuus pahoinvoinnin välillä, mikä tarkoittaa, että vaikeus voi mahdollisesti vaikuttaa pahoinvointiin. Tasapainolaudan vaikeus rajoitti sen potentiaalia vähentää virtuaalitodellisuus pahoinvointia, mikä tarkoittaa, että laudan käytön helpottaminen on avain sen potentiaalin saavuttamiseen. Muutamia ehdotuksia esitettiin tämän tavoitteen saavuttamiseksi.

Avainsanat: Etäläsnäolorobotti, nojaaminen, tasapainolauta, virtuaalitodellisuus pahoinvointi

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FOREWORD

I would like to thank my supervisors Markku Suomalainen and Basak Sakcak for all the support and guidance with this thesis. I would also like to thank Katherine Mimnaugh for their guidance in designing the user study and Alexis Chambers for their help in conducting the study. Additionally, I would like to offer my gratitude to the Perception Engineering group in the Center for Ubiquitous Computing (UBICOMP) for providing me with an opportunity to conduct this thesis and to all of my colleagues in the group for making it a memorable experience. Lastly, I would like to thank my family for giving me motivation and continuous support throughout this process.

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Joona Halkola

LIST OF ABBREVIATIONS AND SYMBOLS

HMD	Head-Mounted Display
JS	joysticks
NASA-TLX	NASA Task Load Index
OSF	Open Science Foundation
SSQ	Simulator Sickness Questionnaire
SUS	Slater-Usoh-Steed
VE	virtual environment
VR	virtual reality
WB	wiiboard
WIP	walk-in-place

F	force
m	meter
N	number of participants
s	second
ω	angular velocity
c	constant
$\circ$	degree

1. INTRODUCTION

A telepresence robot (example shown in fig. 1) can help to remotely attend events when somebody is physically unable to be present with additional benefits of moving in the environment and viewing it through the robot and interacting with people at the location. Hybrid meetings have become a common occurrence as the option for remote work has become increasingly more popular over the last few years, thus dividing workplaces between office and remote workers. However, it has been shown that regular screen-based telepresence robots are insufficient for collaborative work in hybrid meetings because remote participants speak less in conversations and perceive higher task difficulty in group work than the local participants [1]. Currently, available telepresence robots lack in terms of *presence* [2], the feeling of "being there", which can diminish the experience for the remote user. In VEs , presence makes the user behave more naturally [3], thus the lack of presence could be the reason for the behaviour of remote participants. A solution to this problem could be immersive robotic telepresence which enables the ability to feel present in a remote location by embodying a mobile robot via a Head-Mounted Display (HMD) which would offer an experience where remote attendees could feel as if they were really there. However, using an immersive telepresence robot does come with a set of challenges.

Figure 1. A conversation via a telepresence robot. Picture from [4]

An immersive telepresence robot has challenges that are not relevant to a normal telepresence robot. One of the drawbacks of using a HMD is the risk of inducing VR sickness; a common cause for VR sickness is a sensory mismatch [5] from staying stationary while seeing motion in the HMD. It is important to ensure that controlling the robot can be done with a low effort not to be frustrating to use but without succumbing to VR sickness. Controlling the robot should feel easy and engaging to use while considering different travel distances and maneuverability in tight spaces. Previous research on telepresence robots has not had to focus closely on controlling the robot as problems, such as VR sickness, do not exist with regular telepresence robots. While the research on locomotion control methods for VR is extensive and offers some insight into potential solutions, not much focus has been given to the control of vehicles travelling on the ground. The limited research on locomotion control methods and their effects on the experience while controlling a telepresence robot while immersed in an HMD warrants further research.

We explore the use of a balance board, the Nintendo Wiiboard, as a leaning-based control of an immersive telepresence robot. We hypothesized that using the body to control the robot could potentially mitigate the sensory mismatch, thus making the experience less sickening than the joysticks. In addition, the use of the body for control of the robot could provide a method which feels more natural to use compared to joysticks as the body is used in everyday life to control various activities, for example riding a bicycle.

The study is conducted as a simulation in a VE in which the participants control a virtual model of a mobile robot with both, the Wiiboard and the joysticks, and drive the robot along a path which is marked on the floor. While we acknowledged that the Wiiboard will be unfamiliar for the participants and it might provide various physical challenges, the benefits were thought to outweigh the disadvantages. However, it turns out that we underestimated the difficulty of using the Wiiboard, partly based on earlier work which reports using it as easy [6]. In our study, the joystick was found statistically significantly easier to use than the balance board, both subjectively and objectively. Furthermore, we found that the leaning-based control method using Wiiboard induced more VR sickness; open-ended answers reveal that the difficulty of the Wiiboard may have also played a role in the sickness results. We also discuss the findings about presence across control methods. Even though the results were not in favor of using this particular board in the way we imagined, the user study results show the potential of the method with better hardware and more training time than what was allowed in this study.

The following section will present concepts and previous work related to robotic telepresence and its use cases, VR technology and VR sickness, and finally, locomotion control methods in VR with a deeper look into leaning-based control methods. Section 3 will present the technical implementation of the leaning-based control method using the Wiiboard. Section 4 presents the hypotheses for the study, the VE, and the overall study design: procedure of the study, the participants, the tasks completed during the study, and the measures collected. Section 5 displays the results of the study and in Section 6 the results are discussed together with limitations and future work. Finally, Section 7 concludes the thesis.

2. RELATED WORK

2.1. Robotic Telepresence

The term *telepresence* was first suggested in 1980 by Minsky [7] who describes telepresence as remotely operated tools with high-quality sensory feedback which allow one to operate by one's own hands without noticing a significant difference. Draper et al. [8] later defined telepresence as an ability to enable the user to operate in a computer-mediated environment via the use of a synthetic environment.

Telepresence robots have gained more interest over the years as technology has progressed and become more accessible and as of late due to COVID-19, the importance of hybrid meetings has grown. Currently, attending a hybrid meeting via a laptop and camera, the remote attendant is confined to a single position without the ability to move around the meeting environment. Additionally, they are unable to look around and only view what is displayed through a web camera. This limits the interactions with people in the local environment as face-to-face conversations can only happen if the laptop is moved towards the currently speaking person. Telepresence robots offer a solution to give freedom to the remotely attending person to move and look around in the local environment through the robot's camera. The benefit of a better sense of presence, the feeling of "being there", can lead to better social interactions and resemble a normal face-to-face conversation.

In robotic telepresence, a person can connect to a remote environment via a physical robot placed in the environment which enables movement and interaction within the remote environment [9]. For social situations and common everyday life, a telepresence robot can be defined as a robot which has the equipment to enable communication between the robot and people in a remote environment [9]. Those pieces of equipment are commonly a camera, a screen, a microphone, and speakers but not all of the equipment are necessary as two parties can communicate by using microphones and speakers only. The screen and camera are important as social presence is higher when communicating via video and audio than only via audio [10]. The camera is also necessary for showing a video feed to the robot operator to navigate with the robot in the remote environment. Regular telepresence robots display the video feed from the robot's camera on a flat screen, for example, a computer monitor or smartphone. Regular telepresence robots increase presence [11] but are limited by a flat screen. An HMD-based telepresence robot uses a video feed from a 360° camera placed on top of the robot which allows the user to look around the robot freely as they could do in real life. Using an HMD over a computer screen greatly increases the feeling of presence [12] which is essential for an immersive telepresence robot as a stronger sense of presence can increase the performance of the system and lead to a better user experience [13].

Choosing the correct control method can be a defining factor in the success of the system as it can affect a variety of areas, such as usability, presence, and VR sickness. Regular telepresence robots commonly use a joystick, keyboard, smartphone, or automatic navigation as the control method [9]. As VR sickness does not exist with regular telepresence robots, a control method can be chosen solely based on usability and ease of use. More thought has to be put into the control method when considering HMD-based telepresence robots. Dancing on a fine line of balancing usability, presence, and VR sickness is not an easy task and controlling a physical robot brings additional elements to consider. For example, commercially available telepresence robots utilize a differential drive system as it is simple and effective. However, it imposes more challenges on the design choices of the control method as the robot is unable to move diagonally which leads to more rotations while in place. Research on control methods for HMD-based telepresence robots has still a long way to go but control methods used in VR (see section 2.3) would be suitable options.

2.1.1. Use Cases

Telepresence robots are being used in a variety of different areas from the military [14] to more common situations and environments such as conferences [15], schools [16], and healthcare [17, 18].

Neustaedter et al. [15] studied the use of telepresence robots in conference settings. They found that remote participants valued being able to attend through telepresence robots because of their ability to present themselves better and being in control of their "body" while socializing. Telepresence robots also have an important role in enabling attendance for people with illnesses or disabilities.

Weibel and others [19] conducted a study on how telepresence robots can help hospitalized cancer patients to keep up with their classes both socially and academically and ease the feeling of loneliness. Children participants described longing to get back to school as not being present had created distance between them and their classmates. Participants said that the robot helped them to feel that they still belong there and their classmates were observed to treat the robot as a human.

Koceski and Koceska [18] used a telepresence robot for the healthcare of elderly people and studied user perceptions of the telepresence robot used. The elderly participants performed two tasks with the robot, the first task was to navigate from starting point to their nursing room and the second task was to use the robot's manipulator arm to fetch and carry small objects. The caregiver participants were given the same task to navigate the robot and in addition to it, use the electrocardiograph functionality on the robot together with the manipulator arm to apply the equipment needed for the measurement. The robot was also equipped with a camera for the caregivers to easily apply the equipment. The robot's ability to give reminders, for example, to take medicine at the right time, was also evaluated together with calendar functionality. The results showed that the robot's functionalities were perceived to be useful and accepted by both, the elderly and the caregivers.

2.2. Virtual Reality

Research on virtual reality has been going on for many decades. One of the first HMDs for virtual reality was created by Sutherland together with his students in 1968 to try to display three-dimensional objects [20]. The term *virtual reality* was coined in the 1980s by Jaron Lanier [21], a founder of a technology company focused on developing virtual reality products. Earlier definitions of VR were usually based on the hardware and technology used for the VR system [22] which is undesirable as VR technology is evolving rapidly [23]. LaValle [23] defined VR as "inducing targeted behaviour in an organism by using artificial sensory stimulation, while the organism has little or no awareness of the interference".

The first VR headsets available for consumers hit the market in 1995 when Nintendo released the Virtual Boy console but it turned out to be a commercial failure and was discontinued a year later. The VR headset market for consumers went on a long hiatus without any major development until over a decade later in 2012 when Oculus started the development of a new VR headset with a lot of promise. A consumer version of the Oculus Rift hit the market in March 2016 by then multiple companies had already joined the race to develop their own VR headset [24]. HTC Vive SteamVR was released shortly after the Oculus Rift in April 2016 which beat the competition by being the only headset with sensor-based tracking which enabled, now a standard feature, room-scale tracking allowing users to move around while in VR [24]. VR started to rapidly gain more momentum which pushed the technology further and brought down the prices of the headsets to a more affordable level.

2.2.1. Technology

A wide variety of HMDs exists with each having strengths and weaknesses depending on which type of technology and implementation was used. Commonly accepted quality factors, such as the resolution and Field of View, are important but other factors play key roles in the quality of the HMD.

The tracking type can limit how the HMD is used and how accurate the tracking is and affect the experience for better or worse. Currently, HMDs are categorized into two tracking types, *outside-in* and *inside-out* tracking. In *Outside-in* tracking, the common method is to use the so-called Lighthouse system in which one or more base stations (trackers) are placed in the environment and the tracked object is equipped with sensors which act as markers for the base stations [25]. The base stations project lasers to the tracked area which in turn are captured by the sensors in the tracked object [25]. Outside-in tracking limits where the HMD can be moved to as the base stations fixed to a position, thus this type of tracking is usually used with wired HMDs as the wire also limits the usable space. *Inside-out* tracking works in the opposite way where the tracked object is equipped with optical trackers and the objects in the environment act as the markers for the trackers [25]. Inside-out tracking is not limited by the base stations and is used with wireless HMDs as there is no wire to limit the usable space.

Wireless devices have become the norm in today's world and it has caught up with the VR market as well. Wireless HMDs have shown promise to replace wired systems as there has not been a significant negative effect on the VR experience [26]. The most noticeable weak link on wireless HMDs is battery life as the currently popular Meta Quest 2 is limited to only 2-3 hours of usage.

For this project, Meta Quest 2 was due to being consistent with the research groups' previous studies where the same model of HMD was used. In addition, the wireless connection was deemed unreliable, thus the HMD was used in wired connection mode to ensure that the connection was not suddenly lost and to remove the need to charge the headset in the middle of the tests. Controllers from the Quest 2 system were used as the joysticks. Unity was chosen as the game engine to build the project on because of prior familiarity and good support for both Quest 2 and Wiiboard.

2.2.2. VR Sickness

One of the most noticeable problems with VR has been *cybersickness* or *simulator sickness* which to sickness associated with virtual environments. In this paper, the term *VR sickness* will be used to refer to symptoms caused by the usage of VR as suggested by LaValle [23].

Some levels of VR sickness have been shown to occur in 60-95% of the participants during experiments where the participants were exposed to a VE [27]. VR sickness manifests as symptoms similar to the symptoms caused by motion sickness, for example, nausea, headache, and disorientation [5]. The severity of the symptoms varies from person to person; while others might feel slightly uncomfortable, some get sick to the point of vomiting. Besides the obvious adverse effects of sickness symptoms, VR sickness can negatively affect presence [28]. As presence plays an important role in VR and HMD-based telepresence robots, minimizing the amount of VR sickness is a crucial task.

VR sickness is a widely researched topic and various theories have been suggested for the cause of VR sickness. The three main theories are *the sensory conflict theory*, *the poison theory*, and *the postural instability theory* out of which the first is the oldest and most accepted as the cause for motion and cybersickness [5]. *The sensory conflict theory* suggests VR sickness is caused by sensory conflict, where the visual system and vestibular organs receive conflicting sensory information caused by different stimuli experienced by the body in VR versus the real world. The most common sensory conflict is caused by the illusion of self-motion known as vection. Vection occurs when the viewpoint of the user moves around the virtual environment and visual stimuli give the illusion of motion and no physical motion is experienced [23]. *The poison theory* proposes VR sickness to be caused by an evolutionary reason. The theory suggests that the body misreads the adverse stimuli caused by VR, thinking it ingested some sort of toxin and as an early warning system tries to remove the contents of the stomach by vomiting [5]. *The postural instability theory* was developed to challenge *the sensory conflict theory* and was based on the idea that humans always try to maintain postural stability in the environment [5, 29]. VR contains constantly changing environments and visually perceived movement to which normal postural control strategies of the body do not work, thus causing postural instability. The theory states that the cause for sickness symptoms is being in prolonged postural instability [29].

In using a leaning-based control method for controlling a robot, there are both potential mitigating and escalating factors for VR sickness. From one point of view, having to move may mitigate sensory conflict between the visual system and the vestibular organs, which should prevent VR sickness. However, the order of cause and consequence is still complex [30]; thus, it is difficult to predict whether having to balance on purpose can have a causal effect on VR sickness and whether this has a stronger effect on VR sickness than the decrease of the sensory conflict.

2.3. Locomotion in VR

Locomotion is an important part of the VR experience where multiple factors have to be taken into consideration, such as usability, VR sickness, and presence. Choosing a control method is not an easy task as a perfect solution does not exist. A control method could be a great choice for usability but in turn, suffer from causing more VR sickness. The type of VR application or its target users can also impose restrictions on which types of control methods are suitable, for example, the elderly cannot use physically demanding methods. VR has had a large growth in popularity during the last decade with an increasing amount of areas of use. To address this growing popularity, various control methods have been suggested and developed [31] to meet the need of many.

Boletis [31] suggested a typology (see Fig. 2) for VR locomotion techniques with four characteristics: interaction type, VR motion type, VR interaction space, and VR locomotion type. Interaction type is divided into artificial and physical control methods. Motion in VR with artificial control methods is achieved via input devices while physical control methods translate natural movement from motion cues captured through body tracking or similar method [31]. VR motion type can be either continuous uninterrupted movement or non-continuous instantaneous movement [31]. VR interaction space can be divided to open, which supports navigation in a virtual environment surpassing the limitations of the real environment, or limited, in which interaction space for the virtual environment is limited due to the size of the real environment [31]. Finally, he identified four distinct VR locomotion types: motion-based, room scale-based, controller-based, and Teleportation-based.

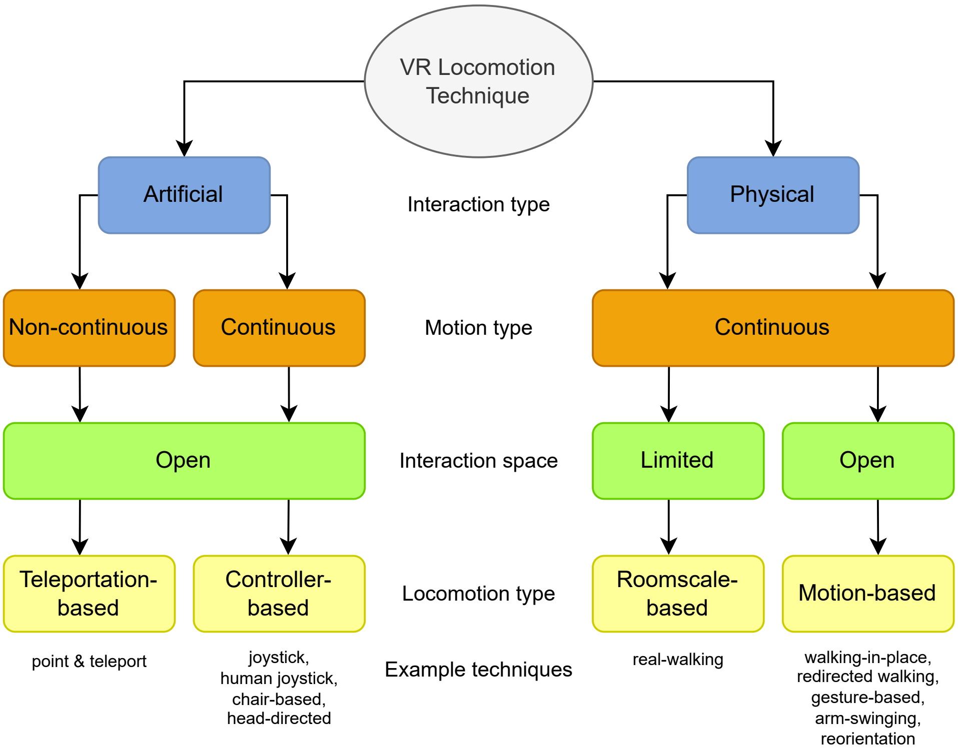

Figure 2. VR locomotion technique typology suggested by Boletis [31]

2.3.1. Popular Control Methods

In this section, the strengths and weaknesses of other popular control methods are shortly presented before moving over to leaning-based control methods. From Boletis' [31] review on VR locomotion, other popular control methods have been joysticks, Walk-In-Place (WIP), real walking, and redirected walking.

Joysticks have gained popularity in gaming consoles which include a hand-held controller with joysticks as the primary control method in video games. Commercial VR systems usually included controllers with joysticks which has led many VR games and applications to default to using joysticks as the primary method for locomotion. Joysticks can offer more precise control over many of the other control methods [32, 33] while also being comfortable to use as little physical effort is needed. However, joysticks often cause more VR sickness compared to most of the other control methods [34, 35, 36] because of sensory conflicts (see section 2.2).

In the WIP control method the user marches or steps in place to create motion similar to walking normally and the motion is captured via various methods, such as an HMD [37] or body trackers [32], and translated to motion in the VR. WIP has been popular due to it being a possible replacement for real walking because it can give stimuli similar to real walking for the proprioceptive system [32]. WIP does not require a large physical space to operate compared to real walking or redirected walking. The walking motion is also a familiar movement for people, thus learning to use WIP would be fairly easy. WIP has been shown to offer good spatial orientation [38, 39] but can suffer from lower precision in navigation tasks [32, 40]. However, WIP can be fatiguing to use as the user has to constantly do stepping motions to move around, especially for a larger VE.

In the real walking control method, the user's walking motion is directly translated to VR motion, usually using sensors from the HMD. VR systems and applications regularly combine both joysticks and real walking to create a locomotion system where joysticks are used for long-distance locomotion and real walking for making small movements. While real walking offers an overall better experience than many of the other control methods [41, 34, 32, 40], it is restricted to be used in small VEs as the size of the VE cannot exceed the size of the physical space.

An alternative to real walking is redirected walking which uses a slight unnoticeable mismatch between movements in the real and virtual world to steer the user away from the boundaries of the physical environment [42], thus enabling the user to navigate a VE larger than the physical environment. Similarly to the real walking control method, redirected walking offers benefits over non-walking control methods [35, 43] but the physical space required for redirected walking is around 25m x 25m to achieve fully uninterrupted and practical experience without the user reaching the boundaries of the area [42, 44]. A physical space that large is uncommon to have for the majority of the users making redirected walking as a control method unfeasible in most cases.

2.3.2. Leaning-Based Control Methods

There has been increased interest in leaning-based control methods [45, 39, 33, 6] as a possible solution for mitigating VR sickness and simultaneously offer a more realistic and immersive method to translate in a VE. Leaning-based control methods could alleviate VR sickness with small movements of your own body matching the motion seen on the screen which should mitigate sensory conflicts (see section 2.2 for more). Previous leaning-based control methods have been shown to increase presence and spatial awareness while decreasing VR sickness compared to joysticks [45, 38]. Common methods to capture leaning motions have been a sensing platform or tracking HMD pose [31, 45, 6]. A sensing platform commonly detects where the pressure of the person is distributed on top of the platform and the leaning direction is obtained from the pressure data (see Fig. 3). With HMD pose tracking, leaning motion can be captured when the HMD moves away from a given center point. Chair-based control methods can be divided into their own category but in most cases, those are a combination of a chair capable of rotation and tilt actions with either a sensing platform underneath [46], a pose tracking device on the chair [33, 46], or tracking HMD pose [45] to detect the leaning motion. Chair-based methods have the benefit of sitting down while in VR, thus might help with fatigue if the person does not prefer to stand for long periods of time.

Figure 3. An experimenter standing on a Wiiboard for leaning-based control of a telepresence robot, he is slightly leaning forwards.

A novel leaning-based control method called Joyman was implemented by Marchal et al. [47] and compared against joysticks. Joyman was based on the metaphor of a human-scale joystick where a board with a safeguard cage attached to it was suspended by springs on a basis and an inertial sensor was attached to the board to measure the current orientation of the board [47]. They found joysticks to be significantly better in terms of task completion time and easiness of use while Joyman was found to be better ranked for fun, presence, and rotation realism. No significant effect was found for VR sickness.

De Haan et al. [6] tested Wiiboard as a control method for translating in a virtual world among other use cases. They implemented forward and backward movement by leaning to the respective directions and strafing movement by leaning to the sides of the Wiiboard. The implementation also allowed rotating in place by applying weight to opposite sides of the Wiiboard with heels and toes. While the testing was limited to the authors and their colleagues, Wiiboard was intuitive to use and smooth to make transitions between forward motions and rotations while forward motions to sideways strafing were more difficult to achieve [6].

A leaning-based control method, Wii-Lean, was implemented by Williams and colleagues [38]. Wii-Lean utilized two Wiiboards as one big sensing platform with a plywood piece placed on top of the boards. Leaning was detected if the user's center of mass moved away from the center of the plywood piece. When leaning was detected, the user moved in VR towards their gaze direction and physical rotations were translated to rotations in VR. Wii-Lean resulted in better spatial awareness than joysticks and equal to WIP, however, Wii-Lean was reported to be favoured over WIP.

Valkov et al. [48] used Wiiboard as a component in a larger navigation system, where leaning forward or backward leads to respective motions and rotating left or right was done by leaning in those directions. Their study was not focused on Wiiboard and they did not compare it to other control methods. Subjects noted the steering to be very natural, however, fatiguing to use and difficult to make a turn in place or within short distance [48].

Ngyen et al. [45] compared joysticks and real walking against two novel control methods, NaviChair and NaviBoard. HMD pose tracking was used for both methods to detect leaning motion. NaviChair used a stool which could freely rotate and was equipped with a spring offering feedback for the person as an indication for leaving the set center point. With NaviBoard, participants stood on top of a board with an inner circle made out of wood and an outer square made out of soft styrofoam. The difference in the softness of the materials acted as tactile feedback of leaving the center point. Leaning was achieved by keeping one foot in the center of the board and stepping with the other in the target direction. They showed that both control methods offer clear benefits over joysticks in terms of VR sickness and task load. Out of the two methods, NaviChair performed better overall and was preferred by the participants.

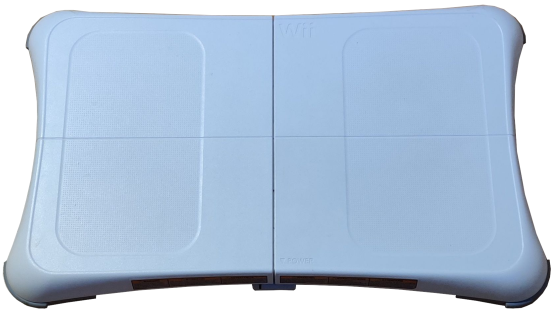

Figure 4. Nintendo Wii Balance Board.

In this study, a leaning-based control method was compared against joysticks; Wiiboard was used as the sensing platform (see Fig. 4). Leaning-based control methods have shown to offer benefits in presence [47], VR sickness [45], and performance [39, 45] over joysticks. The decision was made based on the thought of Wiiboard being suitable to use for a telepresence robot which uses a differential drive system and Wiiboard has been described to be intuitive and easy to use [6].

3. DESIGN AND IMPLEMENTATION

A control mapping was developed for driving a telepresence robot using the Wiiboard; the control mapping was developed to be used with a physical telepresence robot. The implementation for the user study comprised of a VE (more detailed description in section 4.3) with a robot modelled after a real mobile robot, controlled using the control mapping, (shown in fig. 5) moving within the environment. A virtual 360° camera was attached to the robot at a height of 1.5 meters from the base and the camera view was seen through an HMD; this height was suggested by [49] for 360° videos. The robot was able to move and rotate in a two-dimensional plane and was controlled directly by inputs from a Wiiboard or joysticks. Unity3D game engine was used to implement the system and C# was used as the programming language for scripts in the project.

Figure 5. The model of the telepresence robot's base, into which the pole with a camera and other equipment is attached.

3.1. Wii Balance Board

The Wii Balance Board is a piece of equipment made by Nintendo which consists of four pressure sensors, one at each corner. It communicates with a computer via Bluetooth but as it was originally designed for Nintendo consoles, it does not include direct support for a computer. Fortunately, an existing Unity Asset called WiiBuddy [50] was made for the purpose of receiving data and sending commands to Nintendo devices. A software [51] was used to stabilize the Bluetooth connection between the Wiiboard as the connection would sometimes unexpectedly cut off.

3.1.1. Mapping Leaning to Robot Motions

The initial implementation was designed based on [6]. Forward movement with Wiiboard was achieved by leaning forward, and turning while moving forward by leaning towards either of the front corners. However, early testing revealed that rotating in place (putting pressure on the toes with one foot and on the heel with the other) was fatiguing and leaning backwards (pressure on both heels) was difficult due to the stance being unstable. Furthermore, there is a low probability of needing backward motion with a telepresence robot because differential drive robots can rotate in place to orient in any direction. With a new design, the backward motion was disabled and rotation in place was implemented by shifting weight to one of the back corners, which did not fatigue the user and was perceived as reasonably easy to do by turning the upper body towards the desired corner. Another implementation for rotation in place was considered, in which the user put weight directly to the left or right side of the board without leaning forward. However, it caused unwanted rotation as it activated accidentally from time to time when the user tried to start or stop motion while leaning towards either of the front corners.

The robot was controlled by mapping the user input to reference the angular velocities of the wheels. For forward movement, the maximum wheel angular velocity was set to approximately 573° per second which corresponded to a robot forward speed of $0{,}75m/s$. The reason for this choice was motivated by [52] presenting that $1m/s$ is a suitable speed; however, we used a slightly lower value compared to precedents to increase comfort in controlling the robot using a device (Wiiboard) that most participants would be unfamiliar with.

The sensor readings, corresponding to the applied pressure on each corner, were used to calculate the two components that constitute the total motion: go forward (fwd) and turn ($turn$). These were calculated according to the equations, in which $F_.$ is the force measured by the sensor at the respective corner, (see Fig. 6 for the meaning of each index term)

$$\begin{aligned} fwd &= \max\left(\frac{(F_{TL}+F_{TR})-(F_{BL}+F_{BR})}{(F_{TL}+F_{TR})+(F_{BL}+F_{BR})}, 0\right) \\ turn &= \frac{F_{TR}-F_{TL}}{F_{TR}+F_{TL}}, \end{aligned} \tag{1}$$

Note that fwd and $turn$ lie within the ranges $[0, 1]$ and $[-1, 1]$, respectively. In case of rotation in place, $turn$ component was calculated as

$$turn = \frac{F_{BR}-F_{BL}}{F_{BR}+F_{BL}} \tag{2}$$

and fwd was set to 0. Respective reference wheel rotational velocities were calculated as

$$\omega_L = c_f fwd + c_t turn,\ \omega_R = c_f fwd - c_t turn \tag{3}$$

in which ω_L and ω_R are the reference velocities for the left and right wheels, and c_f and c_t are the respective weights. The weights were selected considering limits on forward and turning speeds and ensuring that $\omega_L, \omega_R \leq \omega_{max}$. In the case of rotating in place motion, used for getting out of a collision state, $\omega_{max} = 75deg/s$ was used to avoid uncomfortably fast rotations. This value was selected among three candidates ($132deg/s$, $103deg/s$, $75deg/s$) by performing demo testing on six people.

Value $103deg/s$ was preferred by the users who had previous experience using the implementation while $75deg/s$ was preferred by all inexperienced users.

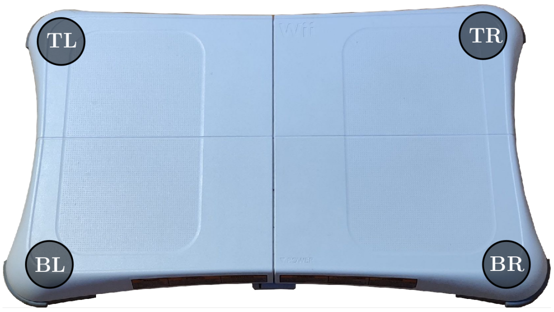

Figure 6. The Nintendo Wii Balance Board with the four sensors at the corners marked.

3.1.2. Calibration

To address the challenge of having a variety of people with different weights and leaning techniques, a calibration process was used to correctly map the sensor readings to robot controls and adjust Wiiboard for each user. In the calibration process, values from the sensors are measured for six different cases: standing still, leaning forward, and leaning towards each of the four corners. Values corresponding to standing still were used as offsets to ensure that the robot does not move at this posture since fwd and $turn$ are zero only when the weight is equally distributed (see Eqs (1) and (2)). However, even after the offset, the robot experienced a slight drift while standing still as it is practically impossible to stay completely still. Because of this, an *idle zone* was created in which the sensor readings are ignored and the robot does not move. The idle zone was achieved by setting a minimum value needed to move the robot. The rest of the cases were used to find maximum values achieved for fwd and $turn$ when the participants leaned *as much as they felt comfortable*. The minimum and maximum values were then used to map the fwd and $turn$ intervals $[0, 1]$ and $[-1, 1]$ so that the robot speed was the lowest at a minimum posture and the highest at an extreme posture. It was noted during testing that most users leaned too much when calibrating (even when told to “lean as much as you feel comfortable") which caused a problem where holding the extreme posture was not feasible without possibly losing balance. Thus, users were not able to go forward at the maximum speed as fatigue started to build up fast. The issue was solved by decreasing the readings corresponding to maximum speeds by taking 60% of the actual calibration values.

3.2. Joysticks

Two joysticks on the Oculus Quest 2 controllers were used as an alternative to contrast the Wiiboard control method. The joysticks were used to control the robot’s motion, the left joystick was used for forward speed (fwd) while the right joystick controlled both rotation speed and direction ($turn$). Moving the left joystick up on the vertical axis was mapped to interval $[0, 1]$ corresponding to fwd; other directions on the left joystick were disabled. The right joystick position on the horizontal axis was mapped to interval $[-1, 1]$ corresponding $turn$; movement on the vertical axis was disabled. Robot motion was achieved by tracking the reference wheel rotational speeds, calculated in terms of fwd and $turn$ using Eq.(3). Participants were standing still when using the joystick in the study.

4. USER STUDY

The aim of the user study was to research a leaning-based control method, Wiiboard, as a suitable option to be used for controlling a telepresence robot. Wiiboard was compared against joysticks to find out how well Wiiboard performed in comparison to a well-established control method. The performance of the control methods was measured in terms of VR sickness, overall task performance, and cognitive load. The study was done as a simulation in a virtual environment with a robot model situated in it. The participants were tasked to drive the robot along a path in the VE while counting paintings on the walls and avoiding collisions with objects and walls. The run was completed once with both control methods and after each run, the participants answered a series of questions.

4.1. Hypotheses

The following three hypotheses were pre-registered, together with the procedure and analyses to be used in the study, in Open Science Foundation (OSF) [1]. From now on we will refer to the **Wii Balance Board control method condition as WB** and **Joystick control method condition as JS**.

H1: Less VR sickness in WB condition as indicated by lower total weighted Simulator Sickness Questionnaire (SSQ) score.

H2: No difference in how far the participants get during the four minutes driving time and no difference in the number of crash events.

H3: No difference in cognitive load as indicated by no difference in NASA Task Load Index (NASA-TLX) scores in any dimension except the physical load.

We hypothesized H1 based on the evidence that incorporating some form of vestibular stimulation can potentially mitigate sensory conflict in VR, as described in Sections 2.3 and 2.2. Even though there is a slight mismatch between the vestibular and visual stimuli (such as forward-leaning being circular and not linear motion, and the rotations providing only an impulse of the motion that then further carries on visually in VR while the vestibular stimulation from the bodily motion ends), we believe that some amount of vestibular stimuli should ameliorate VR sickness as even random stimulation of the vestibular organs has been shown to help [53]. H2 stems from the work of de Haan et al. [6], who reported subjects found the Wiiboard to be easy to use; however, due to our expectation that our sample would have some familiarity with using a joystick, we predicted that there would not be any difference in performance. We postulated H3 for similar reasons; the Wiiboard clearly needs more physical effort, but otherwise, based on the ease of use reported in [6], we expected there would be no difference in cognitive load.

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[1] `https://osf.io/6rxby/?view_only=9990df8e0c104ac9b4bbc03ac72515a8`

4.2. Procedure

Two control methods, with two different starting positions (either end of the path shown in Fig. 7), were tried by the participants in a counterbalanced order such that every combination of a starting position and a control method was used as the first combination an equal number of times. The participant was welcomed by a researcher upon arrival and asked to read the information sheet and the privacy notice and sign a consent form. To pre-screen already sick-feeling people, the participants were asked if they felt nauseous or had a headache, and asked to reschedule if they did. After this, they were instructed to take their shoes off, stand on the Wiiboard, and place their feet in the middle of the textured areas of the Wiiboard (see Fig. 6).

Next, the researcher read out information about the imaginary scenario that took place in the VR during the study. Afterwards, the researcher gave instructions about the practice session to the participant; if the control method was the Wiiboard, the participant was first shown an instruction video on how to calibrate the balance board, after which the researcher instructed the participant how to put on the HMD and told the participant to complete the calibration. Next, the participant was told to take off the HMD and a second instruction video was shown to the participant which explained how to use the Wiiboard; this was done because the calibration was better to do with the HMD on to get realistic values to use with the HMD, but practising with the HMD on would likely have caused too much VR sickness on the participants. If the control method was the joysticks, the researcher read out instructions on how to use the joysticks to move the robot. Finally, the researcher read out the instructions for the practice session, which were identical for both control methods: the participant was told to complete the practice session without the HMD and follow the robot movement from a monitor in front of them. The participant was specifically instructed to crash into a wall to test out the turn-in-place feature and learn how to recover from a collision. After the practice, the participant was asked how confident they felt using the control method on a scale from 1 to 7 and the researcher marked down the answer. Then, the participant was told to put back on the HMD, follow the direction of the white line on the ground and count the sailboat paintings on the walls.

After the participant completed the run, they were told to take off the HMD and controllers and fill out questionnaires on a laptop, after which the same procedure was repeated for the second control method. In the end, the participant was rewarded with a 12€ gift voucher to Amazon and given a short debrief about the study.

4.3. Virtual Environment And Tasks

VE for the study was loosely based on parts of the local university; the VE and the path in the environment that the participants were asked to follow can be seen in Fig. 7. The path was travelled in both directions and each participant ran in the opposite direction on the second attempt (combinations of directions and conditions were also counterbalanced). The path was made to include various turns, straight sections, and tight spaces for the participants to navigate. The environment had five differently coloured lines on the floor as shown in Fig. 8, from which the white line was dedicated as the path to follow during the study. Multiple shortcut locations existed along the path and a decision to block the shortcuts was made based on the expectation of someone eventually taking a shortcut despite giving clear instructions not to. Shortcuts were blocked with either furniture, cardboard boxes, or red rope. The total length of the path was 186.6 meters and travelling through the whole path, without any mistakes, took slightly over four minutes. To make sure that each participant had the same amount of exposure during the study, a time limit of four minutes was set as the duration of one test run. It ensured that no one could fully travel the path as it took slightly over four minutes. Other coloured lines were added as a slight distraction and served as a side task to test whether the participants could still pay attention to the environment while commanding the robot. Another side task was the counting of six sailboat paintings (one seen in fig. 8) scattered around the VE to increase cognitive load and make the participant focus simultaneously on commanding the robot and looking for paintings, similar idea to the additional lines. To prevent memorizing the painting locations, different positions for the paintings were used during the second run of the study.

Figure 7. Birds-eye view of the path (white line) the participants should follow in the main task. The other lines have been removed for clarity.

To prevent the participants from memorising the layout of the environment, a separate small area was made as a practice room (shown in fig.9). The practice room had a white line as a guidance system for the participant to follow and learn how to move with the control method. After following the line to the end, they could freely learn how to use the control method. A maximum time limit of 5 minutes (per control method) was set for the practice session to get the study done in a reasonable amount of time and without accidentally over extending to the next participant's reserved time slot. However, the participant was able to move to the main test session at any point if they felt no more practice was necessary.

A collision avoidance system was implemented in the VE to prevent the robot from crashing into objects and walls. The system used invisible walls acting as triggers to detect if the robot got too close to an object or a wall. A collision halted any movement and prevented further forward movement after which the participant had to use the rotation functionality and turn the robot towards the path. The idea was to prevent further collisions with the same object or wall as the participant could only

Figure 8. Virtual environment used in the user study.

Figure 9. Small practice area for learning the control methods. White line as a guide to try out different types of movements.

move forward after already looking towards the path. While the participant was in a collision state, a text appeared that instructed them to turn towards the path. The text changed indicating that they can move forward after the robot was rotated away from the wall. The text was fixed to the gaze direction to easily see when the robot had been rotated enough.

4.4. Participants

Participants were recruited amongst the staff and students from the University of Oulu. The sample size for the study was 32 participants and the aim was to have an equal split of male and female participants. However, due to difficulties in getting enough female participants, the study was run with 17 male and 15 female participants. All participants reported having normal or corrected-to-normal vision and none of the participants were colourblind.

Initially, an exclusion criterion was set in place regarding collisions; if the participant was stuck for more than 30 seconds the results would be excluded from the study. Only the researcher was notified through the separate UI if the criterion was fulfilled and the participant carried on with the exercise normally to the end. The reason for adding this exclusion criterion was based on the idea of the participant most likely being unable to get the robot to turn properly, and in turn, causing more VR sickness by rotating than on an average run. The threshold of 30 seconds was decided based on the demo testing. However, the number of participants who exceeded this limit was higher than what was expected. Due to the difficulties in recruiting participants, a decision was made to relax this limit and use also the data corresponding to the participants who were stuck for more than $30s$ but otherwise completed the required tasks (4 males, 3 females among 32 participants). On average, participants were stuck for $21{,}05s$ in WB condition and $0{,}87s$ in JS condition for N=32; averages were $7{,}39s$ in WB condition and $0{,}32s$ in JS condition for N=25. Each session lasted exactly 4 minutes.

The pre-registered hypotheses were run both with all participants ($N = 32$) and the subset who did not get stuck for more than $30s$ ($N = 25$). Exploratory results were gathered using only all participants ($N = 32$) as reporting with two data sets was deemed unnecessary.

For VR system usage reported by all the participants ($N = 32$) was: $12{,}5\%$ never, $40{,}6\%$ once or just a couple of times, $25{,}0\%$ once or twice a year, $15{,}6\%$ once or twice a month, $3{,}1\%$ once or twice a week, and $3{,}1\%$ every day. Responses to how often they play computer games were: $12{,}5\%$ never, $15{,}6\%$ once or just a couple of times, $9{,}4\%$ once or twice a year, $18{,}8\%$ once or twice a month, $21{,}9\%$ once or twice a week, $12{,}5\%$ several times a week, and $9{,}4\%$ every day.

VR system usage reported by the subset of participants ($N = 25$) was: $16{,}0\%$ never, $32{,}6\%$ once or just a couple of times, $32{,}0\%$ once or twice a year, $12{,}0\%$ once or twice a month, 4% once or twice a week, and 4% every day. Responses to how often they play computer games were: $12{,}0\%$ never, $20{,}0\%$ once or just a couple of times, $20{,}0\%$ once or twice a month, $24{,}0\%$ once or twice a week, $12{,}0\%$ several times a week, and $12{,}0\%$ every day.

4.5. Measures

Two sets of questionnaires were presented to the participant after finishing each of the sessions. The latter part of the second questionnaire contained post-experiment questions. At the beginning of each questionnaire, the participant filled out a SSQ [54] and SSQ total score was used to measure sickness. SSQ is an established questionnaire for measuring sickness in VR by presenting 16 possible sickness symptoms, which the participants gauge on a scale from none (0) to severe (3). The SSQ total score is calculated by weighting the answers for a maximum score of 236. Higher scores indicate greater levels of sickness experienced. After the SSQ, NASA-TLX questionnaire [55] was administered, which is used to measure six dimensions of workload (mental demand, physical demand, temporal demand, performance, effort, and frustration) of the task. Each dimension was rated on a scale of 1 to 20 and higher values indicate that the task is more demanding in that aspect. Finally, a presence questionnaire, Slater-Usoh-Steed (SUS) [56], was filled by the participant for gathering additional data for possible exploratory analysis. SUS consists of questions which are based on three themes: the sense of "being there" in the VE, the extent to which the VE becomes the prevalent reality over the real world, and the extent to which the participant sense the VE as a real place. Each question is rated on a scale of 1 to 7 with the higher score indicating greater sense of presence. The final presence score is constructed by adding up the number of answer that have a score of 6 or 7.

Additionally, we used 7-point Likert-scale questions, forced-choice questions comparing the two methods, and open-ended questions about reasons for some choices and demographic questions. After a practice session, the participant answered Likert-scale questions on how confident they felt with the particular control method. After a session, they were asked how comfortable and how easy it was to use and further define why in open-ended questions. Additionally, after each session, the participants answered how many sailboat paintings they saw during that session. Forced-choice questions were presented in the second questionnaire after the experiment was over to find out which control method was preferred, easier to control, more comfortable to use, and gave a better sense of presence. Each forced-choice question was followed with open-ended field if the participant wanted to explain why. The participant were also asked to fill in their shoe size. Shoe size was gathered for possible exploratory analysis to find if it affected how well the participant was able to use the Wiiboard. Finally, generic information about the participant and their previous VR and gaming experience was gathered.

During the sessions, various data were collected from the HMD and virtual environment to assess the performance of the two control methods. The HMD and robot model was equipped with a tracking script to record position and rotation in the VE. Per tracked object, the tracking script saved position in x, y, and z -coordinates and rotation in Quaternions; the HMD tracking data was logged in both, the world coordinate frame and the robot's local coordinate frame while the robot's data was logged in the world coordinate frame. The robot's coordinate data was used to calculate the distance the robot drove along the reference path by comparing the reference path coordinate points to the robot's last coordinate point. Rotation data was logged to allow for the possibility to find out the total amount of head rotations if needed for exploratory analysis. Additionally, the total count of collisions with walls or obstacles and the length of time spent in a collision state were logged. Finally, the VE kept a log of how many paintings the participant had passed to compare it to the count reported by the participant.

5. RESULTS

All statistical tests were run in SPSS with significance levels set to $0{,}05$ and with a 95% confidence interval.

5.1. Confirmatory Results

All confirmatory analyses were performed first using the whole dataset $(N = 32)$ and then using only the data corresponding to the participants who were not in a collision state for longer than $30s$ $(N = 25)$.

Less VR sickness in Joystick control method (JS) condition (H1 rejected) A Wilcoxon Signed-Ranks test (two-sided) was performed to compare the differences between the total weighted SSQ scores for JS and Wii Balance Board control method (WB) conditions (see Table 1 for respective means and the corresponding standardized test statistics, significance values, and effect sizes). The test indicated that JS elicited significantly lower SSQ scores compared to WB. We also checked for a potential effect of getting stuck for more than $30s$ on sickness and run the test again using only the participants who did not get stuck or got stuck less than $30s$ $(N = 25)$. We did not observe any significant difference between the total weighted SSQ scores for JS and WB conditions when participants who got stuck were excluded from the analysis, as indicated by a Wilcoxon Signed-Ranks test (two-sided).

SSQ	Means		Test summary
	JS	WB	
N=32	32.02	40.44	Z = -2.32, p = 0.02, r = 0.41
N=25	29.92	37.85	Z = -1.84, p = 0.066, r = 0.396

Table 1. Means and the respective results of a Wilcoxon Signed-Ranks test (two-sided) for the SSQ corresponding to $N = 32$ and $N = 25$ datasets.

Participants reached farther along the path in JS condition (H2 rejected) A paired t-test was run to determine whether in one condition the participants reached farther along the path $(N = 32)$. The total path length was $186{,}6$ meters and none of the participants reached the end (we ensured this by selecting the path length and the time limit on each session so that all participants have equal exposure to the VE). The distances in both conditions were normally distributed, as indicated by a Shapiro-Wilk test, $W(32) = 0{,}956, p = {,}214$ for JS, $W(32) = 0{,}966$, $p = {,}398$ for WB, and there were no outliers in the data, as assessed by inspection of the boxplots. The mean distance was higher in JS condition $(162{,}39 \pm 13{,}52)$ compared to in WB condition $(124{,}86 \pm 26{,}53)$; a statistically significant increase of $37{,}54$ (95% CI, $30{,}30$ to $44{,}78$), $t(31) = 10{,}58$, $p = {,}00$. We removed the data corresponding to participants who were stuck and ran the same test again. The distances conformed to a normal distribution in both conditions as indicated by a Shapiro-Wilk test ($W(25) = 0{,}944$, $p = {,}182$ for JS and $W(25) = 0{,}954$, $p = {,}301$ for WB) and there were no outliers. A paired samples t-test indicated that there was a statistically significant increase in the distances that the participants reached within a given time frame in JS condition from $132{,}83 \pm 23{,}45$ to $165{,}17 \pm 11{,}93$; an increase of $32{,}33$ (95% CI, $24{,}73$ to $39{,}94$), $t(24) = 8{,}776$, $p = {,}00$.

Less collisions in JS condition (H2 rejected) The number of crash events in JS condition $(m = 0{,}4)$ were lower than the number of crash events in WB condition $(m = 1{,}4)$ for $N = 32$, this decrease was statistically significant as indicated by a Wilcoxon Signed-Ranks test (two-sided), $Z = -3{,}477$, $p = {,}001$, $r = 0{,}615$. This tendency in having fewer collisions persisted also when the data corresponding to the people who got stuck in a collision state for longer than $30s$ was removed $N = 25$. There were significantly fewer crash events in JS condition $(m = 0{,}4)$ as opposed to in WB condition $(m = 1{,}2)$, as indicated by a Wilcoxon Signed-Ranks test (two-sided), $Z = -2{,}862$, $p = {,}004$, $r = 0{,}572$.

Higher perceived workload in WB condition (H3 rejected) For each subscale of NASA-TLX, a Wilcoxon Signed-Ranks test (two-sided) was performed to compare the ratings for JS and WB conditions considering both the data with and without exclusions (see Table 2 ($N = 32$) and Table 3 ($N = 25$) for respective means and the corresponding standardized test statistics, significance values, and effect sizes). With $N = 32$ there was a statistically significant increase in the TLX scores in all dimensions other than performance. When the same test was performed with $N = 25$, we observed that TLX scores were higher in all dimensions except performance and temporal demand.

TLX subscale	Means (N=32)		Test summary (N=32)
	JS	WB	
Mental demand	7.88	11.22	$Z = -3{,}73$, $p = {,}00$, $r = 0{,}659$
Physical demand	4.035	11.09	$Z = -4{,}63$, $p = {,}00$, $r = 0{,}819$
Temporal demand	4.5	6.81	$Z = -2{,}64$, $p = {,}008$, $r = 0{,}467$
Performance	6.31	7.81	$Z = -1{,}40$, $p = {,}16$, $r = 0{,}248$
Effort	5.9	11.62	$Z = -4{,}55$, $p = {,}00$, $r = 0{,}804$
Frustration	3.78	8.22	$Z = -4{,}38$, $p = {,}00$, $r = 0{,}774$

Table 2. Means and the respective results of a Wilcoxon Signed-Ranks test (two-sided) for the NASA-TLX subscales corresponding to $N = 32$ datasets.

TLX subscale	Means (N=25)		Test summary (N=25)
	JS	WB	
Mental demand	7.28	10.56	$Z = -3{,}47$, $p = {,}001$, $r = 0{,}694$
Physical demand	4.96	6.48	$Z = -4{,}02$, $p = {,}00$, $r = 0{,}804$
Temporal demand	4.08	10.28	$Z = -1{,}82$, $p = {,}069$, $r = 0{,}364$
Performance	6.44	7.60	$Z = -1{,}02$, $p = {,}307$, $r = 0{,}204$
Effort	5.6	11.12	$Z = -3{,}96$, $p = {,}00$, $r = 0{,}792$
Frustration	3.48	7.88	$Z = -3{,}93$, $p = {,}00$, $r = 0{,}786$

Table 3. Means and the respective results of a Wilcoxon Signed-Ranks test (two-sided) for the NASA-TLX subscales corresponding to $N = 25$ datasets.

5.2. Exploratory Results

We performed an exploratory analysis of all participants ($N = 32$) to get a deeper insight into our results.

5.2.1. *Quantitative Data*

Participants felt more confident in using the JS condition To measure participants' confidence in using either control method, we asked them to rank their confidence in Likert-scale $(1 - 7)$ after each training session. People felt statistically significantly more confident in using JS $(Mean = 6{,}25)$ as opposed to WB $(Mean = 4{,}94)$ condition, as indicated by a Wilcoxon Signed-Ranks test (two-sided), $Z = 4{,}478$, $p = {,}00$, $r = 0{,}79$.

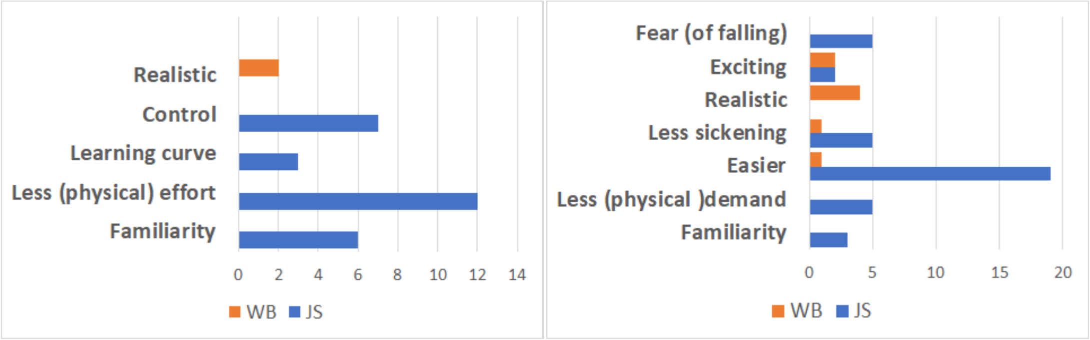
JS condition was found easier to use We measured the relative ease-of-use by explicitly asking: Which control method was easier to use? 30 out of 32 participants (94%) found JS condition easier to use. This bias towards JS condition was statistically significant in an exact binomial test with exact Clopper-Pearson 95% CI and had a 95% CI of $79{,}2\%$ to $99{,}2\%$, $p = {,}00$ (two-sided). In addition to the forced-choice question we also asked 7-point Likert-scale questions to measure ease-of-use. Comparing the ratings in JS condition $(Mean = 6{,}03)$ with the ones in WB condition $(Mean = 3{,}59)$, we found that JS elicited a statistically significant increase in the comfort rankings, as indicated by a Wilcoxon Signed-Ranks test (two-sided), $Z = 4{,}783$, $p = {,}00$, $r = 0{,}846$.

JS condition was preferred When asked explicitly which condition did the participants prefer, 26 out of 32 participants (81%) picked JS condition. An exact binomial test with exact Clopper-Pearson 95% CI indicated that this bias towards JS condition was statistically significant and had a 95% CI of $63{,}6\%$ to $92{,}8\%$, $p = {,}001$ (two-sided).

WB condition did not increase presence When asked "Thinking back to both of the experiences, which one gave a better sense of being in the robot's location?" 19 participants (59%) picked the WB condition, though this bias towards WB condition was not statistically significant in an exact binomial test (two-sided), $p = {,}377$.

5.2.2. *Qualitative Data*

The open-ended data was analyzed using the thematic analysis method with an inductive approach [57]. Fig. 10a presents the frequent codes found in the data related to ease-of-use, divided by which condition was found easier to use. These codes are then grouped into three themes: expectations and previous experience, less (physical) effort, and control. The first theme refers to the previous experience of people in terms of moving in VR or in the real world and their expectations based on that. It encompasses the codes *realistic*, *learning curve*, and *familiarity* containing 11 comments in total. Codes *less (physical) effort* (12 occurrences) and *control* (7 occurrences) are themes of their own referring to less required physical effort to use a control method and the sense of control over the robot, respectively.



(a) Ease-of-use (b) Preference

Figure 10. Frequent codes found in open-ended questions regarding ease-of-use and preference together with their occurrences.

JS were reported to be easier to use because it required less physical effort and was easier to learn The majority of people who found JS condition easier thought so because it required *less physical effort* (“It only required the movements of my thumbs, no more was required."). This is followed by reasons related to their *expectations and previous experience* with VR. In particular, they felt JS was familiar and that it was easier to learn (coded as *learning curve*). Finally, some people thought JS was easier to use because they had more *control* over the robot with this method (“You feel more in control with this method"). Responses given by the two participants who found WB easier stemmed from their *expectations and previous experience*; they thought it was more *realistic*, that is, similar to moving in the real world (“Personal choice of use by feet than hand, more realistic").

Participants who preferred JS reported it to be easier to use and cause less sickness symptoms Codes and their frequencies related to the data on reasons for participants' preferences can be found in Fig. 10b. The codes are grouped under the themes: *bodily feelings* encompassing *less physical demand* and *less sickening* containing 11 comments, *expectations and previous experience* encompassing *realistic* and *familiarity* containing 7 comments, *emotions* encompassing *fear* and *exciting* containing 9 comments, and finally *easier* being an important theme of its own. The most popular reason given by the participants who preferred JS condition was because it was *easier* to use (19 occurrences in JS condition, for example, “I didn't have to focus as much on how to use the control method on the first one..."). This was followed by the reasoning that fell under the theme of bodily feelings, meaning that it induced less negative physiological response or that it was physically less demanding (“...The second one caused more motion sickness-like symptoms."). Some people who preferred JS thought that it made them feel better emotionally (falling under the theme *emotions*), compared to WB, especially since they did not experience a fear of falling down (“I didn't feel like falling").

Participants who preferred WB thought it to be more realistic People who preferred the WB condition named the biggest factor as it being *realistic* based on their *expectations and previous experience* (for example, *"Despite being more physically challenging it gives more movement and feels almost like real movement."*). Other reasons stated fell under having better *emotions* (*“It was cool and made me feel more in the place."*) and having less bad *bodily feelings* (*“And I also felt really nauseous* *doing the task with the controllers but not nauseous at all doing it with the balance board"*).

6. DISCUSSION

6.1. Original Hypotheses

H1 was rejected as JS condition induced less VR sickness on average as indicated by the total SSQ scores. Further evidence for JS condition inducing less VR sickness was found in the open-ended questions, in which the *less sickening* code was used as a reason by 5 participants who preferred the JS and only once by who preferred the WB. However, the total SSQ scores of the participants who did not get stuck for more than $30s$ ($N = 25$) revealed no statistically significant difference between total SSQ scores of JS and WB conditions. Similarly, H2 and H3 were rejected too; participants reached farther along the path and experience fewer collisions while using the JS as opposed to the Wiiboard and the NASA-TLX scores showed that the participants perceived controlling the robot using joysticks less demanding in almost every dimension. Interestingly, the amount of collision between the two data sets (N = 32 and N = 25) change only a little for the WB condition ($Mean$ = 1,4 and $Mean$ = 1,2) while JS stayed the same ($Mean$ = 0,4). The almost identical amount of collisions on average with WB condition indicates that controlling the robot while driving forwards was perceived to be difficult but most of the participants were able to use the turning function correctly after getting stuck to an object as they did not break the $30s$ limit. A possible reason for these results was found in a further look into the open-ended questions which revealed interesting insights.

The answers to the open-ended questions show signs of a potential relationship between perceived difficulty and VR sickness. Two of the participants who preferred the JS condition, because it induced less sickness, stated that *“Not having to look at floor while leaning prevents nausea"* and *“I didn’t have to focus as much on how to use the control method on the first one. The second one caused more motion sickness-like symptoms."* One of the participants who reported having more sickness with the WB condition said that *“Controlling was difficult while turning the robot"*. During the study, the researchers observed that the participants who got stuck for long periods of time commonly ended up rotating back and forth trying to orientate the robot correctly. Some additionally resorted to looking down at the robot to see how the robot was reacting to the movement. Since staring at the floor would result in more optical flow, and thus likely induce more VR sickness, if participants looked at the floor more with the Wiiboard, it may likely have increased their VR sickness levels. This effect was noticeable during initial testing by the researchers, especially when looking down at the robot while rotating. This would explain the difference between the total SSQ scores of the two data sets ($N = 32$ and $N = 25$) as the participants who had difficulties with the Wiiboard experienced more VR sickness.

A potential relation between difficulty and VR sickness was further indicated by looking at the confidence scores of the participants who commented on their respective method to be less sickening. The participant who found the Wiiboard less sickening gave a confidence score of 7 (on a 7-point Likert-scale) for using the WB, whereas the average of the confidence scores given by the 5 people who found WB more sickening was 5,2. Similarly, one participant who mentioned that the WB condition was less sickening rated its ease-of-use as 5 (out of 7), whereas the average of the ease-of-use ratings given by the 5 participants who found the board more sickening was 2,6. Despite being based on a small sample size, these insights further strengthen the implication of difficulty causing more VR sickness. The other possible cause for increased VR sickness with the board is the postural instability caused by the control motions, even though, as mentioned, the order of cause and consequence is unclear [30] and not researched when leaning is used for control.

Interestingly, the Wiiboard was described as “effective and easy to use" by earlier papers [6] when used among the researchers and colleagues. Similar results were found during our pre-pilot testing in which users preferred the Wiiboard and effectively used it to control the robot. Additionally, the users in pre-pilot testing found the Wiiboard to be less sickening than JS. However, during the study, the participants still perceived using the board as more difficult ($Mean = 3{,}59$ on a 7-point Likert-scale). We expected that participants would find using the board more difficult compared to the joystick; this was in part due to the well-known result in 3D user interfaces such that that using a high Degrees of Freedom (DOF) input to control a lower DOF system is typically challenging [58], and in part due to the familiarity of the general population with the joystick. However, we did not expect to see a difference in the perceived difficulty of using the Wiiboard to the extent that we observed (a statistically significant difference in favour of JS in almost all dimensions of the NASA-TLX).

Besides VR sickness, the difficulty had a major impact on preference: 20 out of 32 participants, stated "easiness" as their reason for preferring a particular method, among which 1 person stated it in preference of the Wiiboard and 19 in favour of the joystick. Additionally, when asked why one method felt easier than the other, three people specifically noted the steep learning curve for the Wiiboard *(“The second method is a bit harder to get used to")* and six people mentioned that their familiarity with joysticks may have helped *(“Joysticks are a familiar method and very intuitive too. Balancing takes more effort").*

6.2. Exploratory Data

The initial idea was to have unlimited training duration because we expected that the participants would not be familiar with the board and that using the board would employ a steeper learning curve. However, other sections of the study already took a significant amount of time, thus we had to put a time limit (5 minutes) to keep the duration per participant within an hour. The given time to practice was evidently not enough as the results have shown with Wiiboard being more difficult. Based on these results, we expect that longer practice time could produce more favourable results for the Wiiboard. This was supported by comments of three participants who said that longer practice time should make the Wiiboard easier; for example, *“More exciting and would “become" easier after many practices.", “the commands are quite easy, with enough practice anyone can do it"*.

Additionally, We decided to make participants undergo a training session without the HMD. Training with the HMD on could have caused excessive sickness and differences in training times, as the participants had the option to move on from the practice session at any given time, which could have potentially corrupted the SSQ data. Despite mitigating these potential issues, practicing without the HMD caused a shortcoming in our approach as using WB with the HMD was slightly different than using it without

(“I’m used to moving in VR with joysticks, the balance board was a bit harder to get used to especially because the HMD made it a bit harder to balance myself."). It would be interesting to perform a smaller-sample qualitative long-term study with the board, where we give participants ample time to practice on the board on the scale of days or weeks, and then compare the differences and SSQ scores; we suspect that this kind of study would better bring out the strengths of the leaning-based control using a balance board.

We also wondered whether the body-based locomotion would make participants feel more present; whereas it is well established that having an actual virtual body that tracks your motions increases presence [3], there is, to the knowledge of the authors, no clear evidence whether having “a bit more realistic" body-based control should increase the feeling of presence (in [59] simply moving the body increased presence, but the comparison was standing still, not moving via a joystick or similar). There were hints towards the board making participants feel more present; four participants preferred the Wiiboard because it felt more *realistic ("It was cool and made me feel more in the place. Although it was easier with the first method and I think that I also accomplished the task better with the first method (like no bumping into the wall).")*, and some participants who preferred the joystick at the end still stated the positives of the Wiiboard towards that direction *(“Because I could accomplish the task with the first one and with the second I got stuck. However, the second one was more fun and I felt more engaged.")*. However, the forced-choice question about presence was not significant (even if leaning towards that direction). Nonetheless, there seems potential for more studies on presence with body-based locomotion.

6.3. Limitations and Future Work

A clear limitation of the study was the hardware: the Wiiboard is old technology and has limited sensors, which are not extremely accurate. Despite the technical limitations of the board, the responsiveness of the Wiiboard could have been improved further as it was noted that the robot accelerated slightly too fast. This could have been a reason for nine people mentioning better control of the robot with the joystick as a reason for finding it easier. Additionally, multiple participants reported that using Wiiboard combined with the HMD affected their balance which in turn added to the difficulty (*"It was a bit hard to get used to controlling the robot with the VR headset, because it was harder to balance while wearing it.")*. Altogether 5 participants reported fear of falling off the board as a reason for preferring the joystick; with the Wiiboard, feet are kept side by side, as in a normal standing position, which can make some of the leaning positions to feel insecure and require better balancing from the participant. To alleviate the fear of falling, a viable option would be to use a thin mattress equipped with sensors, allowing free placement of a foot such that the participant can find a stable posture. Additionally, such a system would allow rotating the robot also via rotating the whole body, which has been shown useful in reducing VR sickness and enhancing spatial awareness [45]. Such a combination of the strengths of the methods could provide interesting results.

These results could also be used as a stepping stone to finding out the relationship between postural instability and VR sickness; does active destabilization of the posture, in the form of leaning, contribute to VR sickness? With a more accurate pressure mat, we may be able to differentiate between wanted and unwanted postural sway, and correlate them with the (perhaps continuously measured) VR sickness and HMD tracking data; additionally, if the pressure sensor was used to measure the postural instability also when controlling via the joystick, this comparison could reveal interesting facets about wanted and unwanted postural instability.

7. CONCLUSION

This thesis presents a leaning-based control method on a balance board for an immersive telepresence robot. The thesis introduced an implementation of a leaning-based control method, Wiiboard, which comprised mapping leaning motions to robot movement in VR and a calibration process, to personalize the board for each user better. To evaluate the Wiiboard, we conducted a user study with 32 participants, in which the Wiiboard was compared against a common control method, joysticks. The study was done in a simulation in a VE, where the participants were tasked to drive a telepresence robot along a marked path once with each control method. The results showed that most participants preferred the JS because it was reported to be easier to use and cause less VR sickness. The Wiiboard was noted to have potential, but the unfamiliarity and difficulty prevented the possible positive effects of reducing VR sickness. We identified several reasons making the board so difficult, such as not enough responsiveness, steep learning curve requiring more training than a few minutes before the actual study, training with the headset on even with the chance of inducing VR sickness during training, and the height of the board causing a fear of falling. For future work, we suggested that a more responsive thin mattress equipped with sensors, essentially a pressure mat, could be tested for chances of improvement. This type of device could also allow self-rotations and use one foot as a stabilizer for better balance.

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9. APPENDICES

Appendix 1. Questionnaire After the First Session

Questionnaire after the 1st Session

Mandatory questions are marked with a star (*)

This section is completed by the experimenter.

Subject ID *

Video Code *

○ Wii Board

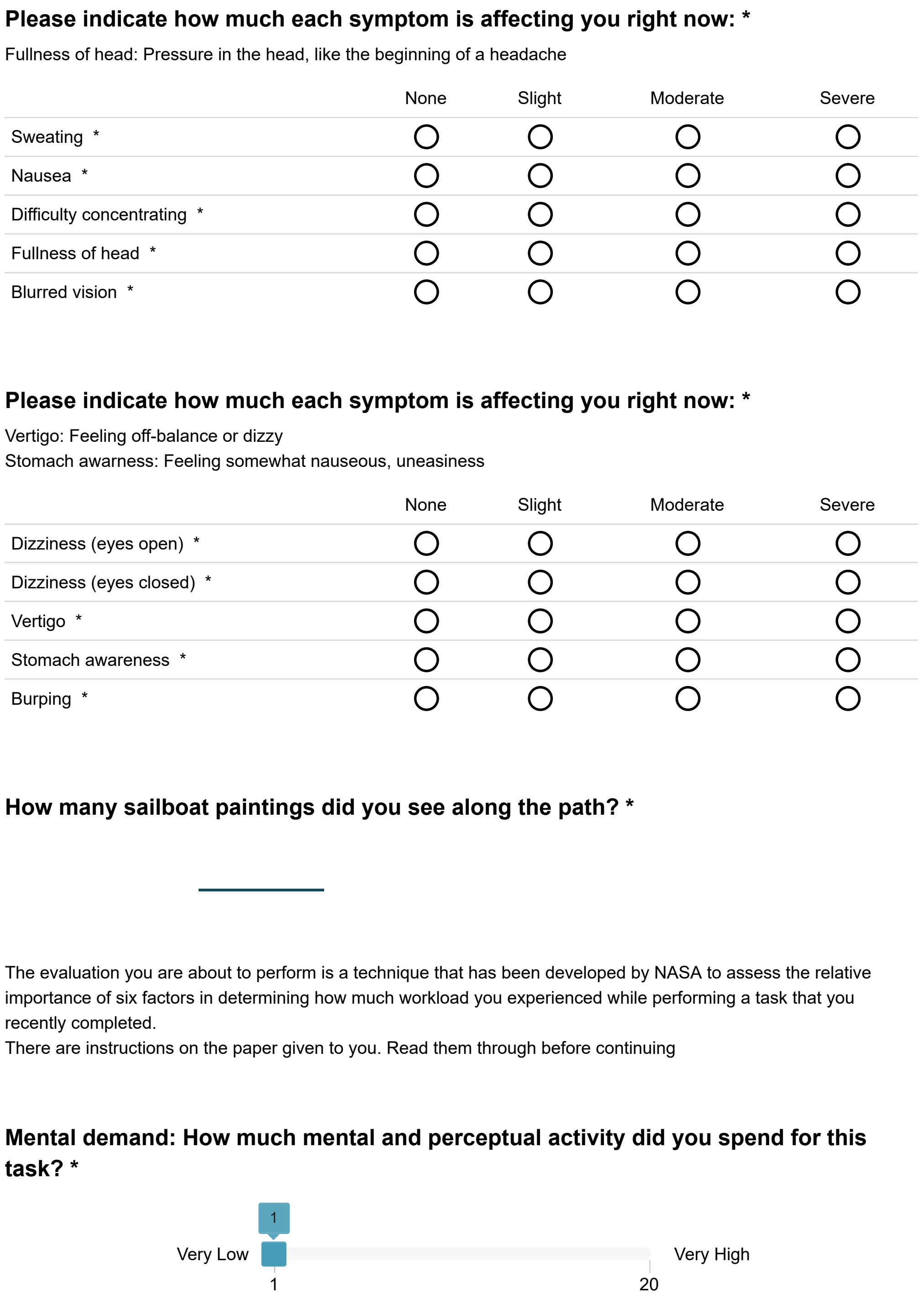
○ Joystick

How confident does the participant feel about using the control method after training? *

	1	2	3	4	5	6	7	
Not confident	○	○	○	○	○	○	○	Very confident

Please indicate how much each symptom is affecting you right now: *

	None	Slight	Moderate	Severe
General discomfort *	○	○	○	○
Fatigue *	○	○	○	○
Headache *	○	○	○	○
Eyestrain *	○	○	○	○
Difficulty focusing *	○	○	○	○
Increased salivation *	○	○	○	○



Please indicate how much each symptom is affecting you right now: *

Fullness of head: Pressure in the head, like the beginning of a headache

	None	Slight	Moderate	Severe
Sweating *	○	○	○	○
Nausea *	○	○	○	○
Difficulty concentrating *	○	○	○	○
Fullness of head *	○	○	○	○
Blurred vision *	○	○	○	○

Please indicate how much each symptom is affecting you right now: *

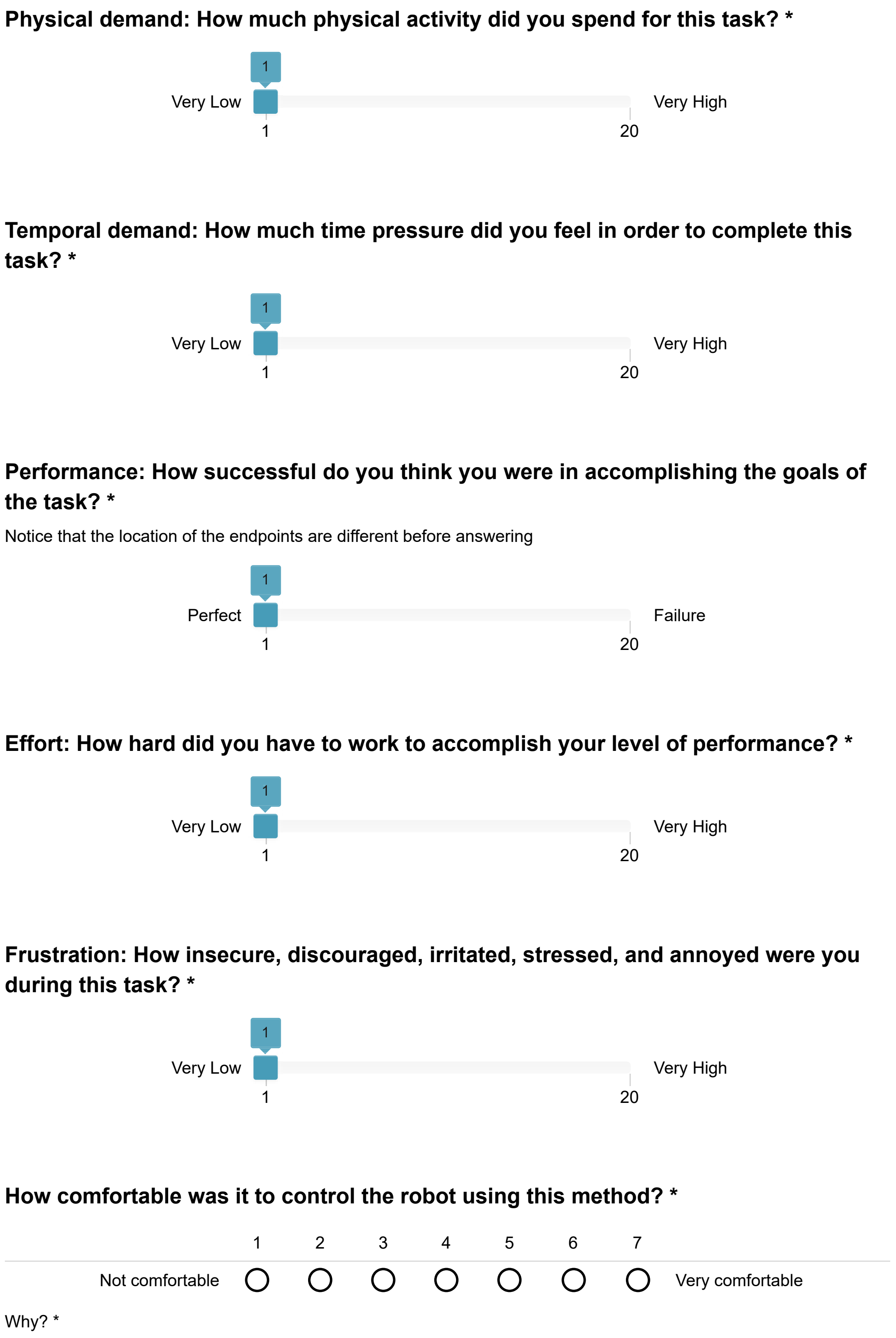
Vertigo: Feeling off-balance or dizzy
Stomach awarness: Feeling somewhat nauseous, uneasiness

	None	Slight	Moderate	Severe
Dizziness (eyes open) *	○	○	○	○
Dizziness (eyes closed) *	○	○	○	○
Vertigo *	○	○	○	○
Stomach awareness *	○	○	○	○
Burping *	○	○	○	○

How many sailboat paintings did you see along the path? *

The evaluation you are about to perform is a technique that has been developed by NASA to assess the relative importance of six factors in determining how much workload you experienced while performing a task that you recently completed.
There are instructions on the paper given to you. Read them through before continuing

Mental demand: How much mental and perceptual activity did you spend for this task? *



Physical demand: How much physical activity did you spend for this task? *

1

Very Low Very High

1 20

Temporal demand: How much time pressure did you feel in order to complete this task? *

1

Very Low Very High

1 20

Performance: How successful do you think you were in accomplishing the goals of the task? *

Notice that the location of the endpoints are different before answering

1

Perfect Failure

1 20

Effort: How hard did you have to work to accomplish your level of performance? *

1

Very Low Very High

1 20

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you during this task? *

1

Very Low Very High

1 20

How comfortable was it to control the robot using this method? *

	1	2	3	4	5	6	7	
Not comfortable	○	○	○	○	○	○	○	Very comfortable

Why? *

How easy was it to control the robot using this method? *

	1	2	3	4	5	6	7	
Very Difficult	○	○	○	○	○	○	○	Very Easy

Why? *

In the following, the remote environment refers to the environment that the robot was moving in.

Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place. *

I had a sense of "being there" in the remote environment

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much

To what extent were there times during the experience when the virtual environment was the reality for you? *

There were times during the experience when the remote environment was the reality for me.

	1	2	3	4	5	6	7	
At no time	○	○	○	○	○	○	○	Almost all the time

When you think back to the experience, do you think of the virtual environment more as watching a movie or more as someplace that you visited? *

The remote environment seemed to me to be more like

	1	2	3	4	5	6	7	
Watching a movie	○	○	○	○	○	○	○	Someplace I visited

During the time of the experience, which was strongest on the whole, your sense of being in the virtual environment, or of standing at your original position? *

I had a stronger sense of

	1	2	3	4	5	6	7	
Standing at original position	○	○	○	○	○	○	○	Being in the remote environment

Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By ‘structure of the memory’ consider things like the extent to which you have a visual memory of the remote environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements. *

I think of the remote environment as a place in a way similar to other places that I've been today

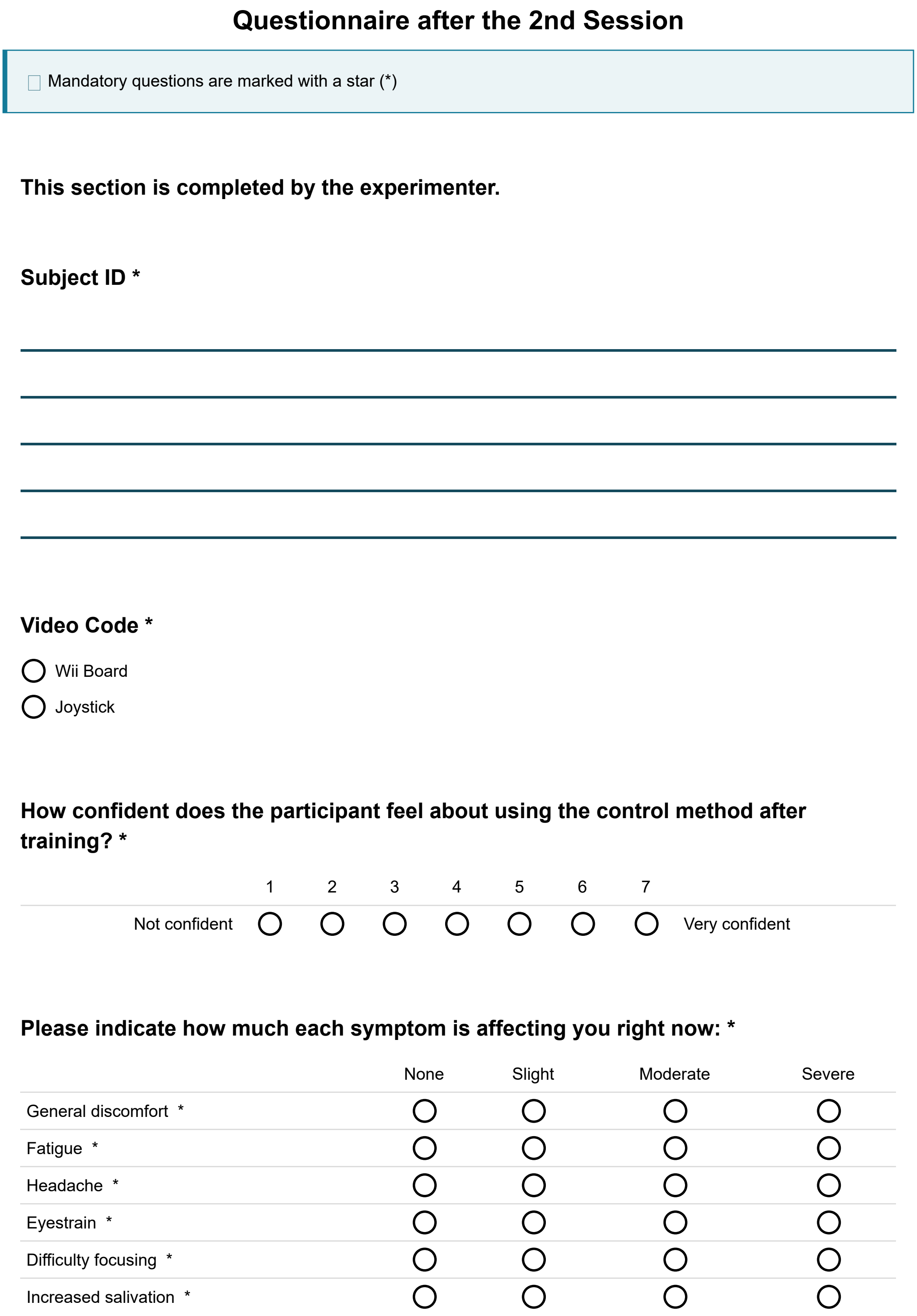
	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much so

During the experience, did you often think to yourself that you were actually in the virtual environment? *

During the experience I often thought that I was at the remote environment

	1	2	3	4	5	6	7	
Never	○	○	○	○	○	○	○	Most of the time

Appendix 2. Questionnaire After the Second Session



Questionnaire after the 2nd Session

Mandatory questions are marked with a star (*)

This section is completed by the experimenter.

Subject ID *

Video Code *

○ Wii Board

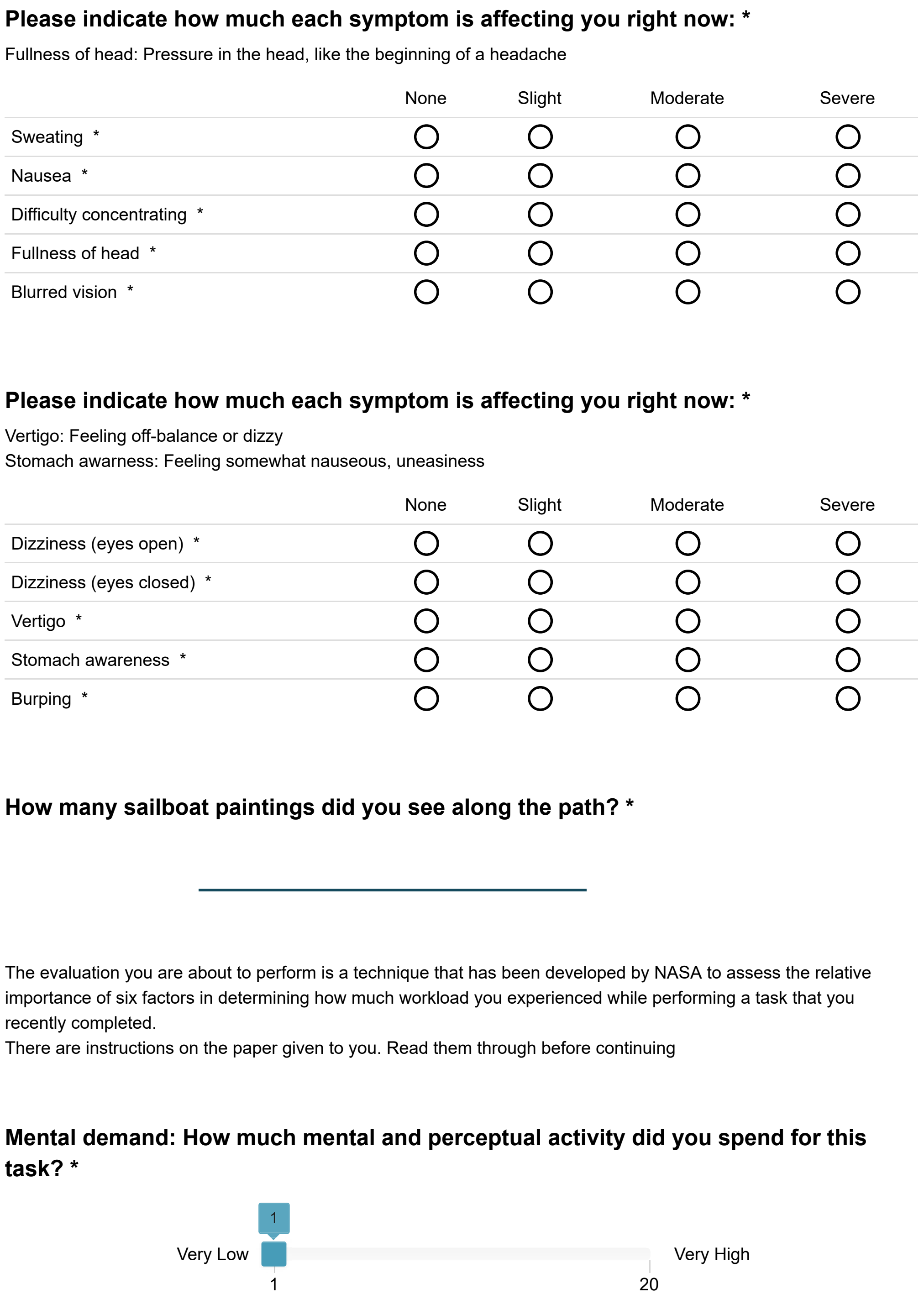
○ Joystick

How confident does the participant feel about using the control method after training? *

	1	2	3	4	5	6	7	
Not confident	○	○	○	○	○	○	○	Very confident

Please indicate how much each symptom is affecting you right now: *

	None	Slight	Moderate	Severe
General discomfort *	○	○	○	○
Fatigue *	○	○	○	○
Headache *	○	○	○	○
Eyestrain *	○	○	○	○
Difficulty focusing *	○	○	○	○
Increased salivation *	○	○	○	○



Please indicate how much each symptom is affecting you right now: *

Fullness of head: Pressure in the head, like the beginning of a headache

	None	Slight	Moderate	Severe
Sweating *	○	○	○	○
Nausea *	○	○	○	○
Difficulty concentrating *	○	○	○	○
Fullness of head *	○	○	○	○
Blurred vision *	○	○	○	○

Please indicate how much each symptom is affecting you right now: *

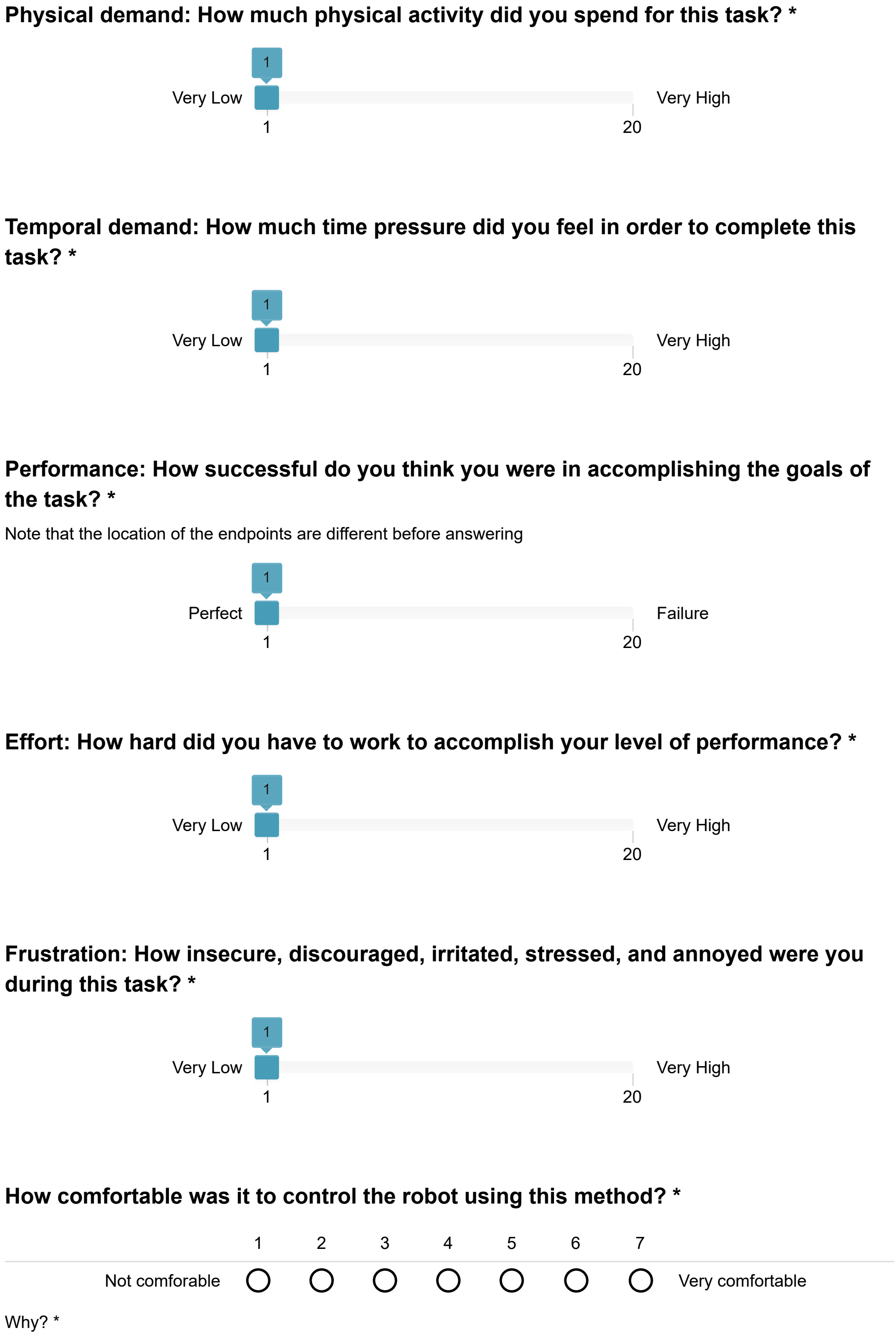
Vertigo: Feeling off-balance or dizzy
Stomach awarness: Feeling somewhat nauseous, uneasiness

	None	Slight	Moderate	Severe
Dizziness (eyes open) *	○	○	○	○
Dizziness (eyes closed) *	○	○	○	○
Vertigo *	○	○	○	○
Stomach awareness *	○	○	○	○
Burping *	○	○	○	○

How many sailboat paintings did you see along the path? *

The evaluation you are about to perform is a technique that has been developed by NASA to assess the relative importance of six factors in determining how much workload you experienced while performing a task that you recently completed.
There are instructions on the paper given to you. Read them through before continuing

Mental demand: How much mental and perceptual activity did you spend for this task? *



Physical demand: How much physical activity did you spend for this task? *

Very Low 1 Very High

1 20

Temporal demand: How much time pressure did you feel in order to complete this task? *

Very Low 1 Very High

1 20

Performance: How successful do you think you were in accomplishing the goals of the task? *

Note that the location of the endpoints are different before answering

Perfect 1 Failure

1 20

Effort: How hard did you have to work to accomplish your level of performance? *

Very Low 1 Very High

1 20

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you during this task? *

Very Low 1 Very High

1 20

How comfortable was it to control the robot using this method? *

	1	2	3	4	5	6	7	
Not comforable	○	○	○	○	○	○	○	Very comfortable

Why? *

How easy was it to control the robot using this method? *

	1	2	3	4	5	6	7	
Very Difficult	○	○	○	○	○	○	○	Very Easy

Why? *

In the following, the remote environment refers to the environment that the robot was moving in.

Please rate your sense of being in the remote environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place. *

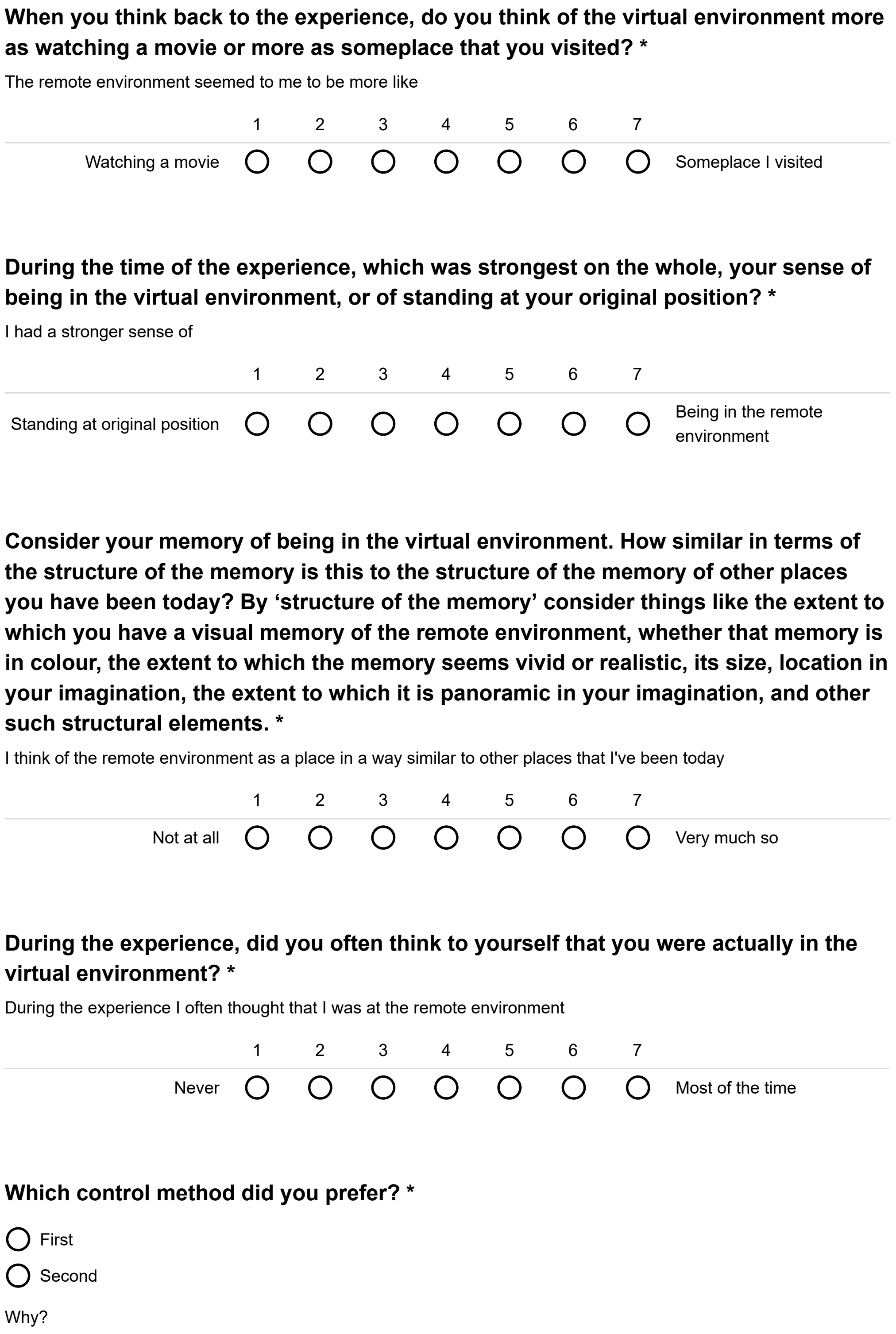
I had a sense of "being there" in the remote environment

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much

To what extent were there times during the experience when the virtual environment was the reality for you? *

There were times during the experience when the remote environment was the reality for me.

	1	2	3	4	5	6	7	
At no time	○	○	○	○	○	○	○	Almost all the time



When you think back to the experience, do you think of the virtual environment more as watching a movie or more as someplace that you visited? *

The remote environment seemed to me to be more like

	1	2	3	4	5	6	7	
Watching a movie	○	○	○	○	○	○	○	Someplace I visited

During the time of the experience, which was strongest on the whole, your sense of being in the virtual environment, or of standing at your original position? *

I had a stronger sense of

	1	2	3	4	5	6	7	
Standing at original position	○	○	○	○	○	○	○	Being in the remote environment

Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By ‘structure of the memory’ consider things like the extent to which you have a visual memory of the remote environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements. *

I think of the remote environment as a place in a way similar to other places that I've been today

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

During the experience, did you often think to yourself that you were actually in the virtual environment? *

During the experience I often thought that I was at the remote environment

	1	2	3	4	5	6	7	
Never	○	○	○	○	○	○	○	Most of the time

Which control method did you prefer? *

○ First

○ Second

Why?

Which control method was easier to use? *

○ First

○ Second

Why?

Which control method felt more comfortable? *

○ First

○ Second

Why?

Thinking back to both of the experiences, which one gave a better sense of being in the robot's location? *

○ First

○ Second

Why? *

How often do you use Virtual Reality Systems? *

○ Never
○ Once or just a couple if times ever
○ Once or twice a year
○ Once or twice a month
○ Once or twice a week
○ Several times a week
○ Every day

For what kind of applications do you use Virtual Reality Systems?

For example, first-person shooters, 360 videos, adventure games, etc.

How often do you play computer games *

○ Never
○ Once or just a couple if times ever
○ Once or twice a year
○ Once or twice a month
○ Once or twice a week

○ Several times a week
○ Every day

What kind of computer games do you play?

For example, first-person shooters, adventure games, etc.

What is your gender? *

○ Female
○ Male
○ Prefer to self-describe
○ Prefer not to say
○ Other

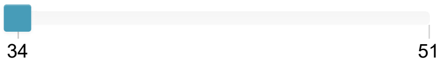
Do you have normal or corrected-to-normal vision? *

○ Yes, I have normal vision
○ Yes, I wear glasses or contacts
○ No

Are you colorblind? *

○ No
○ Yes

What is your shoe size? *


34
51