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EFFECTIVENESS OF A WII BALANCE BOARD AS A LOCOMOTION CONTROL METHOD FOR A VIRTUAL REALITY TELEPRESENCE ROBOT

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ABSTRACT

While virtual reality can greatly contribute to the feeling of presence when operating a telepresence robot, it can come with multiple difficulties to implement in a manner that would make the user feel comfortable. One of those tasks is choosing a locomotion control method. Traditional locomotion control methods for telepresence robot, such as joysticks, might be easy to use but are lacking in immersion. Non-traditional locomotion control methods, for example, a treadmill-type might increase the immersion but the cost of equipment is too high for many users.

In this study, we wanted to explore if the Wii Balance Board could be a suitable locomotion control method for a virtual reality telepresence robot. The Wii Balance Board was thought to possibly offer a low-cost and comfortable leaning-based locomotion control method for a telepresence robot. The Wii Balance Board was compared against joysticks, which were chosen as they are one of the most common locomotion control methods in virtual reality.

For the experiment, we created a simulated environment in which the subjects had to operate a virtual robot through an assigned path with various obstacles. A 3D-model of the University of Oulu was used as the virtual environment, as it was readily available and represented a possible use case environment for a telepresence robot. The experiment consisted of nine three-part runs. After each run, the subjects filled out a form related to their preferences, and performance data was collected during each run. We had planned to run experiments for 40 people, but due to the COVID-19 outbreak, we were forced to conduct tests with only two researchers instead.

After analyzing the results, we conclude that the Wii Balance Board is not suitable for controlling virtual reality telepresence robots in the tested environments. The Wii Balance Board was fatiguing to use after moderate periods of time and did not offer accurate enough control to be used in scenarios other than open environments. For future studies, we suggested to explore other options for joysticks, such as a balance board which would be better-designed for leaning purposes to compensate for the fatigue caused by constant leaning.

Keywords: balance board, joysticks, telepresence robot, virtual reality, control method, preference, performance

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TIIVISTELMÄ

Vaikka virtuaalitodellisuus voi huomattavasti edistää läsnäolontunnetta käyttäessä etäläsnäolorobottia, siihen voi liittyä useiden haasteiden toteuttaminen tavoilla, jotka saavat käyttäjä saadaan tuntemaan olonsa mukavaksi. Yksi näistä haasteista on liikkeenohjaustyylin valitseminen. Perinteiset liikkeenohjaustyylit etäläsnäolorobotille, kuten ohjaussauvat, voivat olla helposti käytettäviä, mutta puutteellisia immersion kannalta. Epätavanomaiset liikkeenohjaustyylit, kuten juoksumattotyyppiset, voivat lisätä immersiota, mutta laitteistojen kustannukset ovat monille käyttäjille liian suuret.

Tässä tutkimuksessa halusimme selvittää, olisiko Wii Balance Board -tasapainolevy sopiva ohjausmenetelmä etäläsnäolorobotille virtuaalitodellisuudessa. Wii Balance Board voisi tarjota halvan ja mukavan nojaukseen perustuvan liikkeenohjaustyylin etäläsnäoloroboteille. Wii Balance Boardia verrattiin ohjaussauvoihin, jotka valittiin, koska ne ovat yksi yleisimmistä liikkeenohjausmenetelmistä virtuaalitodellisuudessa.

Tutkimusta varten loimme simuloidun ympäristön, jossa testihenkilöt ohjasivat virtuaalista robottia annettua reittiä pitkin erinäisiä esteitä väistellen. Ympäristönä käytimme Oulun Yliopistosta luotua virtuaalista mallia, koska se oli helposti saatavilla ja kuvasi mahdollista käyttötapausta etäläsnäolorobotille. Tutkimus koostui yhdeksästä kolmiosaisesta kierroksesta. Jokaisen kierroksen jälkeen koehenkilö täytti kyselyn mieltymykseen liittyen ja kierroksilta kerättiin tietoja suorituskykyyn liittyen. Olimme suunnitelleet tutkimuksen toteutettavaksi 40 henkilöllä, mutta COVID-19 taudin puhkeamisen takia meidän oli pakko suorittaa kokeita vain kahdella tutkijalla.

Tulosten analysoinnin jälkeen päättelimme, että Wii Balance Board ei ole sopiva virtuaalitodellisuus etäläsnäolorobottien ohjaamiseen testatuissa ympäristöissä. Wii Balance Board oli uuvuttava käyttää kohtalaisen pitkien ajanjaksojen jälkeen eikä se tarjonnut tarpeeksi tarkkaa ohjausta muissa, kuin avoimissa ympäristöissä. Tulevia tutkimuksia varten ehdotimme tutkia muita vaihtoehtoja ohjaussauvoille, kuten tasapainolevy, joka olisi paremmin suunniteltu nojaustarkoituksiin jatkuvan kaltevuuden aiheuttaman väsymyksen kompensoimiseksi.

Avainsanat: tasapainolevy, ohjaussauvat, etäläsnäolorobotti, virtuaalitodellisuus, ohjausmenetelmä, mieltymys, tehokkuus

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FOREWORD

We would like to thank our teaching assistants PhD student Katherine Mimnaugh and PhD Markku Suomalainen for all of the great help and guidance they gave during this project. We also want to thank our supervisors PhD Matti Pouke and PhD Aku Visuri for their assistance and ideas with this bachelor's thesis.

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LIST OF ABBREVIATIONS AND SYMBOLS

VR	virtual reality
HMD	head-mounted display
VE	virtual environment
MRP	mobile remote presence
ECG	electrocardiograph
UI	user interface
SSQ	simulator sickness questionnaire
API	application software interface

1. INTRODUCTION

Virtual reality (VR) can mean artificially stimulating any of our senses [1]. In his book, LaValle [1] talks about technologies that can trick our body with vision, feeling, and even different smells that are completely different from reality. In this thesis, we use VR to describe reality that is presented using head-mounted displays (HMDs) which track our head orientation and movement. Using this tracking data, we can show a completely different environment around the user and make them believe they really are inside there.

VR equipment prices dropping down to consumer-friendly levels has increased the need for better modes of locomotion control. There are differences in presence, comfort and navigation efficiency between locomotion control methods, such as using a joystick or real walking [2], thus it is important to find the most suitable method for the task or game in question. Locomotion in VR can be done via multiple different methods such as using a controller, gaze-direction, and real walking; each one having it's advantages and challenges in presence, comfort and usability [3]. There is no one-suits-all method as VR is utilized in a variety of tasks which can make finding the most optimal locomotion control method a difficult task to accomplish.

One big factor in deciding the locomotion control type for a VR experience is so called cybersickness, or VR sickness. Movement in a VR environment should be designed in such way that it minimizes discomfort or disorientation for the user. Researching the cause of VR sickness has proven difficult as it varies greatly between users and content, and it is difficult to measure because people can adapt to the system, which reduces VR sickness [1].

Robotic telepresence systems have become increasingly used in many fields of work [4]. Many of the commercially available telepresence robots use an application or a screen together with controller as a controlling mechanism [5]. These means of control do not promote an immersive experience [2], which is the basic idea behind telepresence: to feel present in another environment [6]. VR systems with HMDs offer an solution to enhance the feeling of presence [2], but the challenge of determining the most immersive and comfortable locomotion control method for telepresence robot still persists.

In this study, we will design and implement a VR telepresence robot simulator with two locomotion-controlling interfaces: joystick-style via the Valve Index controllers and leaning-based-style via the Wii Balance Board. The simulator will use a 3D model of the University of Oulu as a virtual environment (VE). The users will have the task to drive in the virtual environment with the ability to switch between the two locomotion-controlling interfaces. Our aim is to compare these two locomotion control methods for a telepresence robot and see which one users prefer to use, as well as which one results in less VR sickness symptoms.

The motivation for this study is to try to find a suitable option for controlling the locomotion of robotic telepresence systems via VR. This would be a step in to the right direction to making them better suited for general consumers. This study could be the first step in determining whether balance boards, such as the Wii Balance Board, are potentially suitable options.

2. RELATED WORK

2.1. Locomotion

2.1.1. Background

Many different types of locomotion control have been used in simulators, video games, and virtual environments. The different types vary from basic joystick to 360 treadmills. A controller has been a go-to option for many years on gaming consoles [7], while gaming on a computer is mostly done with a keyboard and mouse, as those have been established as the basic input devices for computers. Locomotion control styles in VR varies relatively much, as seen from the review done by Boletsis [3]. Controller-based locomotion control is still one of the most commonly used style [3], but the freedom VR gives to users is raising the need for new types of interfaces.

2.1.2. Locomotion in Virtual Reality

Even though most VR systems still have controllers in the hands of the user for moving around it is not considered as accurate [8] and it can break the immersion and cause the user to feel sick. To keep the immersion, new technologies have been developed to enable the user to use their body to control locomotion. Iwata [9] describes different methods of detecting a person walking while giving as much freedom as possible. Using an omnidirectional treadmill or roller skates that can move to all four directions, people can be held in position even though their body is moving creating a feeling of as if they were physically moving around.

In VR, the most common locomotion type is walking-in-place locomotion while controller or joystick-enabled locomotion came as the second [3]. Other common styles were real walking, redirected walking, gaze-directed and hand-directed steering [10].

In the walking-in-place style, the user's movement is tracked either with an HMD and hand controllers or with extra trackers on the user's legs or possibly on their waist. Treadmill-type input devices can also be used to detect walking motion [3]. By detecting the walking-like movement of the user, an application knows when the user wants to move and can decide the speed from the intensity of the movement.

In real walking and redirected walking, the user walks inside a limited area. Real walking has huge limitations in the area used for movement, which redirected walking tries to overcome by tricking the user to walk in circles when they think they are walking straight [3]. However, in redirected walking, the physical area for movement has to be 25 to 30 meters across [11].

Gaze-directed steering takes the orientation of the HMD and uses that to determine the direction of movement when the user wants to move. With hand-directed steering, the average orientation of a user's controllers are used when deciding the direction. Both of these have their advantages and disadvantages, but hand-directed steering gives the user more freedom for looking around and gives much more spatial awareness [10].

Leaning-based locomotion control interface is a style where the user uses their body to lean in the direction they want to go in the virtual environment [12]. Leaning-based interfaces are not as common as other styles in VR locomotion control but offer a locomotion control technique suitable for long-distance traveling in VEs by not wearing the user down [13]. In comparison to regular joystick-style controller, leaning-based interface can offer more immersive [12], intuitive, and better performing [14, 15] locomotion control style. We used leaning-based interface done via Nintendo's Wii Balance Board (picture of the board in Figure 1) in our study as one of the locomotion control methods.

De Haan and colleagues [14] used a Wii Balance Board as an input device for VR, allowing users to use leaning for horizontal movement and pressing on the toes and heel of opposing feet for rotating around the vertical axis. They found that the Wii Balance Board is an effective, easy, and intuitive method for navigation.

Another interface with a "human-joystick" style, the Joyman, was designed by Marchal and her colleagues [12], consisting of a plate linked to a frame by springs and waist-height cage around it. Their aim with the Joyman was to preserve the sense of balance to improve the feeling of immersion and compare it to regular joystick navigation. The Joyman significantly improved immersive feeling while the joystick proved to still be better for easiness of use [12].

Leaning-based locomotion control has also been done with chairs while sitting down. Kitson et al. [16] compared the joystick (Xbox controller) to multiple different style chairs and a fully head-directed interface, concluding that these leaning-based interfaces did not provide significantly better results over the joystick as they had predicted based on previous studies. However, their prediction for the use of the joystick resulting in better performance in accuracy, controllability, and easy-of-use was supported by the results. While the studied interfaces did not offer significantly higher results, they said participants liked leaning-based styles more as they were more fun, engaging, realistic, and gave a natural feeling of moving.

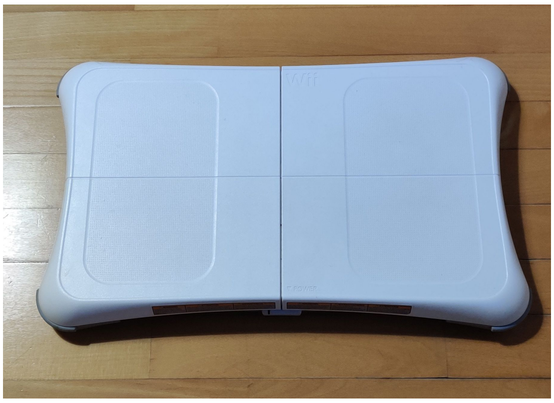

Figure 1. Wii Balance Board.

When designing a locomotion system, especially for VR applications, you have to make sure that moving around will not make the user feel VR sickness. VR sickness is not only caused by movement but it plays a big part in it. Using a controller has been noticed to cause lots of VR sickness but it can be reduced using dynamic field-of-view [17] and fine-tuning the linear and angular speeds of a player character.

2.2. Virtual Reality

Virtual reality has been researched for over thirty years. Sutherland [18] talked about a machine they had engineered that could measure the user's head position and add virtual objects into the user's vision using displays that could provide 3000 lines at 30 frames per second. The headset was quite big and the computers needed to run this took almost half of the room.

In 1995, Nintendo created the Nintendo Virtual Boy, which was the first stereoscopic video game console published to consumers [19]. While it did not have tracking for the head or controllers, it provided a stereoscopic image using light-emitting diodes and oscillating mirrors to produce the picture for both eyes. As only 770,000 consoles sold, which is not much compared to 7 million Playstation consoles that were sold by Sony around the same time, Nintendo discontinued the product a year after its release.

Even though some new applications for VR emerged in the intervening time, it was not until 2012 when the Oculus Rift started the so-called second wave of VR [20]. The advancements in technology for both displays and computers, in general, gave the possibility to create a VR headset that was cheap enough for consumers but was still capable to produce good enough resolution and accurate tracking that new games and VR headsets started emerging.

2.2.1. Technology

A normal HMD consists of one or two displays, optics, and possibly a tracking system [19]. It can also have one or more cameras for positional tracking or displaying the surroundings of the user. The HMD has to be sturdy but lightweight enough not to cause strain to the user and break the immersion.

Two common methods for tracking are used: inside-out and outside-in [21]. Inside-out means that the HMD itself has methods of tracking orientation and location. Almost all VR headsets contain inertial measurement units that can detect changes in velocity and orientation. IMUs cannot be used as primary tracking as small errors in the measurements can cause noticeable drift, and therefore more precise methods, such as cameras, are needed to occasionally correct the drift. The outside-in method uses cameras or other tracking methods to detect the location of the headset. For example, the Oculus Rift uses infrared cameras that detect the position of LEDs mounted on the surface of the headset [22].

For this project we decided to use the HTC Vive system as it was readily available for us and we had some understanding of game development for it. This system gave a large play area and freedom of movement. Figure 2 shows HTC Vive set: controllers, HMD, and base stations for outside-in tracking.

Almost all kinds of game controllers can be used with VR but nearly all VR systems in the present day come with their own controllers. Conventional controllers do not usually work with the tracking and can cause confusion or loss of immersion as they are not designed for that kind of environment. We decided to use Valve Index controllers as HTC Vive controllers did not have joysticks. Index controllers shown in Figure 3.

The most commonly used game engines for virtual reality are Unity3d and Unreal Engine as they are both free and relatively easy to use. For our use, we decided on

Figure 2. HTC Vive set.

Figure 3. Valve Index controllers.

Unity3d to be the best fit as it has a great amount of free assets available and it is easier to use than Unreal Engine.

2.2.2. Virtual Reality Sickness

People tend to call sickness associated with virtual environments as cybersickness. However, as this term has expanded to include any kind of sickness caused by spending too much time with computers or devices in general, using the term VR sickness when referring to motion sickness or discomfort caused by VR has been suggested [1].

VR sickness is a motion sickness-like syndrome caused by visual stimulation coming from the HMD [23]. The difference between motion sickness and VR sickness is that motion sickness can also be caused by vestibular stimulation while VR sickness can only happen through visual stimulation.

Depending on the individual and the equipment, using a virtual reality headset can cause VR sickness in users. VR sickness can cause different kinds of effects on users including eye strain, sweating, disorientation, and nausea [23]. LaViola introduces three main theories for the cause of the VR sickness as follows:

- **Sensory Conflict Theory** explains the cause of VR sickness as a conflict between senses which provide information about the body's orientation and motion which the body does not know how to handle. The body does not know how to react when its vision sensors detect movement when the body, in reality, is not moving. LaValle talks about vection [1], which is when the brain thinks that a person is moving based on the vision, when in reality they are stationary. In VR, vection occurs when a person is moved around the virtual environment while they are standing still. Vection can cause sickness symptoms, such as nausea or even vomiting.
- **The Poison Theory** tries to explain VR sickness from an evolutionary standpoint. The theory suggests that VR sickness happens because the body misreads information it gets from visual and vestibular sensors and thinks it has ingested some kind of toxin. This could cause the body to react in a way evolution has taught us by causing nausea and vomiting.
- **The Postural Instability Theory** says that humans try to maintain postural stability in the environment. Failing to minimize uncontrolled movements of the perception causes postural instability [24]. The theory states being in prolonged postural instability causes motion sickness symptoms. Being in a virtual environment can put the user into constant changing of environments without giving full control to the user, which causes postural instability and might induce VR sickness.

VR sickness causes negative effects in immersion and presence [25], so it is a widely researched topic and new ways to prevent VR sickness are developed constantly.

VR sickness is hard to measure as its symptoms and severity are different for everyone, but different measurements have been developed for it. One of the earliest subjective measurements is Pensacola Motion Sickness Questionnaire [26] which led to Pensacola Diagnostic Index. Other types of questionnaires have also been developed and even self-reporting has been used, which gives a wider scope on the symptoms but is much more difficult to compare between individuals. Another way to measure VR sickness is to monitor users physiological changes, such as heart rate, blink rate, EEG, and stomach upset [26].

Conflicts between senses can also be caused by the lag between action and visual change. If a person moves their head but a change of vision in VR comes in slightly delayed, it can cause vection which leads to VR sickness [1]. Using VR to control telepresence robots will cause a lag between actions and change in robots camera vision. Our simulator will not have this problem but it has to be considered when using our data in further research.

2.3. Robotic Telepresence

In robotic telepresence, a physical robot is placed in the local environment and connected to a user in a remote location with the capability to move around and interact with the remote environment and other people at the location [5]. The feeling of presence is essential for robotic telepresence to allow users to perform in their respective tasks up to the standards of the physical world [27]. Increasing immersion, for example correlating the robot's actions from the local environment to the user, is an important part in the designing of a telepresence robot [27, 28]. Allowing locomotion and other physical interaction elements such as hands permits the user to grab and move objects or do simple tasks, such as a handshake, which can add to feeling more present at the remote location [28]. These interactive elements can be enhanced with haptic feedback to simulate collision or the properties of an object, such as its geometry and weight [27, 29]. Social interaction in robotic telepresence, in terms of speaking, is done via conferencing tools: a screen, a mic, a camera, and speakers [5].

2.3.1. Use Cases

Telepresence robots have gained a lot of use and research in recent years in environments such as search and rescue, healthcare, offices and military [30, 31, 32, 33, 34]. These systems enable missions, which otherwise would be hard or impossible to accomplish, such as exploring hazardous environments.

Lee and Takayama [30] researched a mobile remote presence (MRP) system in a workplace environment increasing performance over normal conferencing system via a laptop. The study used a robot with basic conferencing tools and mobile functions controlled with a web browser and video-conferencing application. They found out that the robot worked great in both formal and informal social situations with the pilot feeling as being present in the workplace and belonging to the conversations. Colleagues of the pilot also reported communication to be easier with the robot than a laptop and impromptu activities with the MRP system happened commonly around the workplace. While the MRP system had many advantages, they found driving to be a negative side as it was time-consuming and the pilot was unable to focus on conversations.

Koceski and Koceska [34] evaluated a telepresence robot for elderly healthcare. The robot used in the study was constructed mostly with the same features as in the study by Lee and Takayama [30], but it also had a robotic arm, a reminder functionality and a calendar and a few special features for healthcare, such as an electrocardiograph (ECG). They aimed to evaluate perceived ease-of-use and perceived usefulness of the robot by conducting four experiments:

- Elderly people driving the robot to the nursing room and having a video conference session with a caregiver.
- Caregiver driving the robot and making use of its features, the ECG measurement tool and the robot arm, to place needed equipment on the patients' body for the ECG.
- The robot arm was used by the elderly for fetching and carrying small objects.
- Use of the reminder functionality and a calendar.

Results showed that both groups found all functionalities to be easy to use and useful. Some features, such as the reminder and calendar, was perceived to be more useful by the caregivers than the elderly. This was expected, as using the robot would reduce the workload when caring for multiple patients. In conclusion, they found the core functions of the robot to be accepted by potential users.

2.3.2. Locomotion In Robotic Telepresence

Most commercially available telepresence robots are controlled via a screen and a joystick/controller [5]. VR telepresence robots are not yet commercially common, but the locomotion methods covered in section *Locomotion* would still be top contenders for robotic use. Ueberle et al. [35] designed a telepresence robot with haptic feedback and used redirected walking for a locomotion control method. Spada et al. [36] implemented a system with an omnidirectional treadmill in which the user was able to rotate freely around and walk in place. While their study did have challenges with delays, it showed promising result on the user's immersion.

A conferencing telepresence robot might get along fine with only rubber wheels, while a robot designed for rough terrains usually need tracks, or something similar, to be able to move. For this reason, the locomotion style of the robot usually determines the available use cases for it. Normal wheels or castors are still the most commonly used method as they are easy and simple to implement, but they come with the downside of complex environments being impossible to navigate [33]. This problem comes out in places such as in healthcare and office environments, which are two of the most commonly used places for telepresence robots [5]. These environments can consist of multiple floors and stairs, and a robot with wheels is unable to use them, thus limiting it to a single floor on the building. While some buildings might have an elevator, it would require the robot to have an arm to use the buttons. One solution to this can be to design a robot with legs but currently it is complex to design, not reliable enough, and limits the travel speed [33].

The most common style of steering for a robot with two wheels is differential steering with a balancing castor [37]. Malu and Majumdar [37] describe the mechanics of a differential drive robot with two wheels. It uses two independently driven wheels on the same axis but opposite sides of the vehicle. Forward and backward movement is achieved by driving both wheels at an equal rate, and rotation is achieved by driving one of the wheels at a higher rate than the other, with the right wheel for turning left and the left wheel for turning right. To control this type of robot, a leaning-based control might be a suitable option, as the motion of turning the wheels in different directions can be simulated with a balance board by pressing with toes and a heel. Such a control method has been done before by DeHaan et al. [14].

2.4. Research Questions

As telepresence robots and VR are becoming more and more common, new locomotion control methods are being investigated to optimize the experience for the user. The Wii Balance Board has been used in various studies, but to the extent of our knowledge, it is yet to be researched as a means for locomotion control of a telepresence robot. By answering to the following questions, we aim to determine if the Wii Balance

Board could be a suitable, low-cost solution as a locomotion control method for a VR telepresence robot. Therefore, our research hypotheses are as follows:

1. How does using a balance board controller compare with a joystick controller, in terms of preference and performance, during locomotion in a virtual reality telepresence robot?
2. Which locomotion control method offers better performance in terms of task completion time and accuracy in a VR environment with pre-selected controls?
3. Which user-selected locomotion control method do subjects prefer in the VR environment during varying environmental conditions?

3. STUDY DESIGN

We originally planned this study design below to be carried out but due to the COVID-19 outbreak, we were forced to change the design. The experiment was meant to be carried out with approximately 40 test participants but because of the unforeseen events, we adjusted it for the researchers to act as the test subjects. The study design stayed mostly the same but slight adjustments had to be made in every part of it. All changes to this study design are reported in section 5.

3.1. Test Methodology

For testing and gathering data, we designed a track to go along in a 3D model of the University of Oulu with added obstacles and roaming people. The track was designed to have the subject navigate different kinds of situations. To introduce the locomotion methods to the subject, we designed a separate learning room in which they were able to familiarize themselves with the method.

The test run consisted of three parts. Each part started with a learning phase in the learning room during which the subject was given time to learn to control the robot with either the balance board or joystick controller method. After a learning phase, the subject was tasked to complete the track. The track was the same for part one and two but for the third part obstacles and roaming people were placed differently in comparison to the first two parts to give an element of surprise. The three parts of the test were as follows:

- In the first part we assigned a locomotion control method for the subject and to prevent bias, the methods were divided evenly across the test participants. The objective for the first part was to be fast but precise, which meant to have as few collisions as possible.
- In the second part, the subject was assigned the other locomotion control method. The objective for this part was the same as in the first part.
- In the third part, the subject was able to switch between the two locomotion control methods with a press of a button. The objective for the third part was the same but the idea was to switch the locomotion control method if the participant felt that one gave better results than the other.

3.2. Test Procedure

3.2.1. Experiment Information

At the start of the experiment, the participant was given general information about the test structure. The participant was told they were going to control a VR telepresence robot with two different locomotion control methods, a joystick and balance board. For parts one and two, the participant would use the locomotion control method assigned to them and in the third part they could switch between the locomotion control methods.

A debriefing was given to the participant at the end of the test. It consisted of explaining what we were researching and how the collected data was going to help give answers to our research. If the participant felt little nauseous from the VR experience, we told them it should wear off in approximately 20 minutes.

3.2.2. Test Procedure

At the start of the test, the participant was told to put their phone to silent. The participant was given information and a consent form to sign. The baseline SSQ was given to the participant to fill in. After the SSQ, we checked the balance board position and the participant was told to step on the balance board. We gave the participant instructions for the calibration and we gave them Index controllers and the HMD to fit comfortably on. After the participant had fitted the HMD, the calibration begun.

For calibration, we told the participant to put the HMD back on. We instructed the participant to first stand still for zeroing the centre of balance on the board and told them that this part of the calibration was also going to be done after parts one and two. For calibrating optimal leaning amount to achieve maximum speed, the participant had to first lean forward as far as possible and then same for leaning backwards.

Next was the first part of the test. We told them to lift off the HMD for listening to the instructions. The participant was told which locomotion control method they were going to use, joystick or balance board, which was assigned to them by us. The participant was instructed to first test and learn the given locomotion control method in the learning room for three minutes. After that, the participant was moved to the start of the track. The participant was given an objective to complete the track fast but to avoid collisions as they would result in a time increase to their total time. The participant was instructed to go in the direction of a dotted line that showed them what path to follow in the environment, but they did not have to stay exactly on top of the line during the run. After the instructions, the participant put the HMD back on and we started the first part.

After completing the first part, the participant lifted the HMD off of their face, filled in the SSQ, and were allowed to stretch their legs between the test parts if they wanted to. Then, we gave them instructions about the second part of the test. The participant was told which locomotion control method they were going to use next. This depended on which locomotion control method the participant was assigned in the first part. The instructions for the learning and track phases were the same as in the first part. Then, we told them to put the HMD back on and standstill for the second calibration. After calibrating, the second part started.

After the second part, the participant took the HMD off and filled in the SSQ for the second time. The SSQ was followed by instructions for the third part of the test. The participant was reminded that they were able to switch between the locomotion control methods in this part. The participant was told to familiarize themself with the switching mechanism in the learning room for three minutes. After that, they would be moved to the start of the track. We also reminded them about the time penalty if they collided with objects. After putting the HMD back on, we calibrated the board for the third time and started the third part of the test.

After the third part, the participant was instructed to take off the VR equipment and fill in the SSQ. The participant was given a questionnaire in Google Forms to fill in. After that, we gave them a debriefing about the test and asked if they had any questions to us. The participant was given a copy of the consent form and the information page at the end of the experiment to take home.

3.3. Gathering Data

Quantitative data was collected via software during the track phase of all three parts. In parts one and two, the gathered data was completion time, accuracy in terms of collisions, and the location of the collisions. In part three, we gathered data on the time spent on each locomotion controlling method, changes in the method, and the location of the changes. We collected qualitative data in the form of a questionnaire about preference after the test, which consisted of questions about the preference of the locomotion controlling methods and background information of the subject. The SSQ was also gathered at the beginning and after every part of the test.

3.3.1. Outcomes

Data gathered from parts one and two were intended for measuring the performance of the two locomotion control methods. Completion time and accuracy were used to answer which method performed better, thus answering research questions number one and two. Collision locations were collected for comparing performance in different kinds of environments, and to see how each method performed in those. Quantitative data collected from part three and qualitative data collected at the end of the experiment were used to answer research questions number one and three. The time spent on each locomotion control method and the answers to the questionnaire were used for determining which method the subject preferred, both overall and in specific situations. The background information of the subject showed if they had previous experience with VR applications. The SSQ was gathered to see if there was a trend to get more VR sickness from one or the other of the locomotion control methods. While the SSQ was gathered after every part of the test, we analyzed the data only from the baseline and after part one.

3.4. Test Participants

We planned to recruit test participants from the University of Oulu. We were going to start recruiting by informing our acquaintances about our study and asking them to spread the information to their acquaintances. Signing up for the study would have been done via an online form, which would have been a quick and easy solution to use allowing us to keep track of our participants and be in contact with them. The online form was intended to give the participants some information about the experiment and function for reserving a time slot for the test.

We were aiming for 40 participants. Participants were not required not to have any special background, such as age, gender, or previous experience with VR to be able to participate in the test. The idea was not to exclude anyone if they wanted to participate, but we planned to ask people with previous knowledge of being sensitive to motion or VR sickness to consider not to participate.

We could not follow these plans because of the reasons explained later in chapter 5.

4. IMPLEMENTATION

4.1. Implementation And Management Plan

4.1.1. Implementation Plan

The implementation plan determined after discussing the study design is as follows:

- 3D model of the University of Oulu
- 3D model of a robot and controls for the robot
- Design a track to go along the university
- Create a learning room for the locomotion control methods
- Roaming people and obstacles for the test track
- Wii Balance Board: connection, reading data, and calibration
- Data gathering system
- UI design and implementation
- Create a questionnaire
- Visualizer tool for data analysis

4.1.2. Management Plan

For the technical part of the implementation plan, we assigned most of development tasks to Juho. The implementation plan consisted of the implementation regarding Unity and the software we planned for running the experiments. Joona was assigned to work with the Wii Balance Board, design the UI, and create the questionnaire. The test track was designeded with contribution from both researchers.

For a time frame, the 3D model of the university needed to be done before designing the track and adding obstacles to it. For the other implementation pieces, the time frame was not a strict one, as the majority of the components did not need other components to be ready.

4.2. The Software

4.2.1. Requirements

The program had to be able to measure the user's performance using two different locomotion control methods. This was done in the first part of the test when the user was forced to use a specific locomotion control method and their time was measured while they did the tasks given to them. The program had to also give them the freedom of choice, which enabled measurement of preference between the locomotion control methods. This was done in the last part of the test where the user was free to change their locomotion control method during the task. Enabling the measurement of preference, we needed to keep track of time spent on each locomotion control method and the number of times the user switched the locomotion control method.

4.2.2. Use Cases And Scenarios

We knew from the beginning that we would use the 3D model of the University of Oulu as the scene for the experiment. The models were freely available on the UBICOMP website [38] and were easy to edit to have varying environments to thoroughly assess differences in the locomotion control methods. They also offered a realistic environment to run the experiments in. At first we got the model from an old project of an acquaintance, but it was missing all the textures. The correct parts for the model were eventually found and the model was assembled with the correct textures.

As obstacles, we decided on 3D-modeled cardboard boxes and people who walked around in predefined paths. The reasoning for using cardboard boxes was to let boxes move out of the way and not let the user get stuck on an obstacle. As a user was going to be using new locomotion control methods, it would have been frustrating to get stuck on immovable obstacles. Cardboard boxes were big enough to be easily seen, but did not punish the user too much in case of a collision, which could have lead to the user avoiding a specific locomotion control method later in the test. We also wanted to avoid rotating the user on collision, as too much rotation could easily cause VR sickness.

Some of the obstacles were planned to come as a surprise to the user. For example, people would suddenly come out from behind a corner and the user had to navigate past them without colliding. The first iteration of the movement system for the people had randomly generated paths to follow. This would have led to inconsistent tests, and we decided on using predefined paths to keep the tests similar for every user.

The route was shown using a dotted line on the ground. We thought about using a constant line, but it could have made the user think they had to stay on top of the line, which we did not want to happen. The dotted line was vague enough to let the user know they had to follow it but not be exactly on top of it.

At first, we were planning multiple short tasks with an ability to switch the locomotion control methods. The scene would have changed between tasks and the user would have been tasked to figure out their way through the scenes. We realized this implementation would have made evaluating performance between the two different locomotion control methods a difficult task. Without seeing the two locomotion control methods performed in the same situations, no useful data would have been gathered. Later, we decided to force the user to use specific locomotion control methods for the first and second parts and to give them the freedom of choice in the third part. In this way, we were able to compare performances between the locomotion control methods by using the data from the two first parts and measuring their preference in the last part.

4.2.3. Robot And Movement

The movement of the robot was first made by using wheel colliders and the physics engine in Unity. This way, the movement was as close to a real-life robot as possible. The first version of the robot used four wheels for moving around. This caused some problems with the physics as the wheel colliders were not made for differential drive controlling. We later decided not to use the wheel colliders as they caused a lot of problems. They were not meant for stiff wheels and had a slight play causing the robot to go in weird directions. In the final implementation, the movement was done by giving the robot linear velocity and angular velocity depending on the received controls.

The movement script took in two values which represented the desired speed of both sides of the robot. The robot would try to match the speed on each side by accelerating towards the target speed. To give both locomotion control methods similar acceleration, we decided to limit the acceleration overall. This way, even if it is faster to turn the joystick to the maximum value than lean all the way forward on the balance board, the user was able to accelerate equally fast with both methods.

4.2.4. Tracking And Visualization

For tracking, we created a script that lists all the events that happened during the test track as tracking points. We had five different tracking event types: start, end, collision, change of locomotion control method,and position update. These tracking points were stored in JSON-files. The filenames consisted of the subject ID and an indication of which part of the test was done (first, second or third). To visualize and analyze these files, a visualization program was made which drew paths as lines on the map of the university. A change of the locomotion control method changed the colour of the line and collisions were visualized as red dots. Pictures of the visualized tracking can be seen in Figure 4.

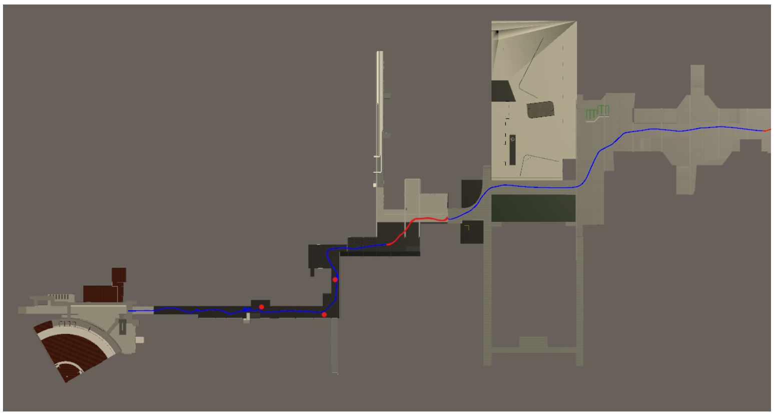

Figure 4. A run visualized using our program.

4.3. Balance Board

4.3.1. Accessing The Balance Board

One of the two controlling methods we implemented for this study was the Wii Balance board. The balance board had four sensors, one on each corner, which measured weight distribution between them in kilograms. Accessing the data and the board's different connection features was done via a suitable software's application program interface (API).

The first choice for the software was a program called *Wii Balance Walker*[1] made by Richard Perry. This software was used for demo purposes, but it became quickly clear that its API was almost non-existent and lacked features needed for our purposes. The program had options only for simulating a joystick or converting movement from the board to keystrokes. After searching for more options, we found an asset from the Unity Asset Store called WiiBuddy [39]. The asset had an extensive API for controlling everything related to Wii accessories and fulfilled the needs for this project.

4.3.2. Connecting To The Computer

The board was made by Nintendo to be part of the accessories for the Wii gaming system, and thus was not designed to be used with a computer. However, it communicates via Bluetooth which enabled us to use it in this study. Unfortunately, the board had connection issues with our computers. The Wii Balance Board had two buttons, one on the bottom for pairing and one on the front for powering on and connecting back to a paired device. After pairing the board, it worked as intended but restarting the computer dropped the connection to the board, and thus it needed to be paired again after every restart. This was fixed with software [40] from Richard L. Lynch to permanently pair any Wii accessory to a computer.

4.3.3. Functionality Design

WiiBuddy offered two functions for accessing data from the board. One function gave the total weight on the board and the other gave a vector which included weight distributions of front-back and left-right. We also needed weight distributions between the opposite corners for the differential drive system of the robot. This was achieved with a custom function.

While testing the board, we noticed that the centre of balance was slightly off while standing still. We discussed this problem and decided to tackle the problem with a function which created an off-set to centre the balance on the board to match with the participants' centre of balance. The idea at first was to run the function at the start of the software, but we ran into problems with this idea. The function for connecting to the board sometimes did not work and resulted in an error, which forced us to restart the software. As this was a problem with the WiiBuddy itself, we did not start to try

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[1] The software was found from an archived link and the original website is not available anymore

to fix it. Instead, we decided to assign the function to a key which would trigger the calibration. This allowed us to connect the board before the participant came to do the test, which resulted in less hassle and time waste.

At the start of the design for controls of the balance board, we noticed that the board was too sensitive to slight movement and made the robot move slightly when standing still. For making the use of it better, we created thresholds for taking data only after a certain point. Finding those thresholds was done by trial and error to see where the sweet spot was. As we had more discussions on the use of the board, we decided to make limits on the software side for leaning both forwards and backwards. We took the maximum points of leaning a participant was able to do and set the point of the full speed of forward to 70% and backwards to 80% of the maximum values. These values were found by trial and error.

4.4. Questionnaire

We created a questionnaire for the participants to fill after the last part of the test. The questionnaire was designed to give us more information about their preference between the two locomotion control methods and information about the participant such as age, gender, and prior experience with VR or gaming. While we used the software to gather data, which would give us an indication about preference, we wanted answers to other factors which were not answered by the data. The list of questions relevant for data gathering are listed below:

1. Why did you select the locomotion control method you did at the start of the course?
2. Which method felt more intuitive to use?
3. Which method felt easier to control?
4. Which method felt more comfortable to use?
5. Which method was more fun to use?
6. Which method did you like more?
7. Why?
8. Did you switch locomotion control methods during the course?
9. Why did you choose to switch or not to switch?
10. Do you have any prior VR or gaming experience? If so, how many hours per week on average?

We decided to implement the questionnaire with Google Forms because of ease-of-use and its ready-to-use data analysis tools for the answers.

4.5. User Interface

At the start of this study, we thought there was no need for a user interface (UI). The test at first did not need a UI but after refining it, we noticed that some UI elements would give the participant a better experience.

4.5.1. First Draft

The first element we decided to add was the line to follow on the track. We designed the route to go through the university for the participant to follow. The second idea we came up with was to add a speedometer to help the participant see if they were going full speed as the test emphasized being fast in completion. Figure 5 shows the first draft of the UI design, done with Paint 3D, which includes the dotted line and speedometer.

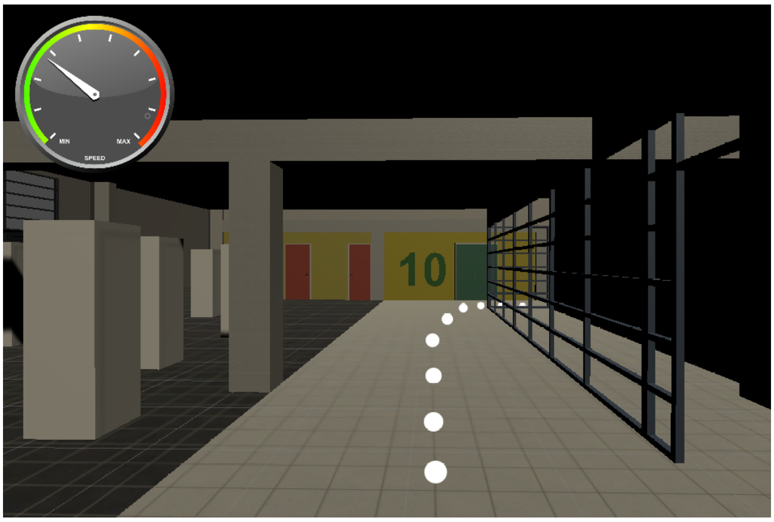


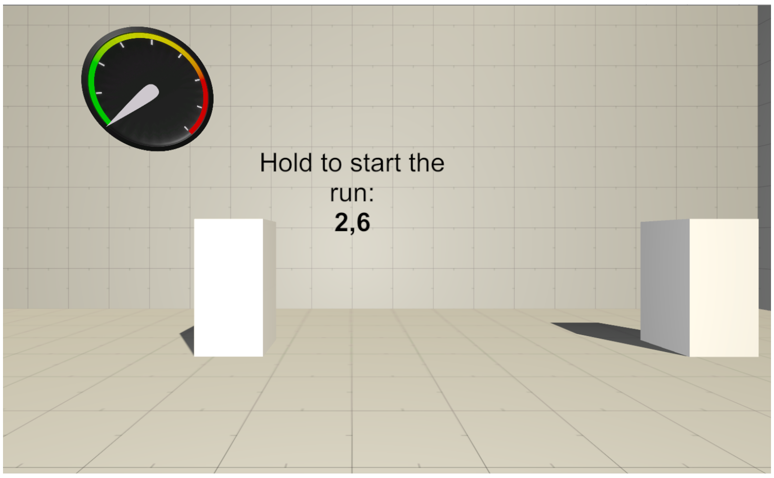
Figure 5. First draft of UI design.

4.5.2. Final Implementation

We considered some other elements to add to the UI, such as a timer to see the duration of the track and an icon to indicate which locomotion control method they are using at that moment. After discussing the pros and cons of these elements, we concluded that they were not necessary. The reason for this decision was that the icon would not add any value to the experience and a timer would have been a distraction, possibly causing collisions.

The first design ended up being the final design and the implementation of it is shown in Figure 6. The UI for the track parts shows a speedometer and dotted line, which has a tear-shaped dots pointing in the direction of the goal. We also implemented text instructions in VR for the non-track parts of the test. An example of a text instruction appearing to the participant while wearing the HMD is illustrated in Figure 7.

Figure 6. Picture of the implemented UI for the track parts of the test.



Hold to start the run:
2,6

Figure 7. Text instructions on the screen during a learning phase of the test.

5. SIMPLIFIED STUDY DESIGN

During this thesis, the COVID-19 outbreak occurred. As a result of the outbreak, the University of Oulu was closed and it was recommended to keep a distance to other people. These circumstances forced us to change the experiment as we could not hold the experiments in-person as was planned. We decided to run tests with two researchers, alternating between being the test subject or the researcher. This naturally changed our data outcome and we created new hypotheses for analysis of the data.

5.1. New Test Methodology

We designed multiple different test runs in which we focused on creating varying scenarios for data collection. The idea was to analyze these varying scenarios to distinguish differences in performance or preference between the locomotion control methods. An additional element gained from the new test methodology was the effect of multiple runs on the performance and preference.

Counterbalancing was done by switching the starting locomotion control method. For example, one researcher started a run with the joystick and other with the balance board. During test runs, the subject and the researcher did not discuss opinions about the runs.

For evaluating the experiment, a set of questionnaires was created for answering after the third part of each test. Similar to the original questionnaire, the new questionnaires focused on gathering information about preferences for the different locomotion control methods. Unnecessary questions about background information were omitted. All questionnaires are included in appendix 3.

5.1.1. Test Runs

To assess the performance and preference differences between the locomotion control methods, nine test runs were designed for the third part of the test. These new test runs were designed to produce data for different scenarios and help to better answer which locomotion control methods suited these scenarios. Some tests consisted of two parts, as can be seen from runs one and two, in which the idea was to complete the same task with both locomotion control methods. These runs are referred with its number as run ID.

1. Open environments with balance board and narrow environments with joysticks
2. Open environments with joysticks and narrow environments with balance board
3. Joysticks when people are present, otherwise balance board
4. Balance board when people are present, otherwise joysticks
5. Frequently changing between locomotion control methods during the run
6. Using joysticks to travel as close to walls as possible without colliding

7. Using the balance board to travel as close to walls as possible without colliding
8. Freely choose between locomotion control methods with the best possible time in mind
9. Freely choose between locomotion control methods with comfort and preference in mind

Test runs were designed to answer the hypotheses shown below:

H1: Joysticks perform better and are preferred in narrow hallways and other difficult-to-navigate situations, as measured by fewer collisions and subject-reported preference

H2: Joysticks give better overall performance over the balance board, as measured by fewer collisions and lower completion time

H3: Joysticks are preferred for moving close to walls, as measured by subject-reported preference

H4: Balance board is preferred over the joysticks in an open environment where the risk of collision is low, as measured by subject-reported preference

H5: Balance board offers a more comfortable and enjoyable experience, as measured by subject-reported preference

H6: Frequently switching between locomotion control methods is not preferred, as measured by subject-reported preference

5.1.2. Test Protocol

The procedure for a test was modified to suit being done by two researchers. In the initial plan, the test procedure included instructions, consent form and debriefing for the participant. Those were deemed unnecessary as both researchers were familiar with the test protocol. We modified the test procedure to include the researcher iterating the objectives of the test run as a reminder to the test subject. Other parts of the initial test procedure stayed unchanged.

5.2. Experiment

During the test runs, one researcher was the test subject while other was the researcher running the experiment. During the test runs, the researcher prepared the SSQ forms for filling out after every run of the test and the preference questionnaire for filling out after the third run of the test. The whole experiment was done in a day, lasting roughly five hours. Throughout the experiment, each subject spend approximately 25 minutes using the joysticks and 30 minutes using the balance board. The longest continuous use of either of the locomotion control methods was approximately four minutes.

Both subjects were mid-20s males and had prior experience with VR applications and gaming.

Some problems during the experiments occurred. The software had an unforeseen bug, which did not occur during testing periods before the main experiments. Most of the tests were fine but two had to be restarted because the locomotion control methods did not register any movement. The reason for this failure was not found, but the solution was to test for the failure before starting the test. Notes of these failures were added for each test in which it occurred.

After the experiments, a bug was found in some of the tracking data files. In the third part of the tests, in which the switching locomotion control methods occurred, the software registered the switching twice to the tracking file. As a result, the visualization tool did not show any switching between the locomotion control methods. The solution for this problem was a custom script which corrected the data files.

6. RESULTS AND ANALYSIS

6.1. Data Processing

The tracking data was processed by using two C# scripts. The first script was made for correcting the unforeseen bug in tracking data files. The second script collected run ID, starting locomotion control method, completion time and the amount of collisions that occurred during a test run; and output the information to a comma-separated file for easier reading.

A visualization tool was used to qualitatively observe differences between different test runs, such as the route taken and the locations of collisions. This allowed us to visually see which locations were prone for collisions and if the taken route changed depending on the locomotion control method.

6.1.1. Collisions And Completion Time

The analysis for collisions and completion time were done for the first and second parts of the tests. The results were divided by locomotion control method and used for measuring performance between the locomotion control methods.

Completion times over the course of the experiment can be seen plotted in Figure 8. No significant improvement in performance can be detected from the chart on either of the locomotion control methods.

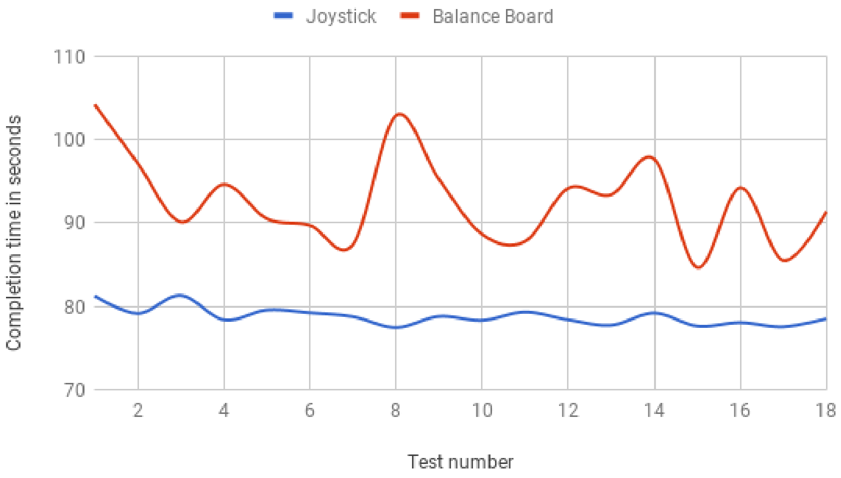


Figure 8. Completion time (seconds) over 18 test runs

For better evaluation of the performance between the locomotion control methods, the minimum, maximum, average, and standard deviation of the completion times for the joysticks and the balance board were calculated from the tracking data. The results from the calculations are shown in Table 1. The full list of completion times for the joysticks can be found in Appendix 1 and for the balance board in Appendix 2. The maximum completion time with the joysticks was lower than the minimum completion time on the balance board. The average and standard deviation were significantly lower for the joysticks compared with the balance board, indicating far better performance with the joysticks.

Table 1. Measurements of the completion times

	Joystick	Balance Board
Min	77.43s	84.63s
Max	81.29s	104.21s
Avg	78.79s	92.73s
SD	1.07s	5.30s

Collisions were used to analyze the accuracy of the locomotion control methods. Total amount, minimum amount, maximum amount, average amount, and standard deviation of the collisions were calculated from the tracking data for both joysticks and the balance board. The result can be seen in Table 2. Collisions for each run are displayed for the joysticks in Appendix 1 and the balance board in Appendix 2. The total and average amount of collisions suggests significantly better accuracy for the joysticks over the balance board.

Table 2. Measurements of the collisions

	Joystick	Balance Board
Total	24	97
Min	0	0
Max	6	11
Avg	1.33	5.39
SD	1.80	3.45

A visualizer tool was used to find common places on the test course in which collisions happened frequently. Collisions with the joysticks are shown in Figure 9 and with the balance board in Figure 10. Several collisions occurred at the same location, which made the amount of collisions seem lower on the visualizer tool. The narrow hallway at the end of the course seemed to be the most difficult place to navigate for both locomotion control methods. The visualised data also indicated a 90-degree turn to be difficult to perform on the balance board without colliding with a wall.

Figure 9. Occurred collisions on joystick runs

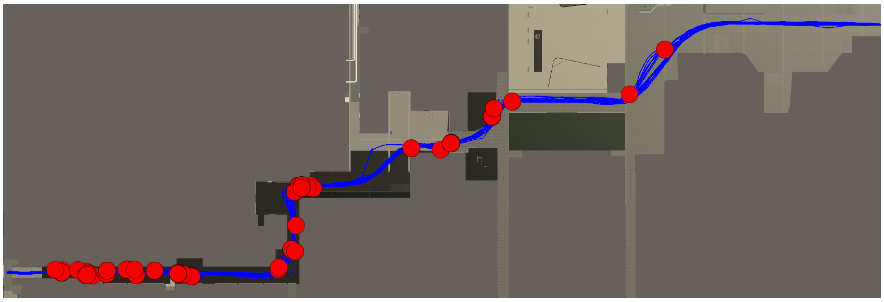


Figure 10. Occurred collisions on balance board runs

6.1.2. SSQ Results

The results of the SSQ were scored using the formulas stated in the original study of the SSQ [41]. As a result we got four values from each questionnaire. The questionnaire scores can be seen in Appendix 4. The SSQ completed after the first part of the tests were considered for the analysis as the results of second and third SSQs can be affected by the parts done before them.

We did not find any significant changes between baseline and the first part SSQ on either of the locomotion control methods. The results indicate no difference in VR sickness between the locomotion control methods. It is important to note that both subjects had extensive previous experience with VR, so this could have effected their lack of symptoms.

6.2. Questionnaires Results

A questionnaire was filled out after the third part of every test. Data collected by these questionnaires was focused on preference between the locomotion control methods. In questionnaires from one to seven, suitability of a control method in the test situation was asked in the Likert scale from strongly disagree to strongly agree. Result are shown in Table 3.

Run ID 1 And 2. The results were similar for both subjects, as can be seen from Table 3. Both agreed that the joysticks were suitable for both narrow hallways and open environments, while the balance board was only suitable for an open environment. Despite the suitability of the balance board, the joysticks were still the preferred locomotion control method. Subjects commented that the joysticks were easy to use as their precision was great, but their performance with the balance board suffered on turns and narrow places because small precise movements were difficult and fatiguing to do. One subject noted the balance board requiring more focus, resulting in better awareness of their surroundings.

Run ID 3 And 4. Both subjects liked to use the joysticks over the balance board because of its better precision, thus feeling more in control and improving their ability not to collide with anybody. Both also agreed the balance board would be adequate while navigating between people, but added that they suspected the balance board may not be adequate in a heavily crowded environment.

Run ID 5. Table 3 shows that subjects did not feel switching between the locomotion control methods to be annoying or difficult to do. On the contrary, they expressed a preference for being able to switch between the joysticks and the balance board. Both subjects said switching making use of the balance board was more comfortable, as one can switch to the joysticks for difficult turns and narrow spots.

Run ID 6 and 7. For moving close to walls, both subjects strongly preferred the joysticks over the balance board, as shown in Table 3. Great precision control was again the main reason that subjects gave for preferring the joysticks.

Run ID 8. When trying to get the best possible time, both subjects opted for the joysticks. Better controlling and the ease of maintaining full speed were given as the reasons.

Run ID 9. For a comfortable and enjoyable experience, one subject opted to only use the joysticks and the other liked to use a combination of both. The subject's reasons for choosing only the joysticks were that it was easier to control with them, and looking around while moving was better, as these things were reported to be difficult on the balance board. The subject gave additional feedback with a suggestion about combining the locomotion control methods by using the balance board for controlling velocity and the joysticks for controlling the rotations. The other subject preferred to use both as the balance board was more fun to use but changing to the joysticks on the challenging situations was said to be necessary, as turning on the balance board was fatiguing and difficult.

Table 3. The Likert scale results from the questionnaires

Question	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Joysticks for narrow hallways	0	0	0	0	2
Balance board for narrow hallways	0	2	0	0	0
Joysticks for open environment	0	0	0	1	1
Balance board for open environment	0	0	0	1	1
Joysticks for navigating between people	0	0	0	0	2
Balance board for navigating between people	0	0	1	1	0
Joysticks for moving close to walls	0	0	0	0	2
Balance board for moving close to walls	2	0	0	0	0
Switching control methods felt easy to do	0	0	0	1	1
Switching control methods felt annoying to do	1	1	0	0	0

In many of the questionnaires, the subjects gave additional notes about the fatiguing nature of the balance board. Small movements on the balance board were reported to cause a notable amount of strain to the legs, which can be a problem when having to move for longer periods of time.

7. DISCUSSION

H1 predicted the joysticks would offer better performance over the balance board when moving in narrow hallways and in other difficult-to-navigate situations. This proved to be correct as runs done with the joysticks resulted in significantly fewer collisions in narrow places. From the visualizations of the runs, we saw that even in tight places it was possible to move close to walls and obstacles when using the joysticks. Few collisions happened in even the narrowest hallway when using the joysticks, and the number of collisions was lower than in runs done with the balance board. The balance board was reported to be difficult to make fine adjustments with while changing direction, which made it easier to get stuck. The easy nature of the joysticks is probably due to it only requiring small movements on the stick to change direction or speed.

H2 was about overall performance measured by the number of collisions and the completion time. As we predicted, the joysticks resulted in significantly less collisions, an average of 1.33 compared to the 5.39 average with the balance board. Even the longest joystick run had a lower completion time compared to the fastest run done with the balance board. Both subjects reported having had experience playing games and using VR beforehand, which means they probably had used joystick controls outside of this experiment. The balance board, on the other hand, was likely a new locomotion control method for both subjects. This gave the joystick locomotion control method a slight advantage, but even after 9 runs with both locomotion control methods, the runs done using the joysticks produced better results in both time and the number of collisions.

As predicted in H3, the subjects preferred the joysticks when moving close to the walls. The ability to do fine adjustments and to keep a straight line without any effort made it a better fit for this kind of situation. This could be fixed with better implementation for the balance board or by longer practising, but that was out of the scope of our experiment.

In H4, the balance board was predicted to be preferred over the joysticks in an open environment with low risk of collisions. While the test subjects did agree that the balance board was suitable for the mentioned environment, preference was given for the joysticks. The reasons for this seemed to be that the balance board was fatiguing to use and the subjects felt more in control with the joysticks, which can contribute to feeling safe as the risk of collisions is lower.

Our prediction in H5 that the balance board offered a more comfortable and enjoyable experience had conflicting results. While the test subjects did not find the balance board to be comfortable due to fatigue, they expressed it was fun to use. Developing a better balance board model with some kind of relief system for toning down the strain could potentially make the balance board more comfortable to use in the future.

The last hypothesis H6 predicted that switching between the locomotion control methods would not be preferred. On contrary to H6, both test subjects found the switching to be easy and useful. Switching made use of the balance board more enjoyable as the subject could switch to joysticks if they felt fatigued or if the situation was difficult to navigate with the balance board.

The SSQ tests indicated no difference between the locomotion control methods. These results can be biased as both of the subjects had almost no symptoms during any parts of the tests and the sample size was small. VR sickness is known to be heavily based on the person and their prior experience with VR and gaming overall, so it is not surprising that our subjects, who had plenty of prior VR and gaming experience, did not experience any symptoms.

Although our sample size was rather small, causing our results to not be statistically meaningful, it is possible that our finding that the balance board is not a suitable devices to use as a locomotion control method for a telepresence robot could also be found in subsequent studies with larger sample sizes. De Haan et al. [14] commented the Wii Balance Board to be a suitable input device for moving around in a VE. Our findings were opposite of that and, while use cases were different in their study and our study, we think it came down to our implementation of the control mechanisms being insufficient and the design of the Wii Balance Board not being optimal for this use case. While the performance of the Wii Balance Board could be improved with better implementation of the control mechanisms, but the underlying issue with the fatiguing nature of the balance board is still there. The balance board might be suitable option for use case in which the user does not have to travel longer distances or do multiple difficult turns. The idea of combining the balance board and joysticks, suggested by one of the test subjects, could be a working solution but based on this study, we think it would not make the balance board a locomotion control method for traveling longer distances. A balance board with a better design for leaning purposes could be a viable solution to reduce the fatigue caused by constant leaning. While the Wii Balance Board might be more fun to use than joysticks, we suggest to consider other options if searching for a replacement locomotion control method for joysticks and use case is similar to our experiment.

8. CONCLUSION

There are many things to be considered when choosing a locomotion control method for a VR application. In this study, we aimed to find out if there are any benefits from using the Wii Balance Board as a locomotion control method compared to the traditional joystick-based controllers. The experiment was intended to be done with 40 participants, but due to the COVID-19 outbreak we were forced to change the plan. Two researchers carried out a total of 18 tests, with 9 test each. The test runs were pre-planned to include as much variance as was needed for gathering the necessary data.

Although the experiments had only two test subjects with very similar backgrounds, we were able to find important points related to the balance board and concluded that, while possibly suitable for shorter periods of time, it is unsuitable as a locomotion control method for a VR telepresence robot when used for longer distances and difficult-to-navigate situations. Turning with the Wii Balance Board was difficult and leaning caused fatigue moderately fast. The joysticks performed better and were preferred over the balance board in every tested situation.

While our implementation could be improved to enhance the experience with the Wii Balance Board, we suggest exploring other options, such as a better designed balance board, in future studies to replace joysticks.

9. CONTRIBUTIONS

Approximately an equal amount of work was done by both researchers. Kalliokoski focused more on programming as he had much more experience with Unity, while Halkola wrote more to balance out the amount of work.

The introduction was done by contribution from both researchers. In related work Kalliokoski gathered information about virtual reality and while Halkola researched robotic telepresence. For locomotion part, Kalliokoski researched different locomotion control methods and Halkola gathered information about previous use cases and studies of balance board applications.

In implementation, Kalliokoski focused on the software, and the visualizer tool, while Halkola worked on the Wii Balance Board, drafts of the UI, and creating questionnaires.

The new test methodology was planned together. During the tests both acted as a subject and a researcher in turns.

Both researchers contributed to the data analysis together.

Table 4. Time used and contribution on the thesis by each group member

Name	Time used (Hours)	Contribution %
Joona Halkola	242	50 %
Juho Kalliokoski	240	50 %

Link to a GitHub repository containing the source code and instructions on how to use the software used in this study: `https://github.com/Jskallio/VR-Teleprecence-simulator`

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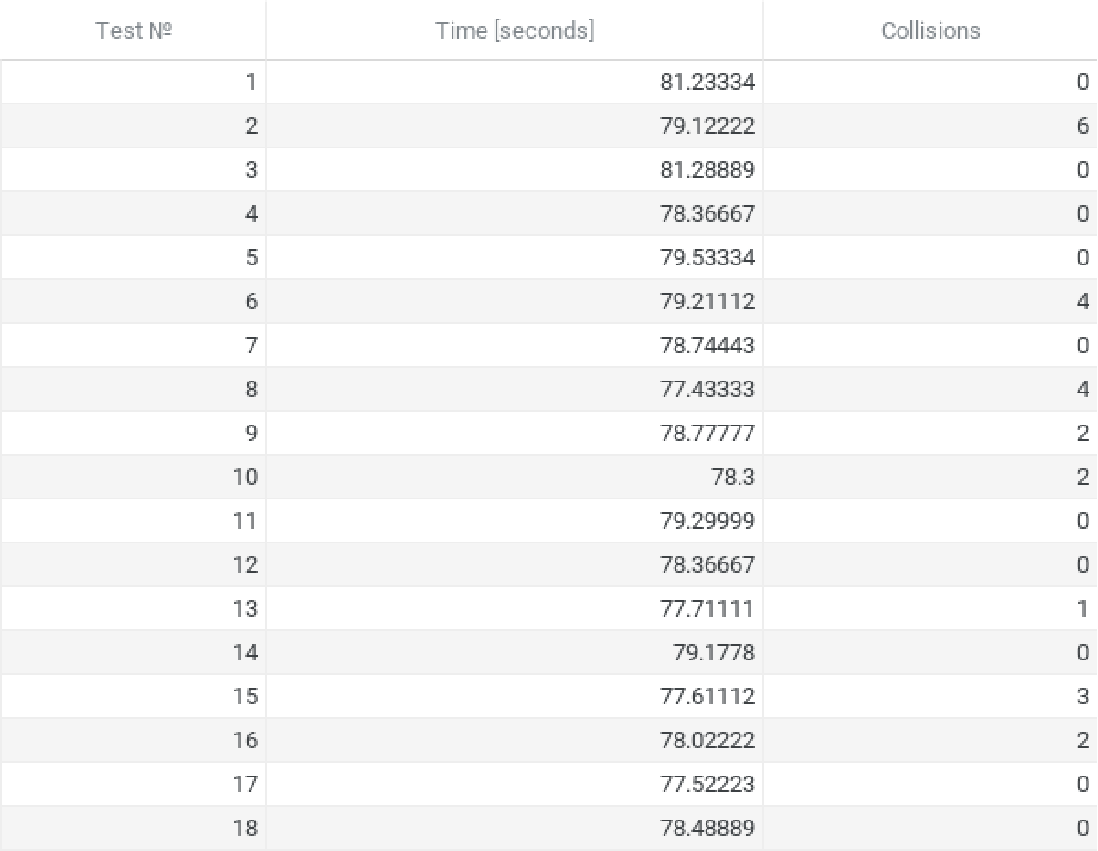
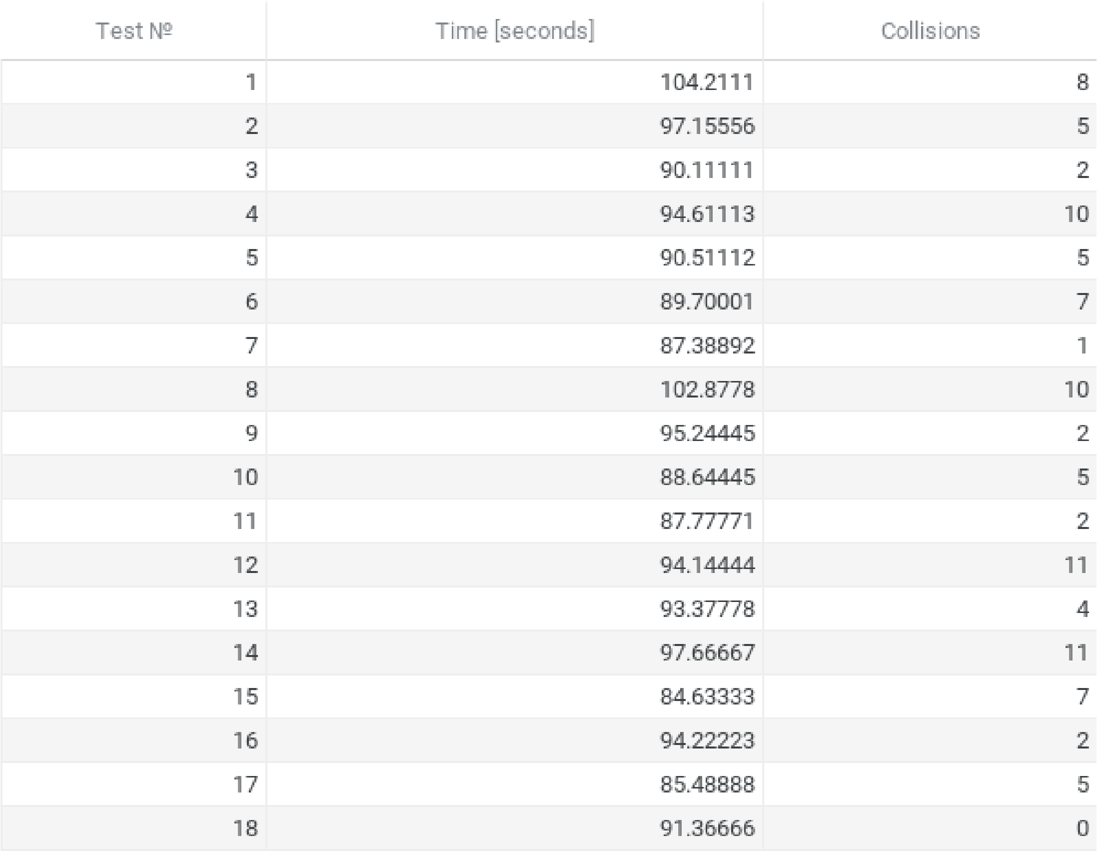
11. APPENDICES

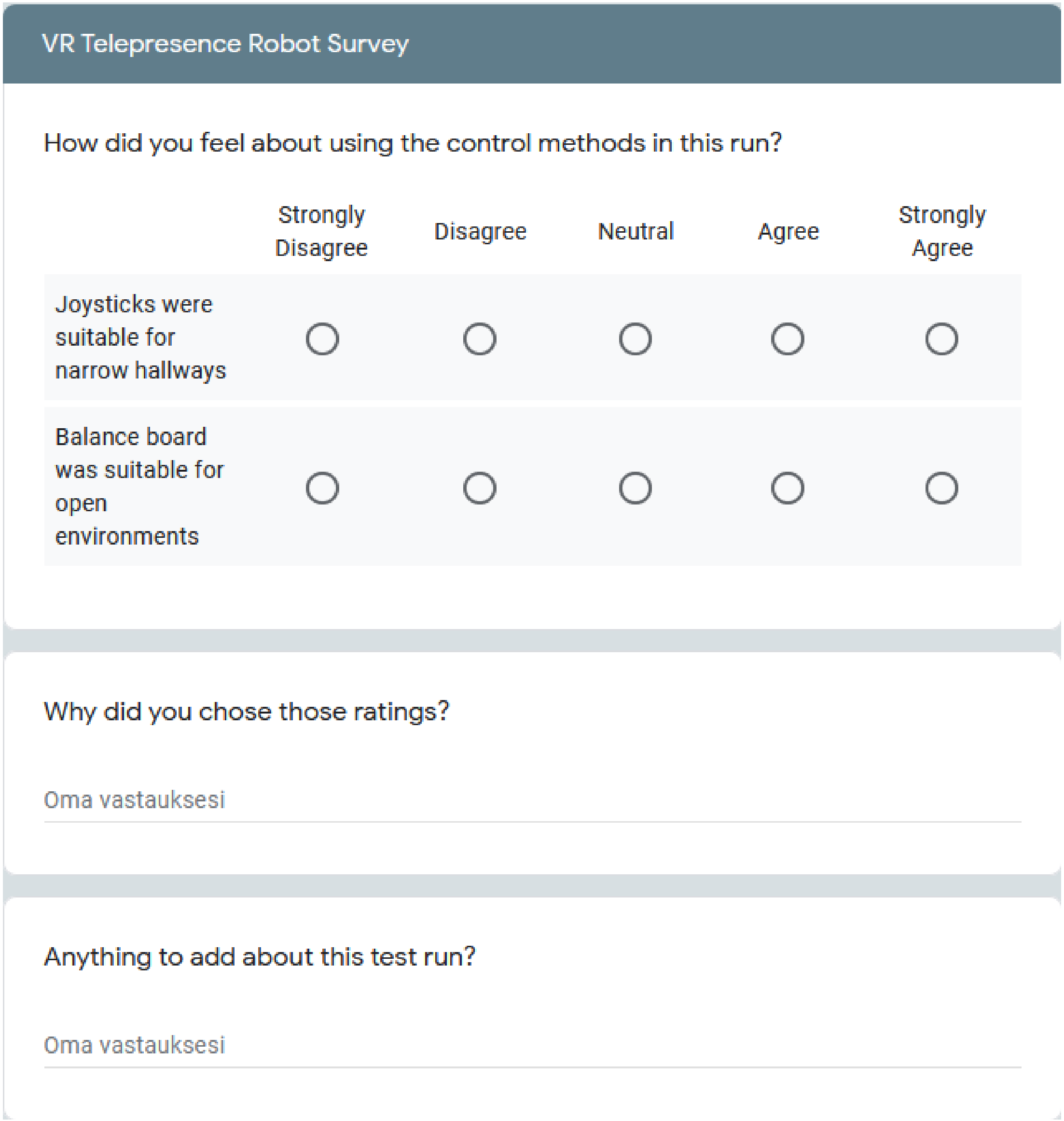
Appendix 1	Times and collisions of joystick runs
Appendix 2	Times and collisions of balance board runs
Appendix 3	Preference Questionnaires
Appendix 4	SSQ scores



Test №	Time [seconds]	Collisions
1	81.23334	0
2	79.12222	6
3	81.28889	0
4	78.36667	0
5	79.53334	0
6	79.21112	4
7	78.74443	0
8	77.43333	4
9	78.77777	2
10	78.3	2
11	79.29999	0
12	78.36667	0
13	77.71111	1
14	79.1778	0
15	77.61112	3
16	78.02222	2
17	77.52223	0
18	78.48889	0



Test №	Time [seconds]	Collisions
1	104.2111	8
2	97.15556	5
3	90.11111	2
4	94.61113	10
5	90.51112	5
6	89.70001	7
7	87.38892	1
8	102.8778	10
9	95.24445	2
10	88.64445	5
11	87.77771	2
12	94.14444	11
13	93.37778	4
14	97.66667	11
15	84.63333	7
16	94.22223	2
17	85.48888	5
18	91.36666	0



VR Telepresence Robot Survey

How did you feel about using the control methods in this run?

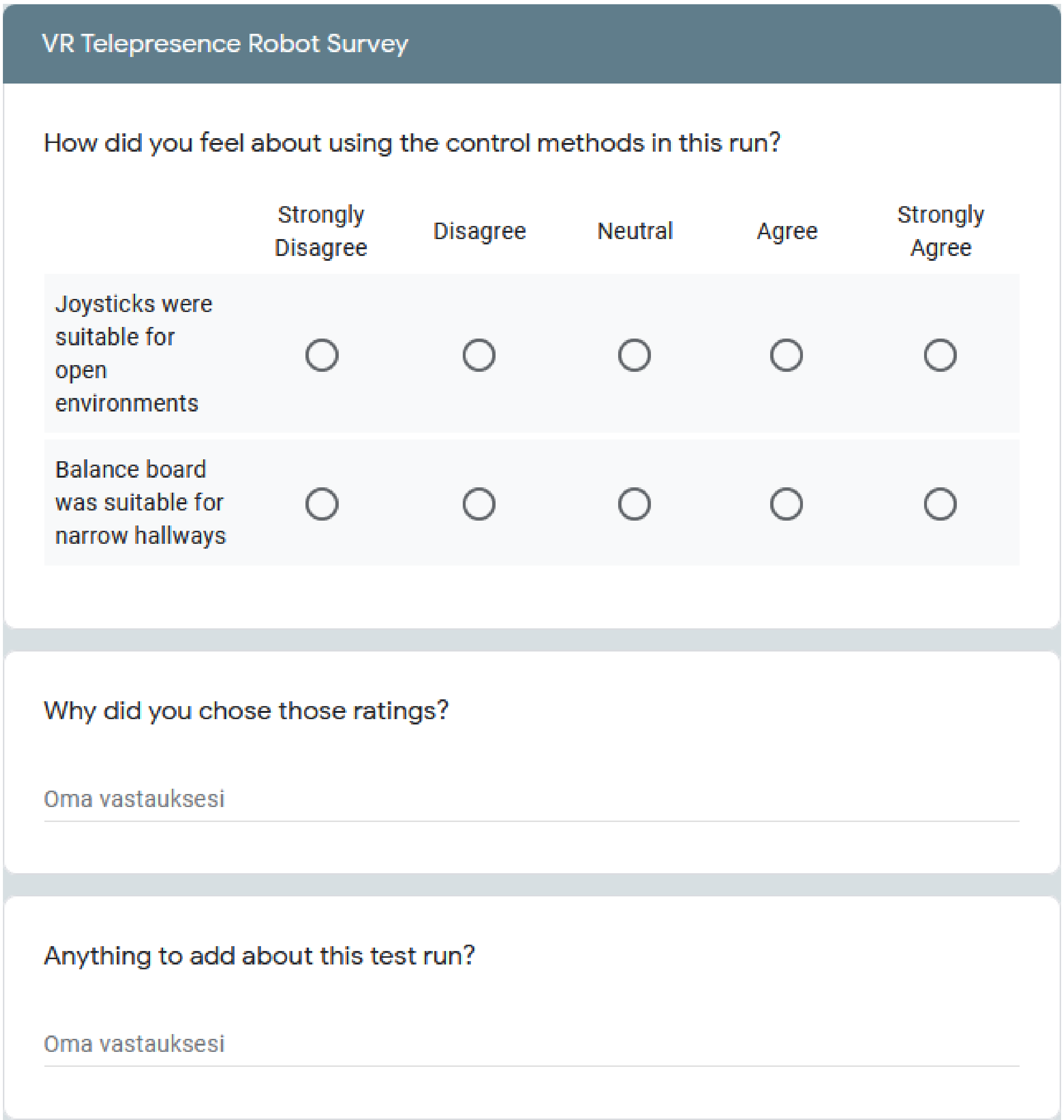
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Joysticks were suitable for narrow hallways	○	○	○	○	○
Balance board was suitable for open environments	○	○	○	○	○

Why did you chose those ratings?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

How did you feel about using the control methods in this run?

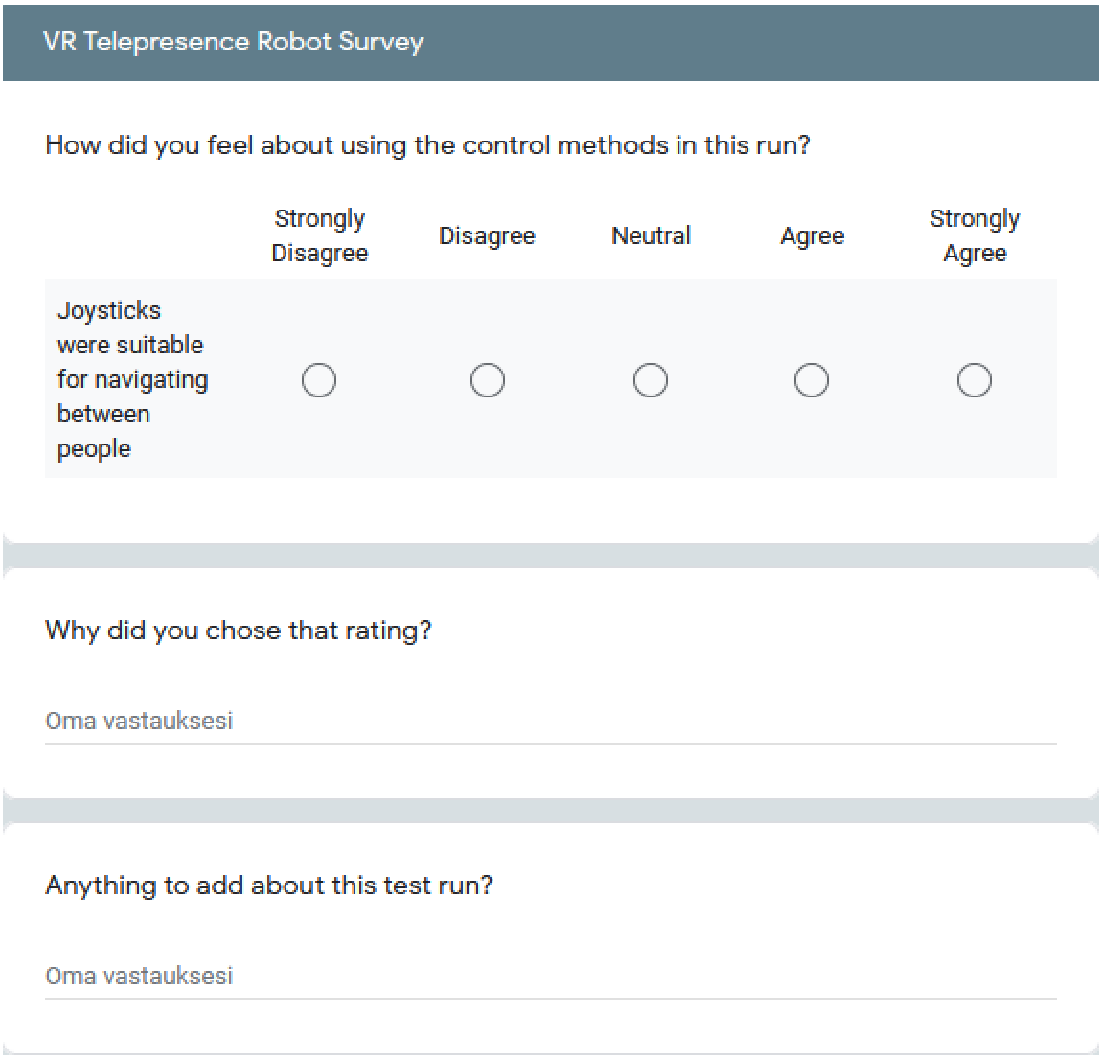
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Joysticks were suitable for open environments	○	○	○	○	○
Balance board was suitable for narrow hallways	○	○	○	○	○

Why did you chose those ratings?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

How did you feel about using the control methods in this run?

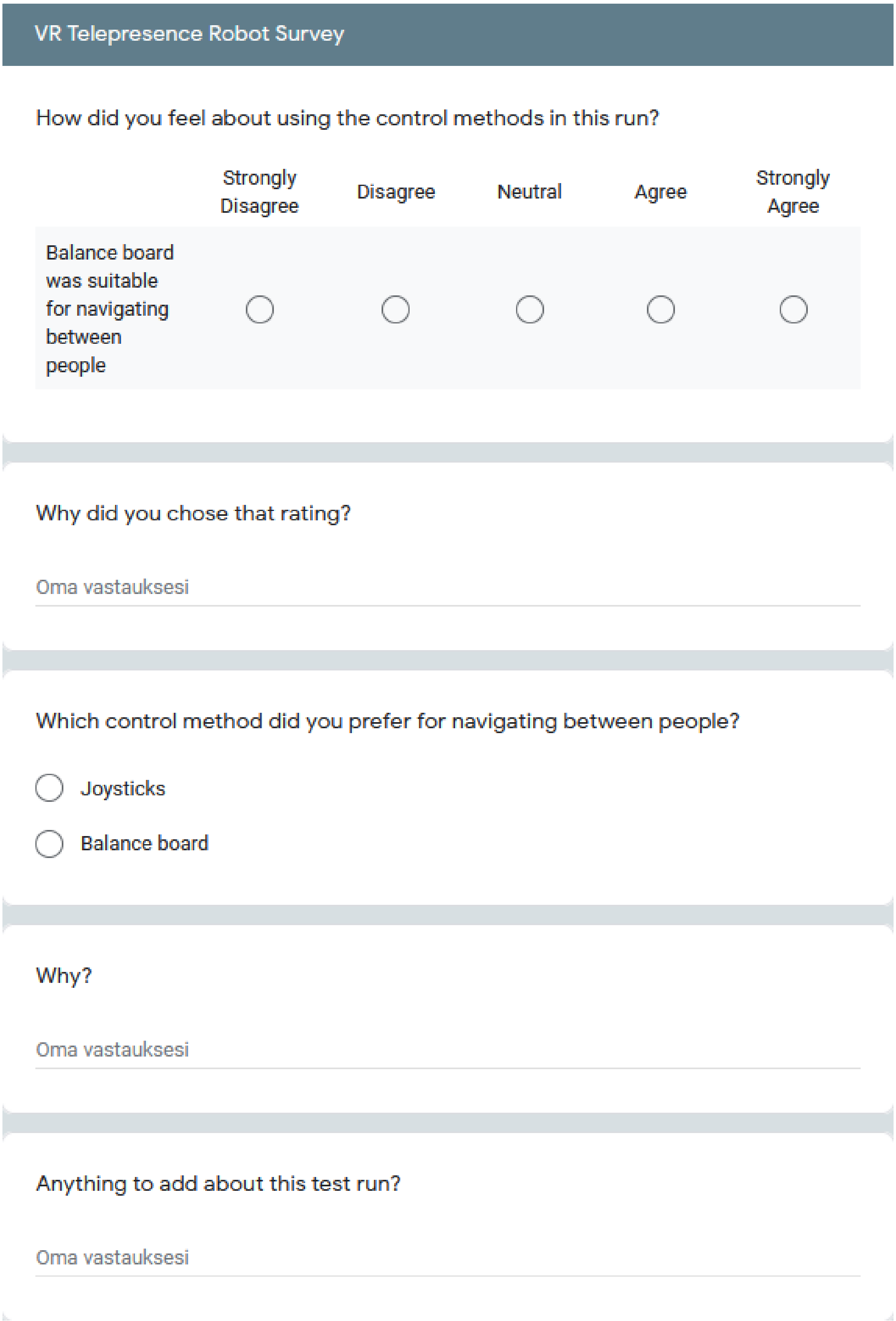
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Joysticks were suitable for navigating between people	○	○	○	○	○

Why did you chose that rating?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

How did you feel about using the control methods in this run?

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Balance board was suitable for navigating between people	○	○	○	○	○

Why did you chose that rating?

Oma vastauksesi

Which control method did you prefer for navigating between people?

○ Joysticks

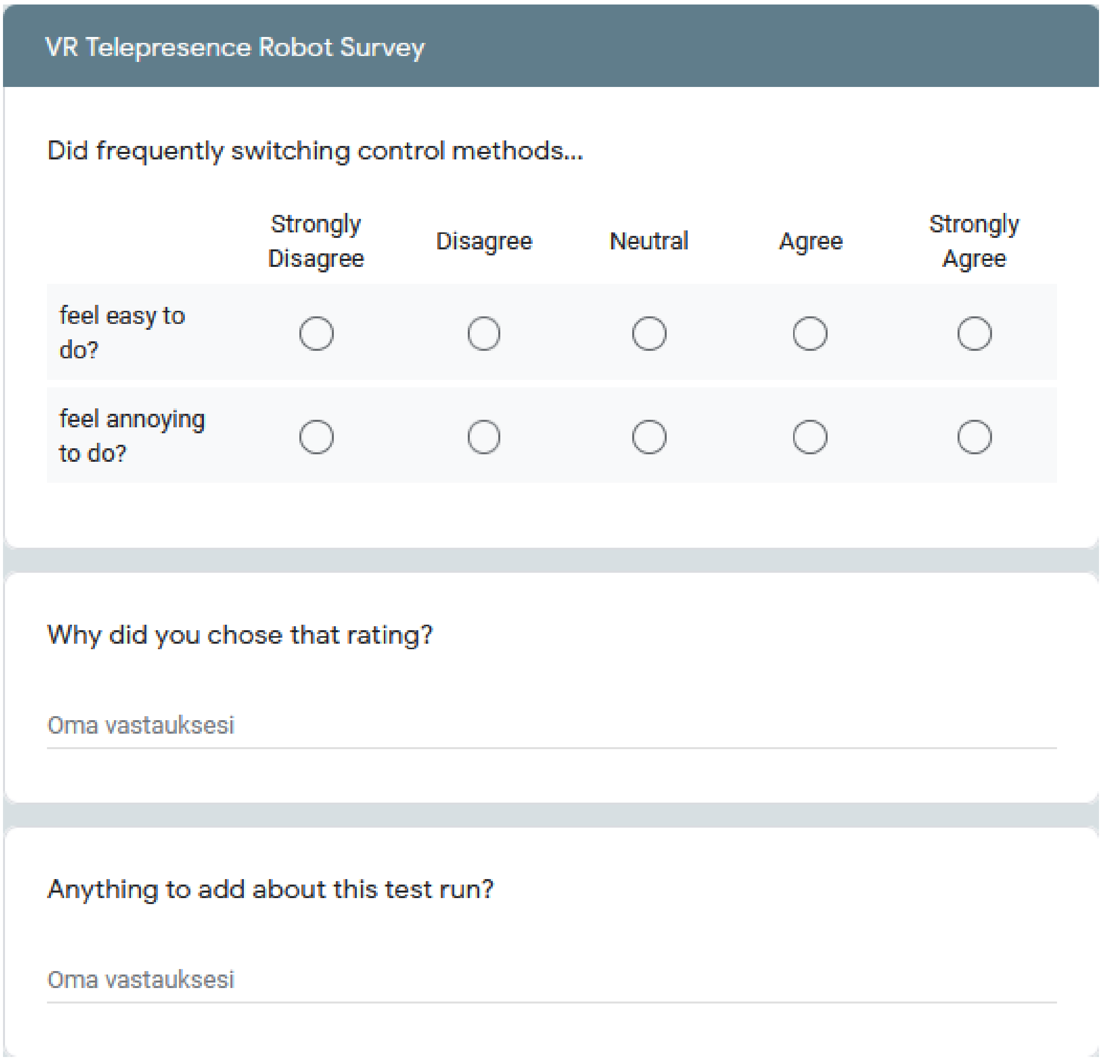
○ Balance board

Why?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

Did frequently switching control methods...

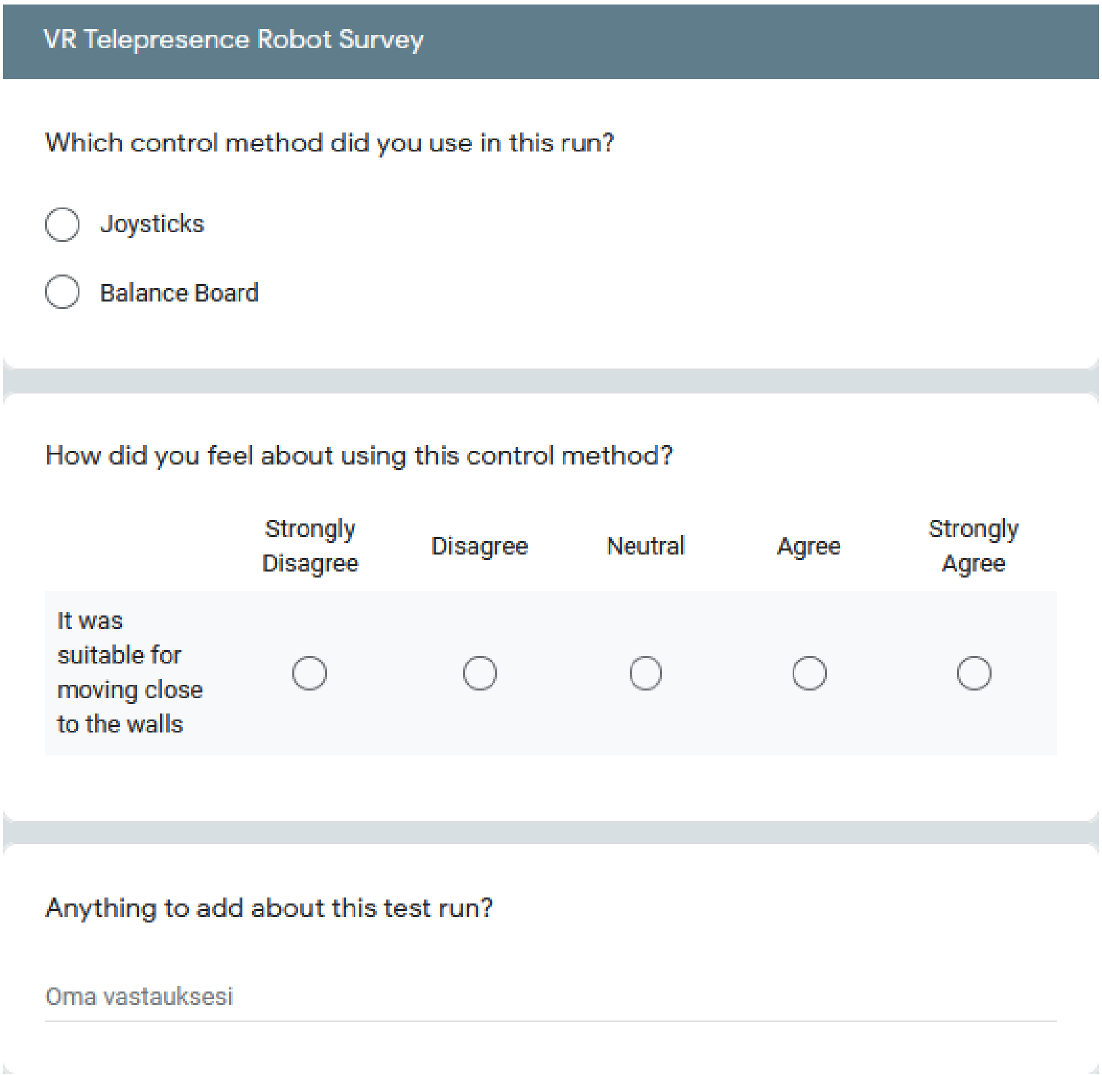
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
feel easy to do?	○	○	○	○	○
feel annoying to do?	○	○	○	○	○

Why did you chose that rating?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

Which control method did you use in this run?

○ Joysticks

○ Balance Board

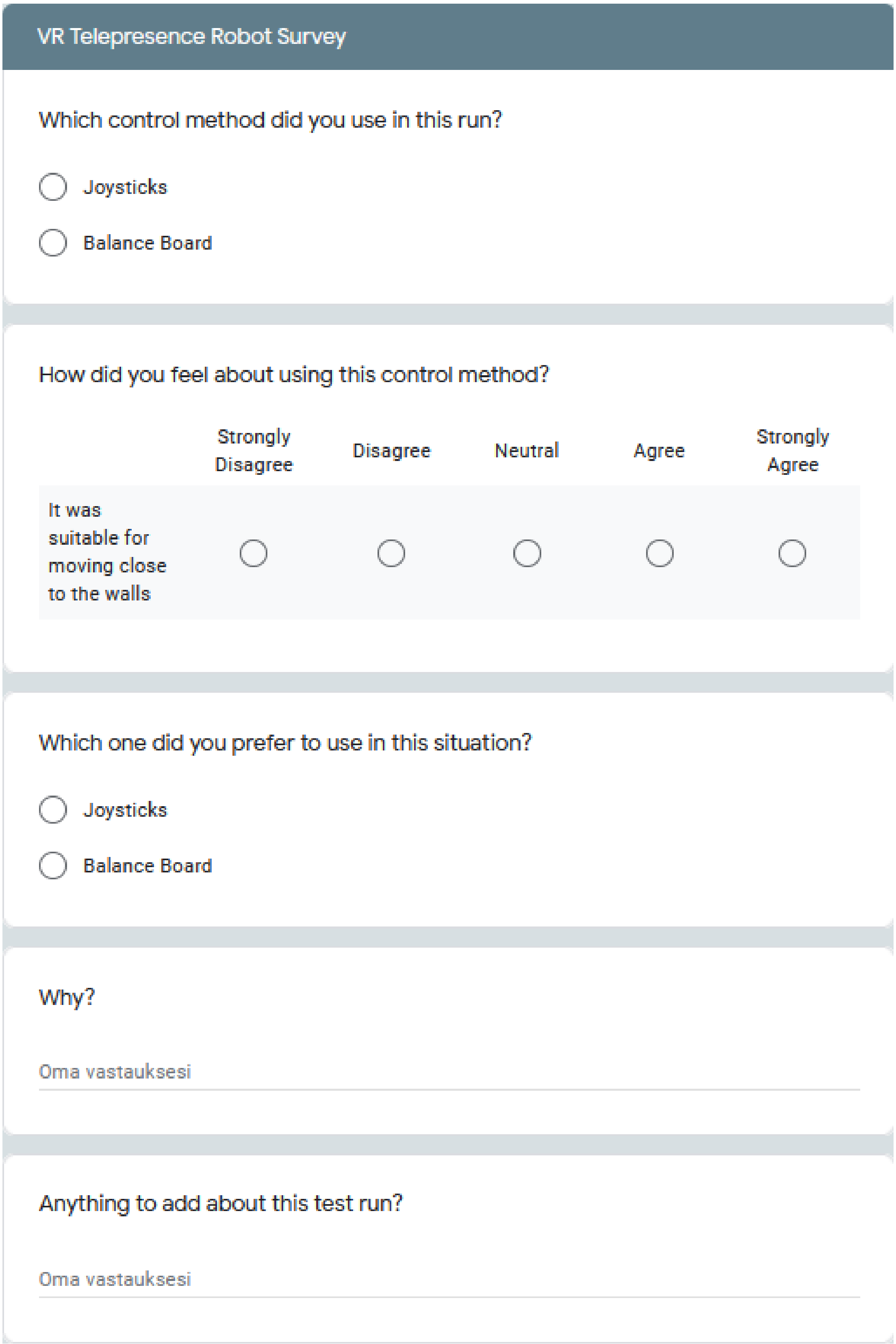
How did you feel about using this control method?

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
It was suitable for moving close to the walls	○	○	○	○	○

Anything to add about this test run?

Oma vastauksesi

RunID 7 Questionnaire



VR Telepresence Robot Survey

Which control method did you use in this run?

○ Joysticks
○ Balance Board

How did you feel about using this control method?

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
It was suitable for moving close to the walls	○	○	○	○	○

Which one did you prefer to use in this situation?

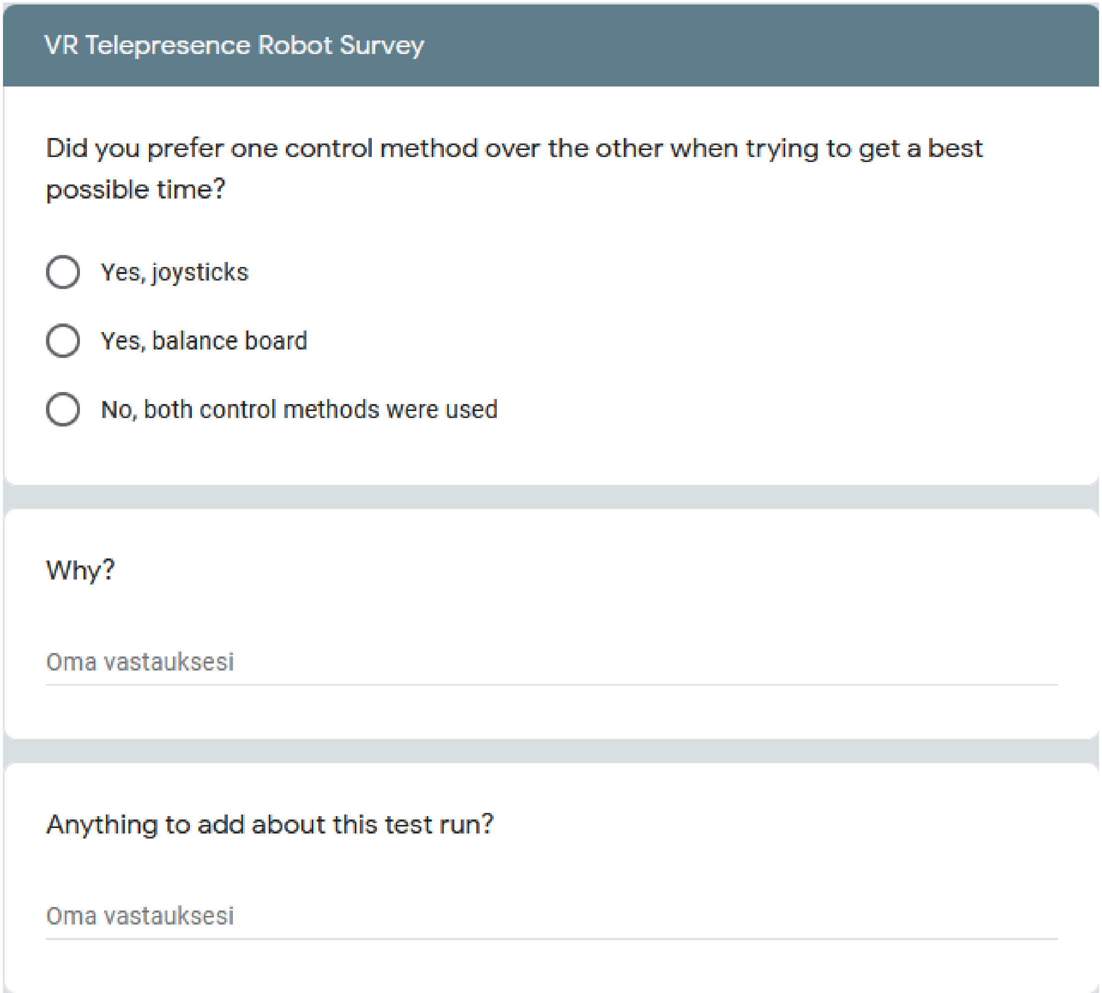
○ Joysticks
○ Balance Board

Why?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

Did you prefer one control method over the other when trying to get a best possible time?

○ Yes, joysticks

○ Yes, balance board

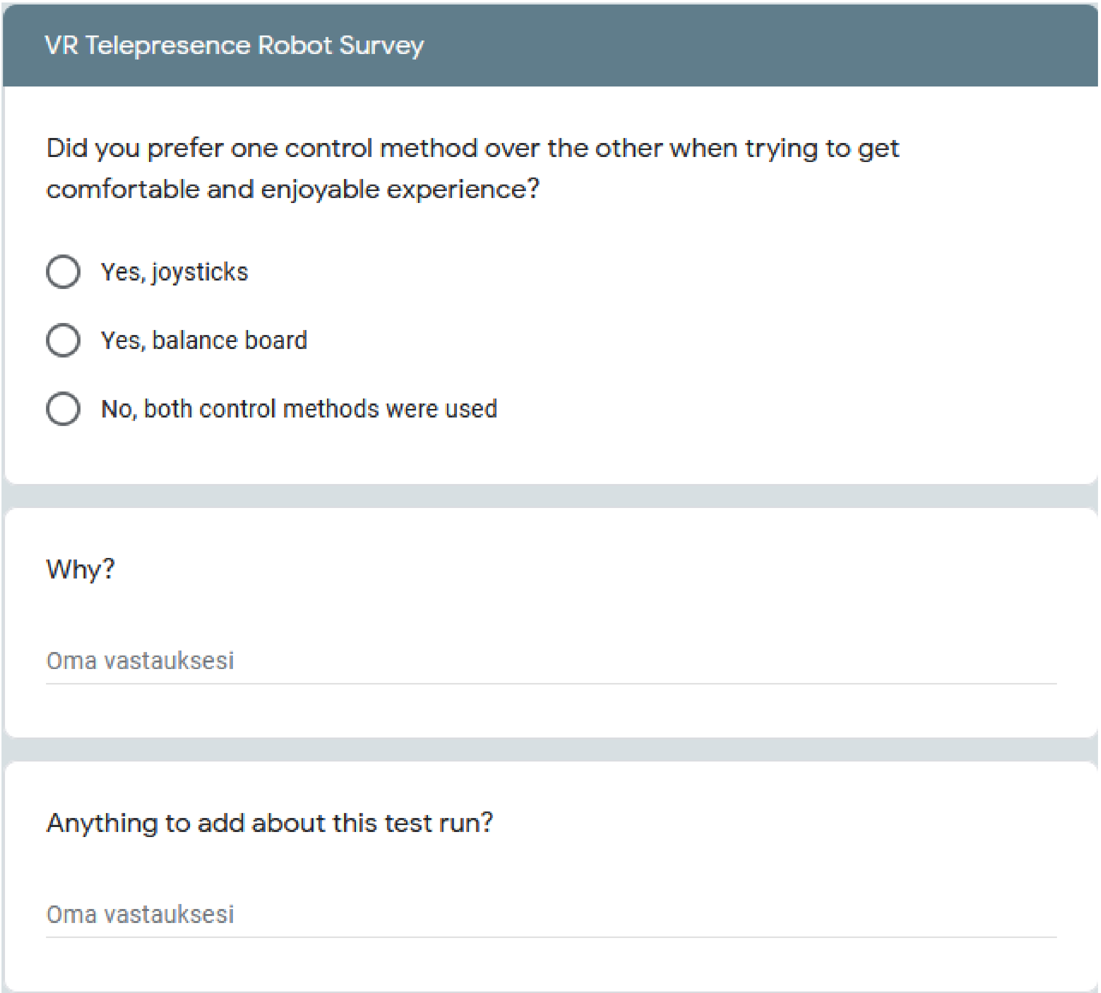
○ No, both control methods were used

Why?

Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



VR Telepresence Robot Survey

Did you prefer one control method over the other when trying to get comfortable and enjoyable experience?

○ Yes, joysticks

○ Yes, balance board

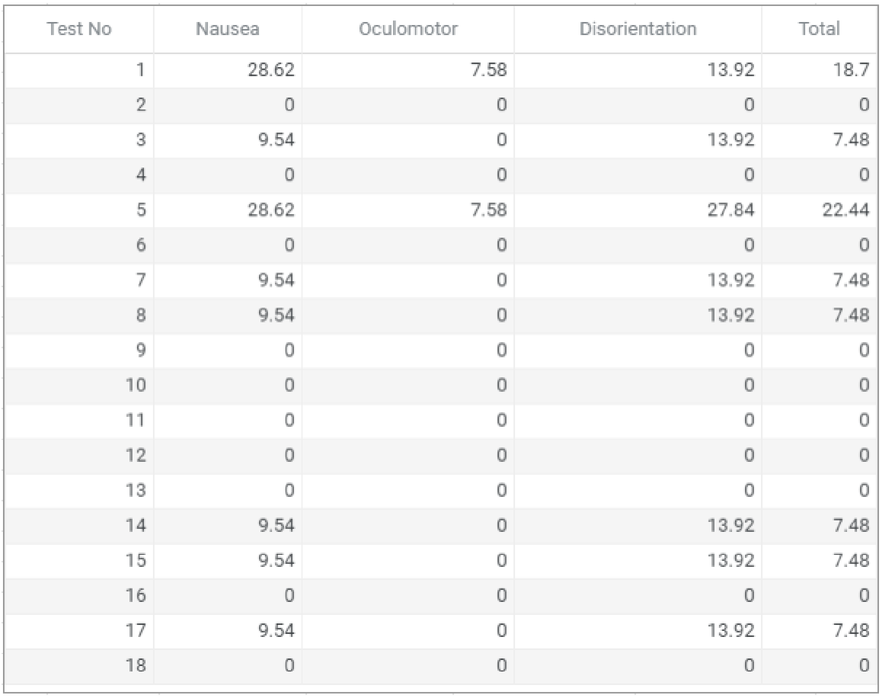
○ No, both control methods were used

Why?

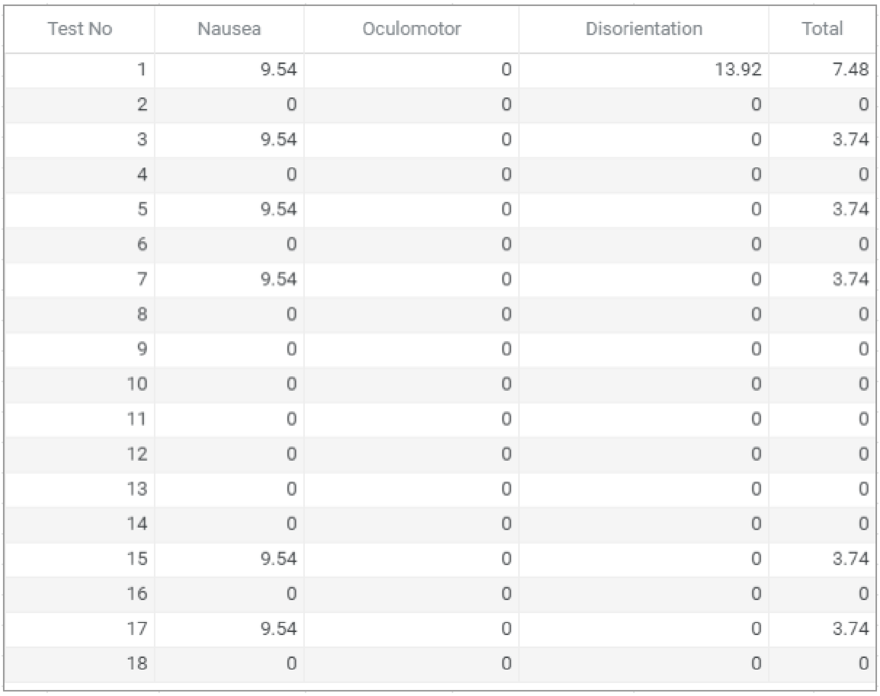
Oma vastauksesi

Anything to add about this test run?

Oma vastauksesi



Test No	Nausea	Oculomotor	Disorientation	Total
1	28.62	7.58	13.92	18.7
2	0	0	0	0
3	9.54	0	13.92	7.48
4	0	0	0	0
5	28.62	7.58	27.84	22.44
6	0	0	0	0
7	9.54	0	13.92	7.48
8	9.54	0	13.92	7.48
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	9.54	0	13.92	7.48
15	9.54	0	13.92	7.48
16	0	0	0	0
17	9.54	0	13.92	7.48
18	0	0	0	0



Test No	Nausea	Oculomotor	Disorientation	Total
1	9.54	0	13.92	7.48
2	0	0	0	0
3	9.54	0	0	3.74
4	0	0	0	0
5	9.54	0	0	3.74
6	0	0	0	0
7	9.54	0	0	3.74
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	9.54	0	0	3.74
16	0	0	0	0
17	9.54	0	0	3.74
18	0	0	0	0