UNIVERSITY
OF TURKU

Moving walkways as a way to navigate in virtual reality

Interaction Design
Master’s Degree Programme in Information and Communication Technology
Department of Computing, Faculty of Technology
Master of Science in Technology Thesis

Author:
Matias Mäkipelto

Supervisors:
Senior Researcher Seppo Helle
Doctoral Researcher Taneli Nyyssönen

February 2023

Master of Science in Technology Thesis
Department of Computing, Faculty of Technology
University of Turku

Subject: Interaction Design
Programme: Master’s Degree Programme in Information and Communication Technology
Author: Matias Mäkipelto
Title: Moving walkways as a way to navigate in virtual reality
Number of pages: 37 pages, 3 appendix pages
Date: February 2023

Abstract:

In this thesis, we will look at moving walkways as a locomotion technique in VR. We will take a look at how much they induce motion sickness, what speed should virtual moving walkways have, and should their shape differ from a physical moving walkway. To achieve this, a virtual environment was created where users can test moving walkways of different shapes and compare them to controller movement. We find that moving walkways can potentially be used to reduce VR sickness experienced. The speed of moving walkways should be adjustable to suit people with different tolerances for VR sickness. One has a lot of freedom with the shape of a moving walkway, but it should include a static frame of reference and it should fit the aesthetics of the environment.

Keywords: VR, virtual reality, VR sickness, moving walkway, locomotion technique

Table of Contents

1 Introduction 1

1.1 VR sickness 1

1.2 Locomotion techniques in VR 2

1.3 Moving walkway in VR 4

1.4 Research questions & hypotheses 6

2 Experiment explanation 7

2.1 Virtual environment 7

2.2 Physical environment 11

2.3 Test process 11

2.3.1 Controls 13

2.3.2 Test proceedings 14

2.4 Questionnaire 14

3 Experiment 16

3.1 Demographic 16

3.2 Observations 17

4 Results 18

4.1 Walkway speed 18

4.2 Controller movement vs MWs 21

4.3 Virtual walkway model 24

4.4 General results 27

4.5 Analysing research questions and hypotheses 28

5 Discussion 30

6 Conclusion 32

References 33

List of abbreviations 37

Appendix: Questionnaire 38

1 Introduction

Virtual reality (VR) is defined as “an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment” [1]. The aim of virtual reality is to make the user feel like they exist within the virtual environment (VE) and forget about their physical environment. In other words, VR tries to create as immersive an artificial experience as possible.

VR shows a lot of potential in both business and entertainment. Its global market share in 2020 was around 4 billion USD [2] [3], and it is predicted to grow with a compound annual growth rate of around 30% between 2020-2025, surpassing the growth of other media segments [4] [5]. Between 2021-2028, even compound annual growth rates of around 44.8% have been predicted [3].

As a relatively new field, VR still holds many unsolved problems. Some of these include interfaces/devices used to interact with VR, ways of interacting with virtual content, and design rules for applications in VR. One of the biggest problems, however, is movement inside VR. While there exist devices that allow the user to walk into any direction while staying physically still (i.e., omnidirectional treadmills), they do not feel identical to normal walking. Therefore most of the movement inside VR happens completely digitally, which creates two problems: the digital movement either does not feel immersive, or it induces VR sickness in the user.

1.1 VR sickness

Humans may experience motion sickness in many ways. Visual, vestibular (sense of balance and acceleration), and proprioceptive (sense of limb position) senses come together to induce a perception of self-motion in people. This perception of self-motion enables us to estimate our position and movement. However, when some of these senses contradict with others, one may experience motion sickness [6]. In other words, when expected motion differs from actual motion, one may experience motion sickness. This can happen in vehicles where visual stimulus can contradict vestibular and proprioceptive senses, or it can happen in VR, where one receives no vestibular or proprioceptive stimulus relating to movement, while receiving visual stimulus that indicates movement.

When a visual stimulus is the dominant sensory input that causes motion sickness, the motion sickness is called visually induced motion sickness (VIMS). VIMS is further divided by the cause of the sickness into categories, such as simulator sickness, gaming sickness, and VR sickness. VR sickness falls under VIMS, as there is little sensory input apart from visual stimulus yet. Perhaps when omnidirectional treadmills or other appliances are used to match proprioceptive, vestibular, or other senses with visual stimulus, VR sickness will no longer fall under VIMS. This paper is written under the assumption that VR sickness falls under VIMS.

VIMS is closely linked to the illusion of self-motion, also known as vection [7]. An example of vection is when one sits on a still train and sees a train outside of the window starting to move. One then often feels as if their own train started to move. This feeling is easily induced in VR and often leads to VR sickness. Vection can appear without any motion sickness, but VIMS is possibly always accompanied by vection [8].

In other words, if the virtual avatar is made to walk in a VE without the user walking physically, the user is likely to experience VR sickness. Conversely, if the user's movements are synchronized with the VE, so that the virtual avatar of the user moves in the same way as the user moves physically, there is little sensory conflict and thus little to no VR sickness.

The lack of natural ways of navigating inside a virtual environment still remains one of the biggest impediments to VR. Current locomotion techniques tend to either easily cause VR sickness, or greatly reduce the sense of presence, the immersion that the user experiences. A great locomotion technique would help match the expected motion with the actual motion to reduce VR sickness. The reduction in the sense of presence caused by some locomotion techniques is also a severe impediment to VR, as the increased sense of presence that VR offers can be thought of as the greatest advantage VR has over applications used with a standard monitor.

1.2 Locomotion techniques in VR

There are two established locomotion techniques in VR: controller movement and teleportation. In controller movement, the user points towards any direction with their controller and presses a button to move at a fixed speed in that direction. Alternatively, controller movement can be done using a joystick. With a joystick, one may also control the speed of controller movement, as the joystick does not need to be held completely down. The direction in controller movement may also be tied to the direction where the user is looking at instead of the direction where the user points towards. Controller movement is highly VR sickness-inducing, as the disparity is great between what the user perceives (expected motion) and what the user experiences (actual motion). The strength of VR sickness that controller movement induces can be somewhat reduced by reducing the field of vision (FoV) during movement [9] or by reducing the movement speed (unless speed is so great it reduces the sense of presence) [10] [11].

The other established locomotion technique is teleportation. It circumvents the problem of VR sickness by inducing little to no feeling of movement at all depending on the implementation. Typically the user points to a direction and presses a teleportation button to appear where they pointed at. There may then be some transition effect, such as blurring the scene, or showing some key frames from the space one teleports over. While teleportation is usable by everyone as it is unlikely to induce VR sickness [12] [13], it greatly reduces the sense of presence of the user and is thus not a very enjoyable locomotion technique.

The most ideal locomotion technique in VR would perhaps be matching real life movement to movement in a VE. However, this has the obvious problems of the user walking out of the sensor range and bumping into objects that do not exist in the VE. There exist a few platforms that allow the user to walk while staying in place in real life to circumvent these problems [14]–[16], but the experience is still not up to par with normal walking, and the platforms tend to be above the price range for consumers.

There exist several other locomotion techniques that have not yet gained traction. One of these is the walk-in-place technique by which the user typically runs, walks, or sways in place to move the virtual avatar forward [17]. Although this technique is very similar to controller movement in that the user does not experience movement forward as they are moving in place, they still perceive themselves moving forward. Research shows that the walk-in-place technique actually reduces the amount of VR sickness that the movement induces in the user [18].

Another locomotion technique that has yet to gain traction is redirected walking [19] [20]. Redirected walking is a walking technique where the visual feed to the user is altered in a way that keeps the user from walking into physical objects or straying away in the physical environment. In practice, the rotations a user takes or the distances a user moves may be slightly exaggerated or downplayed to accomplish this. One example would be rotating the

VE when the user walks forward physically to make the trajectory of the user circular if they want to keep moving straight in the VE. This allows the user to walk theoretically infinitely long distances in the VE. Redirected walking is a very natural way of traversing in a VE as all of the movement is done by walking. However, there is still a disparity between what is experienced and what is perceived. Redirected walking also cannot deal with every path a user may want to move in.

Every locomotion technique seems to have flaws. So, there still exists a demand for immersive locomotion techniques that do not induce VR sickness in the user while allowing the user to move distances greater than their physical environment. While such techniques exist and have been researched, the 'use of moving walkways' (MWs) in VR has been under-researched.

1.3 Moving walkway in VR

At first glance, MWs in VR seem very similar to controller movement. The user does not physically experience motion, although they perceive motion in the VE. However, the movement on an MW in VR is highly similar to that of the physical counterpart. In both of them, the user can stay still while they are propelled forward. This leads to an assumption that MWs would not induce much VR sickness in the user despite the likeness to controller movement, as it should help bridge the gap between expected and actual movement sensations. In addition, several studies have shown that introducing a static frame of reference can reduce the experienced VR sickness [21] [22].

Still, the experience of an MW in VR will not be exactly the same as with a physical MW. With the virtual counterpart, the user does not experience a nudge at their feet when they enter the walkway at the wrong speed, nor do they need to exert extra force to stop their movement when exiting the walkway. As such, it is hard to deduce how much VR sickness the user will actually experience with virtual MWs without an experiment.

Physical MWs tend to move at a speed of between 1.8 – 2.7 km/h [23] [24], although there are also high-speed walkways that can travel even 12 km/h [25]. A typical MW is thus slower than the typical walking speed of around 5.0 km/h [26] [27]. With physical MWs, people sometimes opt to walk on them to increase their travelling speed in addition to being propelled forward on their own. This is sadly not as feasible in a VE as the user would likely bump into objects or travel outside of the sensor range. As such, the movement speed of the

MW needs to be adjusted for a satisfactory user experience. The balance of VR sickness and user experience can likely be adjusted with the speed of the MW to an extent.

MWs in VR can be used in the same way as they are used in the physical world: as static objects placed around the environment to serve as a connection between points A and B. In addition, the VE offers new ways to use MWs. They can be used as a locomotion system where the user places MWs themselves into the environment and thus decides their movement destination. In such a case, the MW can visually represent e.g. a hologram of an MW, so that it does not break the immersion too much, a moving platform (e.g. a flying carpet), or should virtual sickness allow, the virtual MW can even take on the shape of a gust of wind for greater immersion. With such a locomotion system, the movement inside any VE can be done in a fairly immersive way with hopefully little VR sickness. MWs can also cover slopes. On a slope, the MW can be tilted to be parallel to the ground, or it can take on the shape of an escalator. Additionally, MWs can curve.

In VR, there are no such safety concerns as there are with MWs in the physical world. There is no fear of having fingers or hair get stuck between moving parts should the person using the walkway fall. However, falling down on the MW may be more (or perhaps less) common in VR as virtual MWs do not replicate the acceleration and deceleration of stepping into and out of one. Since the dangers of virtual MWs are not as great as their physical counterparts, virtual MWs do not need to have handrails for safety. It may even be better for virtual MWs to not have handrails so that the user does not try to lean on them, and that the user can walk out of the MW partway through.

Since physical MWs are expensive, they are mainly used in places with a lot of people and long walking distances such as airports and railway stations. As such, they are not encountered a lot in daily life. Since there are no steep monetary constraints for having MWs in VR, they are worth doing more research into.

There are also potential downsides to virtual MWs. As a locomotion technique, while they may be immersive, they are not very engaging. Every time the user wants to move somewhere, they need to take a couple of steps and then wait. Some people also get sick on MWs, so virtual ones would likely not reduce the VR sickness experienced by such people. MWs may also be awkward when a user wants to move several short distances in different directions in order to avoid obstacles.

1.4 Research questions & hypotheses

This paper aims to answer the following questions:

Q1 *How much VR sickness do MWs induce compared to controller movement?*
Q2 *How fast should a virtual MW be?*
Q3 *What shape should a virtual MW have?*

A virtual environment was created with Unity to help answer these questions. Test users used the VE to find a pleasant speed for walkways, moved through a course with both MWs and controller movement, and finally tried different shapes of MWs.

Two hypotheses were formed for the research questions. For Q3, no hypotheses were formed, as the aim of that research question is to find guidelines for designing virtual MWs.

H1 *Virtual MWs can be used to reduce the VR sickness experienced.* This is expected due to MWs having a static frame of reference and a stabler direction of movement than controller movement.

H2 *Virtual MWs should move faster than their physical counterparts at around normal walking speeds.* Since MWs are expected to reduce VR sickness compared to controller movement, it follows that they should move faster than controller movement. This is because, as a passive locomotion technique, higher movement speed is expected to lead to a better user experience. This would make them move at around normal walking speed.

2 Experiment explanation

2.1 Virtual environment

Figure 1. The virtual environment.

The virtual environment created for the tests is shown in Figure 1. It featured a park with a large semicircle portion and an elevated area. The environment was created by modifying the asset “Parking Garage – Complete” from 255 pixel studios [28]. Skybox used in the VE was “Casual Day” from Skybox series by Avionx [29]. The VR controllers had a hand asset created by Adam Wentz applied to them for added realism and to be able to see the controllers inside the VE [30]. The hands were not animated. Four different MW models were also created specifically for this research, of which the wind type walkway used leaf assets created by adam127 [31].

The VE was made as realistic as possible as VR sickness tends to be more pronounced in graphically realistic scenes [32]–[34]. This should have made it easier to spot differences in the level of VR sickness that the different locomotion techniques caused. Additionally, there were no FoV limitations or other VR sickness-reducing methods during either of the locomotion techniques for the results to be more comparable. The VE was completely static apart from the MWs in order to not distract the user. The VE also had only visual stimuli.

Several MWs were placed into the VE for the tests. Two of them were placed on a slope to test both ascending and descending MWs, and one was placed on the semicircle to test a curving MW. The slope was at a 11.7-degree angle, which is close to common inclinations for inclined MWs [35]–[37] with a length of around 9.3 metres, while the curving MW had a radius of around 17 metres and spanned 180 degrees making its length around 53 metres. The results will not differentiate between the different types of walkways (straight, inclined, or curving). The metrics used in the test were the default Unity metrics with one unit corresponding to one metre.

To make the MWs act like physical MWs in the game engine, they were set to move in a direction with a fixed speed with collision physics enabled, and in the opposite direction with the same speed without collision physics enabled. These movements cancelled each other out, so that the walkway stayed still, but every object that collided with the walkway experienced forces as if the walkway was moving to one direction. The textures of the MWs were set to scroll with the correct speed to match the aesthetics of an MW.

This way of implementing an MW in Unity required the player to also have physics enabled. This is not the case by default when using the XR interaction toolkit, as the player will only have a camera and controllers attached to them, but no body. To make the player behave like a physical object without creating a body, as the test will not use full-body tracking, an invisible collider was added to the player along with a physics component (rigidbody). The collider, shown in Figure 2, resembled a squashed sphere, but the edges and the bottom were slightly adjusted to prevent clipping through walls and to make it easy to ascend the slopes and move onto the MWs. The rigidbody component was added to the parent of the camera, and the collider was added to a new game object as a sibling to the camera.

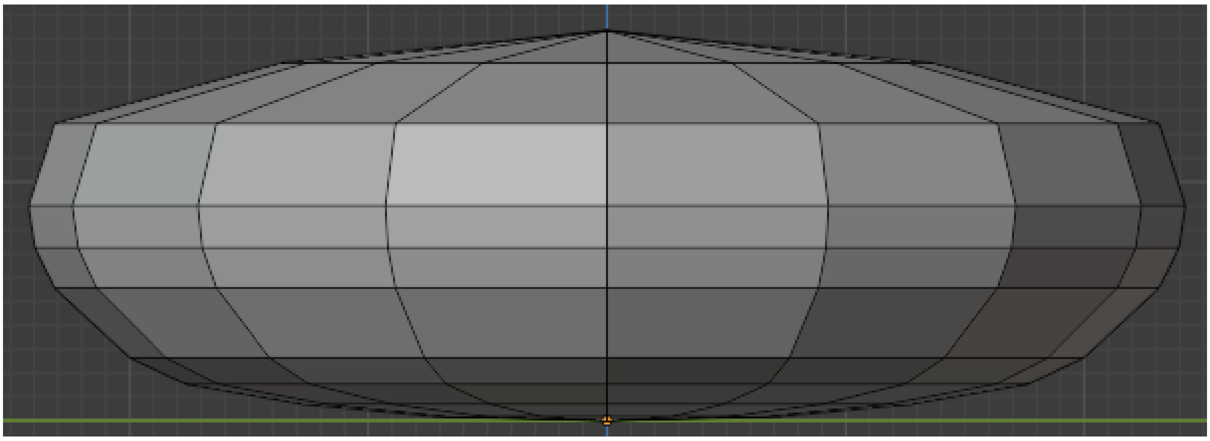


Figure 2. The player collider.

This collider had a diameter of 34 cm and was set to always stay under the player camera on the ground with a script. This made it so that the user could not go through walls and other objects, instead the camera would not move even if the player moved against an object. There was a chance that this would cause motion sickness, but the chance of the test users bumping into objects was very minimal as the collider was also very narrow. The obstacle the player was most likely to collide with had its collider disabled. This way of implementing collisions had its faults, such as if the user did not take a step away from the MW when it ended, it was possible for them to lean slightly backwards and thus re-enter the MW. Using full-body tracking, one could make the collisions more realistic and less likely to cause unintended movement. It would have been possible to remove physics from the MWs after the user had exited them, but that would have made the walkways less realistic and as such gone against the aim of this research.

Rotation of the player due to physics was prevented everywhere apart from the curving MW, where the collider was allowed to turn along the top-down axis to keep the user faced forward throughout the MW. Preventing rotations due to physics prevented the camera from turning on slopes and on the edges of MWs where the collider touches both the MW and the ground. Unintended rotation of the camera at the edge of an MW was still possible on the curving MW, as the physical rotation of the camera had to be enabled there to turn the camera similar to how a person would turn on a curving MW. Still, there were no instructions on the test for the test users to step out of the curving MW partway through, so this should not have caused any unwanted rotations of the camera.

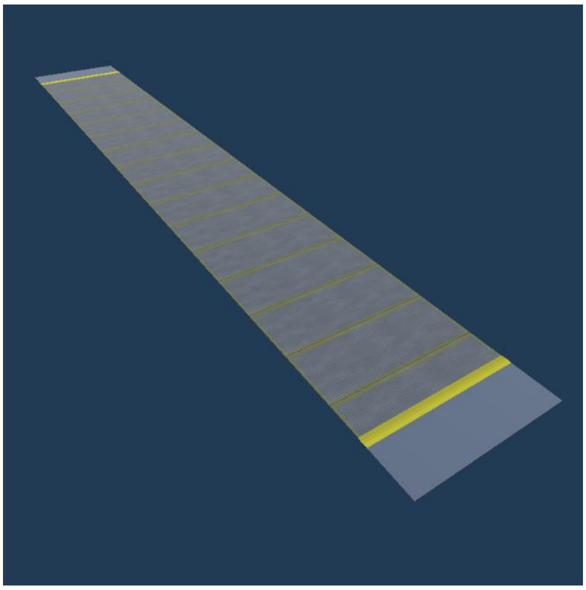


Figure 3a. Realistic walkway without handrails.

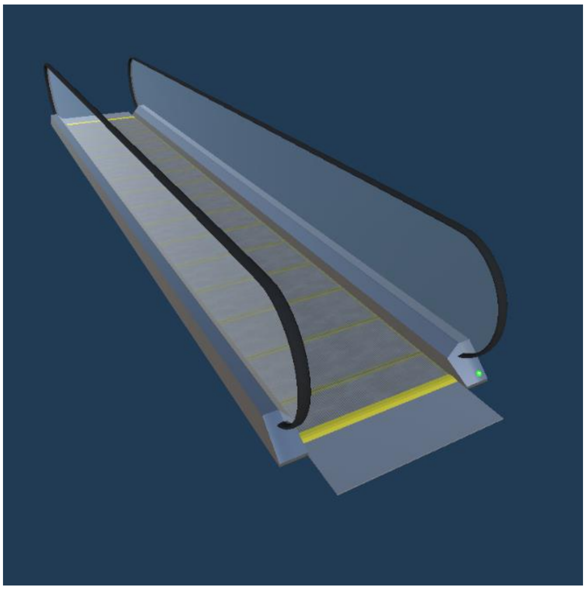


Figure 3b. Realistic walkway with handrails.

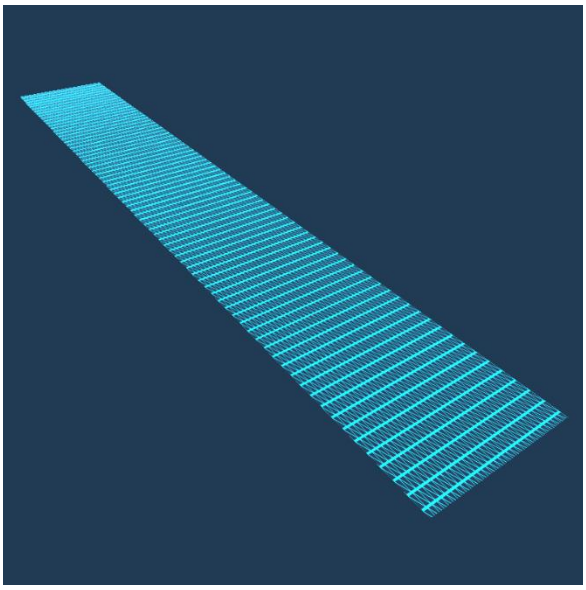


Figure 3c. Hologram walkway.

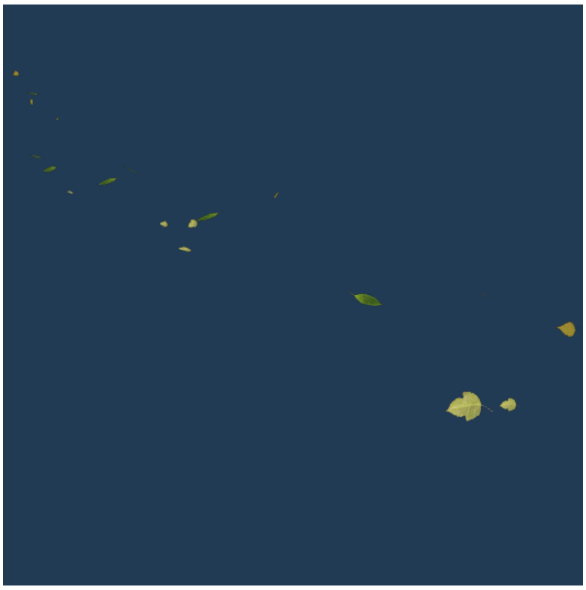


Figure 3d. Wind walkway.

Figure 3. The four walkway styles.

Every MW in the experiment behaved in the same way apart from the curving walkway, which was set to rotate in a similar manner as how the other walkways moved linearly to make the physics behave properly. Not including the ascending, descending, and curving MWs, there were four walkway models used in the experiment, shown in Figure 3. The walkway that had side rails did not have colliders on the side rails to prevent glitches with player collision. The wind walkway had the same kind of walkway on the ground as the other models, but the walkway had been made invisible. The leaves in the wind covered a slightly larger area and moved slightly faster than the invisible walkway on the ground, so that the user would feel that they were surrounded and pushed by the wind whenever the walkway propelled them forward.

2.2 Physical environment

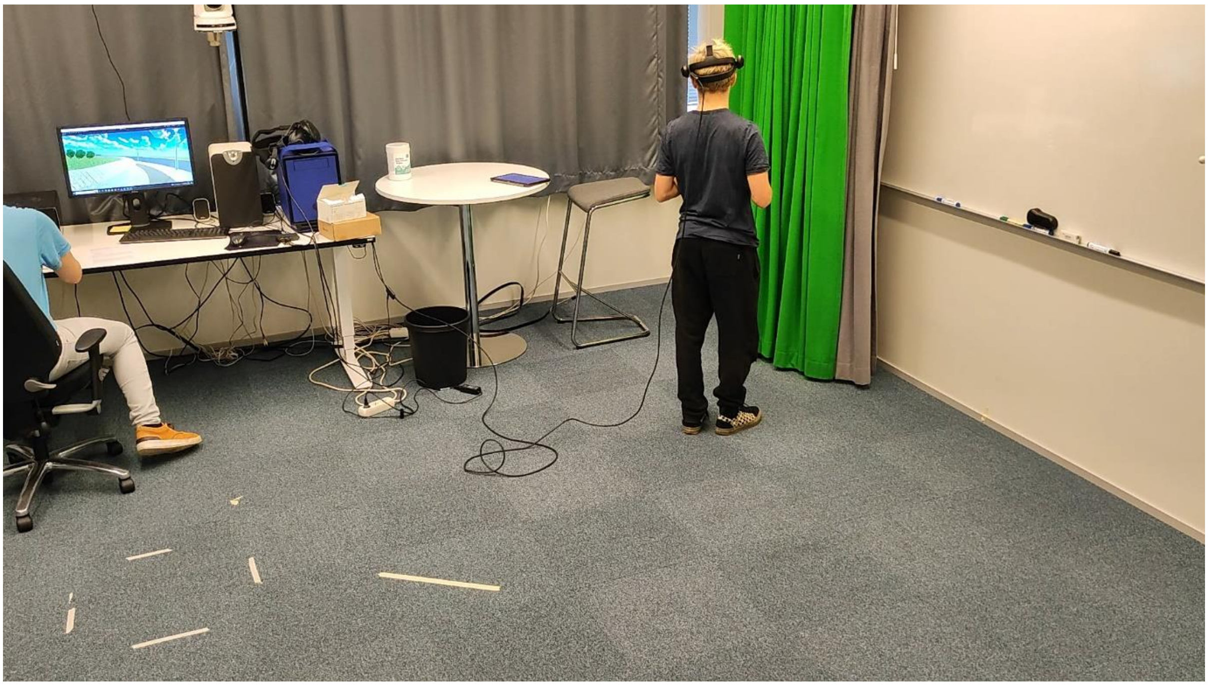


Figure 4. Test in progress.

The experiments were conducted at the University of Turku in the mixed reality research laboratory. An image of the laboratory is shown in Figure 4. The laboratory featured around 12 m^2 of unobstructed space for the tests. The VR headset used in the test was HP Reverb G2 with its native controllers. It featured inside-out tracking, 2160 x 2160 pixels per eye, 90 Hz refresh rate, and 98° horizontal and 90° vertical FoV. Controller movement was implemented with joysticks.

2.3 Test process

The test was divided into three parts. Every part started in the same position in the VE: at the right end of the red line in Figure 1 next to the three walkways. In the first part, the test users needed to set a pleasant speed for the walkways. They could do this using two walkways at the start that were next to each other and went in opposite directions. They could go back and forth between the two walkways as many times as they needed until they found the speed of the walkways pleasant. The test users were not told this, but the speed they set for MWs was used for controller movement as well to make the comparison of the strength of VR sickness easier. Had the test users known this beforehand, they might have taken it into account when choosing a speed for the walkways, which would have gone against the purpose of this research.

After setting the speed, the test users needed to navigate to the other side of the park using either controller movement or MWs. The red line acted as a guide for the route they needed to take. When using MWs, the path first contained a flat MW, then an ascending MW followed by a descending MW, a flat MW, and finally a curving MW. While using controller movement, the path was the same and had the same features.

The locomotion technique used in the first test was random. If a test user was assigned to start the first test with controller movement, only the two walkways that were used to set the speed of MWs moved. The other MWs were stopped, so navigating through the park had to be done using controller movement. If a test user started with MWs, controller movement was disabled, so they had to use MWs to navigate through the course. The test users were split into these two groups since it has been shown that extended exposure to VR is associated with stronger symptoms of VR sickness [32], [38], [39]. The results would not have been comparable otherwise due to this.

When moving between the two walkways used for setting the speed, the test users used the locomotion technique they started with, which might have had some influence on the speed of the walkways they chose. However, the MWs were so close to each other, that this influence should have been very minor.

After reaching the green goal line on the other end of the large semi-circle, the test users needed to take the VR headset off and answer questions related to the VR sickness experienced with the locomotion technique they used. In the second part of the test the test users had to navigate through the same course as in the first part, but this time with the locomotion technique they did not start with. In the second part of the test, they no longer needed to set a speed for the MWs. After reaching the goal again, the test users once again needed to remove the VR headset and answer similar questions related to the VR sickness they experienced.

In the third part of the test, the two walkways that were used to set the speed, in the beginning, were replaced with a longer, around 32 metres long walkway that reached from one end of the park to another. All other walkways were stopped. The test users could change how this walkway looked, and they had to go from one end of this walkway to the other once (not back and forth) using each of the four walkway styles. The test users then answered a questionnaire about the different walkway styles. The test concluded with the users answering general questions about the test, such as possible problems they experienced with the test application or devices.

2.3.1 Controls

When using the MWs to navigate the park in either the first or the second test, the test users could teleport in front of the walkways. Teleportation was not allowed anywhere else. Teleportation was activated with the left-hand trigger and a ray that was cast from the left hand in the shape of a projectile curve. Teleportation was enabled in this part of the test because of the considerable distances that the test users would otherwise have had to walk physically to reach the next MWs. Teleportation causes little VR sickness, so its effect on the results should be minimal. Teleportation was possible in the third part of the test as well if the test users felt that they needed to use it to reach the first MW.

Since teleportation delivered the test users in front of the MWs, they still needed to walk about one step physically to get onto the MWs. As the test users had to walk physically, they could reach the edges of the physical room. When a test user got close to the edge of the room, so that they did not have physical space left to walk forward, they needed to turn physically into a direction with open space, and then turn back in the application using 45° snap-turn with the right joystick. When close to the edges of the room, a floating wireframe of the room boundaries appeared to help guide the test users when turning. Snap-turn was possible in every part of the test. Another way to avoid edges of the room was to walk back to the centre of the room and then teleport again.

When using the controller movement to navigate through the park, it functioned with the left-hand joystick. The first and third parts of the test also featured a menu. The menu could be opened and closed with the primary button of the right hand (A button) and could be interacted with using the right-hand trigger with a straight ray that was cast from the right hand when the menu was open. The menu was used to set the speed of the MWs in the first part and to change the model of the walkway and its direction in the third part. Teleportation was disabled when the menu was opened to help prevent the test users from leaving the menu open in the background. A floating menu could have affected the VR sickness experienced.

2.3.2 Test proceedings

With each test user, the experiment started with an explanation of the outline of the whole test. After listening to the explanation, the test users read the privacy notice and agreed to the terms of the experiment through the questionnaire. Then they filled out the background questionnaire. After that, they needed to adjust the interpupillary distance of the lenses of the headset followed by an explanation of the controls used in the first test and their tasks in the first test. After the first test, the test users filled in one table of questions related to VR sickness. Then the controls used in the second test and their tasks for the second test were explained. The test users then completed the second test followed by answering questions related to VR sickness in it. The same was done for the third test, and finally, some general explanations were given about the test to the participants, such as not having a reduced FoV during controller movement and using the movement speed set for MWs for controller movement as well.

2.4 Questionnaire

The questionnaire was done with Google Forms and presented to participants with a tablet. The questionnaire used a simulator sickness questionnaire (SSQ) to determine the strength of VR sickness experienced [40]. Simulator sickness is another type of VIMS that has been studied a lot, and the stimulus from simulators matches with VR somewhat closely, which is likely why it has become the de facto method of inquiring about experienced VR sickness. According to Chang et al. [32], there were 77 articles between 1992 to 2019 about experiments that studied VR sickness. Of those 77 articles, 58 of them used SSQ as a subjective measurement of the strength of VR sickness. The complete questionnaire can be seen in appendix 1.

The symptoms of VIMS in the simulator sickness questionnaire can be used to calculate four different key figures of motion sickness: nausea, oculomotor, disorientation, and total sickness scores. This is done by converting the answer choices of none/slight/moderate/severe into a scale of 0 – 3, summing scores of symptoms corresponding to a key figure, and then multiplying the key figure with a scalar number (specific for each key figure) to make the key figures comparable. The total score is calculated by summing the key figures that have not yet been multiplied with a scalar number and then multiplying the result with a scalar number. This results in some symptoms being part of up to two key figures and thus having a bigger weight on the total score. Calculating the four key figures are shown in the following equations. The symptoms in the equations need to be substituted with the answers that have been converted to numbers 0 – 3. Unweighted key figures are denoted with the subscript uw, and the final key figures are denoted with the subscript kf.

$$Nausea_{uw} = General\ discomfort + Increased\ salivation + Sweating + Nausea + Difficulty\ concentrating + Stomach\ awareness + Burping$$

$$Oculomotor_{uw} = General\ discomfort + Fatigue + Headache + Eyestrain + Difficulty\ focusing + Difficulty\ concentrating + Blurred\ vision$$

$$Disorientation_{uw} = Difficulty\ focusing + Nausea + Fullness\ of\ head + Blurred\ vision + Dizzy\ (eyes\ open) + Dizzy\ (eyes\ closed) + Vertigo$$

$$Nausea_{kf} = Nausea_{uw} \cdot 9.54$$

$$Oculomotor_{kf} = Oculomotor_{uw} \cdot 7.58$$

$$Disorientation_{kf} = Disorientation_{uw} \cdot 13.92$$

$$Total\ sickness_{kf} = (Nausea_{uw} + Oculomotor_{uw} + Disorientation_{uw}) \cdot 3.54$$

The questionnaire asked general background questions of each participant to help in identifying factors that affect e.g. the speed chosen for a walkway and the VR sickness experienced. The questionnaire also ended with general questions to help identify problems with the experiment, the used application, and the hardware.

For the preferred shape of an MW, there likely does not exist relevant questionnaire templates, so more freedom was used when deciding the questions of the test portion. The portion had questions about the perceived VR sickness and the preferred walkway model along with a free text answer about the importance of handrails. The VR sickness was asked with simple comparison questions instead of an SSQ due to the overall short time each model was used. Since the model comparison part of the test did not require participants to go around the park, but simply use a linear walkway once, an SSQ would likely not have shown noticeable differences between the models. In addition, the absolute difference in VR sickness between the models was deemed unimportant for answering the research question, which led to using a simple comparison question. The model used in the comparison was decided to be the realistic walkway without handrails as those were used in the earlier portions of the test as well.

The questionnaire was also supposed to have a question along the lines of "Which did you prefer: controller movement or MWs?", however since the experiment did not have the typical reduction of FoV, making controller movement a lot less enjoyable than normal, the result would have been moot. Instead, VR sickness levels deduced from the questionnaire will be used to shed light on this question.

3 Experiment

3.1 Demographic

A total of 14 test users were recruited for the tests. 5 participants were females and 9 males with their ages shown in Figure 5. Every participant was healthy during the experiment as required by the SSQ [40]. The prior experience with VR of the participants is shown in Figure 6. The starting locomotion technique was different based on testing order: half of the sample (every other user) started with controller movement and the rest with MWs. Of the 12 participants with prior VR experience, seven had experienced VR sickness before, with one of the seven saying that they knew it was VR sickness, but they did not feel discomfort from it.

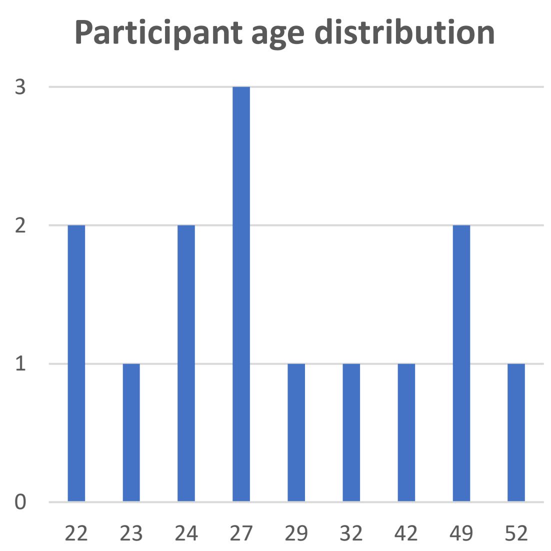


Figure 5. Participant age distribution.

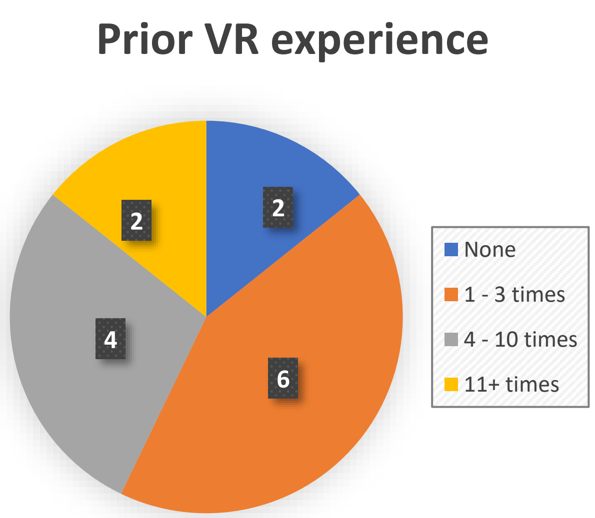


Figure 6. Prior VR experience of participants.

Most of the participants never felt sick while using physical MWs or escalators. One participant felt sick on MWs rarely, one felt sick on escalators rarely, and one felt sick on both MWs and escalators often. Every participant had used a physical MW before.

3.2 Observations

Over half of the participants had little experience with VR. Thus, they had difficulties with the controls, as they were not used to the controllers let alone using teleportation. Although the first test only had four buttons one needed to remember, using them in the intended manner seemed difficult. For example, to use teleportation one had to point in front of an MW so that the ray that was cast from the left hand turned green before pulling the trigger on the left hand. Several instructions needed to be told to nearly every participant during the experiment until they got familiar with the controls, as the briefing before the experiment seemed to contain too much information to digest. This communication might have reduced the sense of presence in the VE, which in turn may have reduced the amount of VR sickness experienced. The test users did not need that many instructions during the other parts of the test, since they had already gotten familiar with the controls in the first part, which may have distorted the results a bit.

The most difficult part for the test users was navigating in a way that they did not hit room boundaries. Some test users with less experience with VR started walking towards the walkways without first teleporting only to end up near the edge of the physical room. The wireframe was difficult to notice when one got close to the edge of the room resulting in most of the participants going out of the room boundaries set up for VR. Going out of the wireframe boundaries shown in VR did not matter too much, since the headset used inside-out tracking, and the boundaries were set for VR to be slightly narrower that the actual room boundaries. Since there was space even after the boundaries set for VR, it was possible to notice when a test user had gone out of the boundaries and thus know when to give advice to them to position themselves better physically. However, altogether this resulted in more instructions given to the test users during the test, which was not optimal in general. In order to not give as much advice during the test, every participant was told how to handle getting close to the room boundaries, but since there was so much to take in, few remembered the instructions. Instead, they needed to be guided to get them back facing the centre of the room. Since the room was large, most test users had to reposition themselves only once during the test, and some did not need to position themselves even once. The people who were more experienced with VR had no trouble repositioning themselves when they saw the room boundaries and seemed to prefer moving a few steps back before teleporting, or just moving a few steps back while on an MW to position themselves better and faster during the test.

As earlier mentioned, the test users were not told that the speed set for MWs during the first test also affected the controller movement. The test users who started with controller movement, however, might have noticed this themselves, as they needed to use controller movement to reach the two walkways used to set the speed in the beginning. Although unlikely, this might have influenced the speed set for the walkways when starting with controller movement. Also, since the controller movement was used with a joystick, it was possible to reduce the speed of controller movement by not holding the joystick completely down. This made it possible to move with a slower speed when using controller movement than what was set for the MWs, but it did not seem like any test user realised this or they simply did not want to use it.

As people tend to walk on real walkways, and since this test had people take a physical step to reach the walkways, a couple of participants also started walking on the walkways in the beginning. They needed to be reminded of the limited physical space to move in when that happened. One participant stepped out of walkways as people do in real life. Also, three people swayed after several walkways, as they likely tried to decelerate their speed at the end of a walkway.

No one dropped out of the test, vomited, fell to the ground, or showed other strong symptoms of motion sickness, although one had to take medicine after the test in order to not develop a migraine due to the test. This person said their strong VR sickness was due to controller movement, although it is hard to say how strong their symptoms would have been had the FoV reduction been in place. The overall tame symptoms are likely partly due to the test users setting the speed of the walkways themselves in the beginning.

4 Results

4.1 Walkway speed

The experiment had the speed of the MWs set to 1.00 m/s by default. This was due to controller movement having that speed as default in the default locomotion controls of the XR Interaction Toolkit in Unity. The test users were instructed to: “Set the walkways to a pleasant speed. One that you think would be good if you had to use MWs in VR often." It was possible to set the walkway speed to values between 0.01 m/s and 4.00 m/s. These resulted in the test users setting the walkways to the speeds shown in Figure 7. The test users took 1 – 7 times to adjust the speed of the walkways.

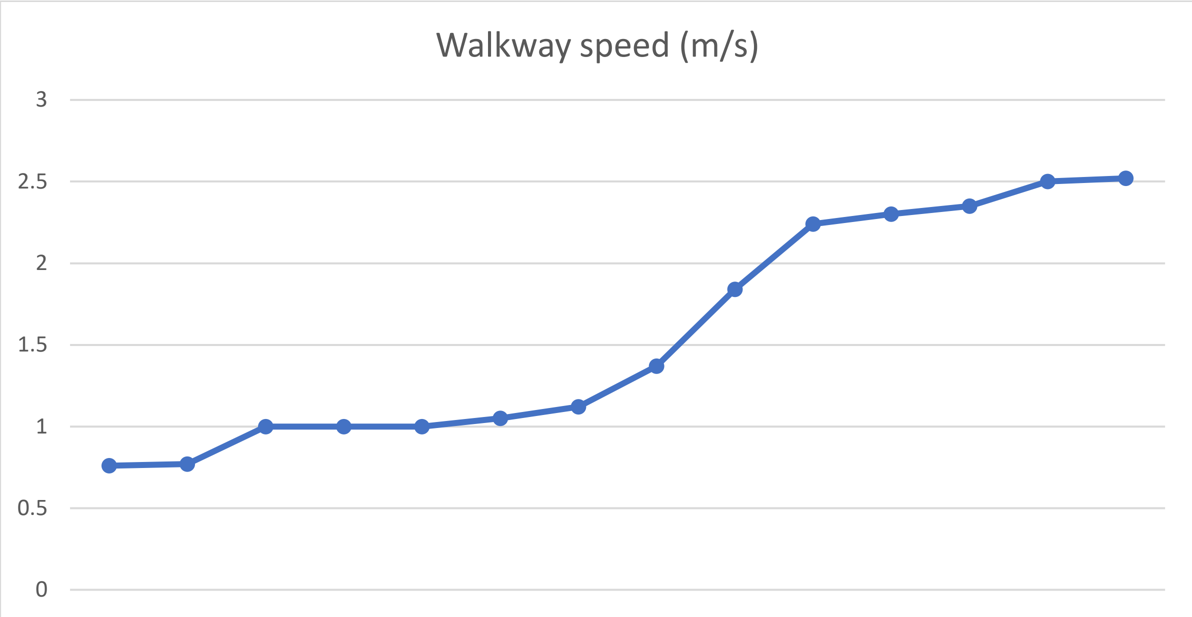


Figure 7. Walkway speeds set by each participant from smallest to largest.

From the results, we see that 1 m/s was the most commonly set speed. While the test users who chose this speed tested it and found it pleasant, the test should have been designed in a way that each test user would have had to alter the speed of the walkways, e.g. by setting the default speed of the walkways to 0 m/s. While this flaw caused a bias to the speed 1 m/s, several interesting points can still be seen from the results.

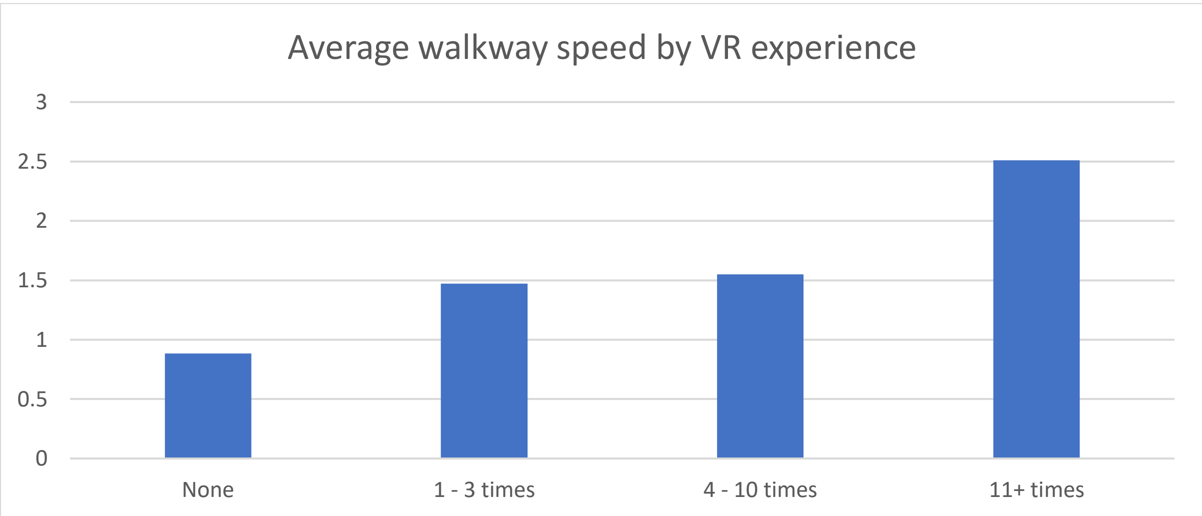


Figure 8. Walkway speed by experience with VR.

Figure 8 shows the average speed of the walkways by experience with VR. From the figure, we can see a tendency for people with more experience in VR to set the speed higher. Still, this may only be due to the personal traits of the participants, as both the people with no experience and the people with 11+ times of experience with VR each had only two people. The test users with 11+ times of experience with VR both said that they wanted to go fast. Similarly, both of them felt little to no VR sickness using MWs. On the other hand, one of the two people with no experience with VR said that they would have gotten much sicker had they set the speed any higher (their speed was 0.77 m/s), but they did find the speed very slow as the test took much longer to complete.

Every speed set by the test users was higher than the typical speed of a physical MW (0.5 – 0.75 m/s) with the lowest speed set being 0.76 m/s. Eight test users set their MWs to speeds lower than the average walking speed of 1.4 m/s, while six set it higher. Of the six people who set the speed higher than the typical walking speed, five users set the speed to over 50% higher than the typical walking speed.

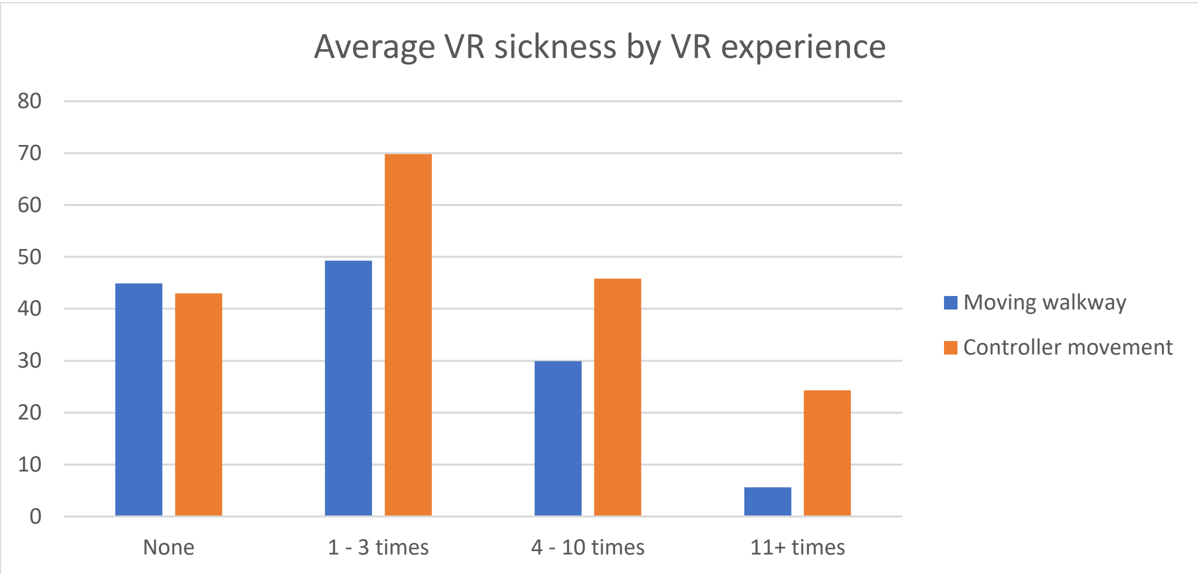


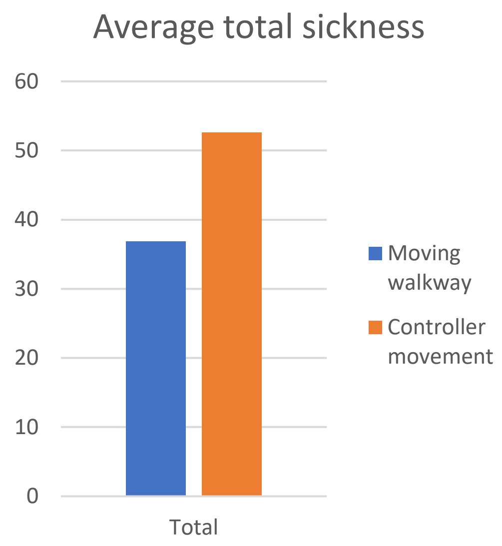
Figure 9. Average of total sickness experienced with a locomotion technique calculated for each participant divided into prior VR experience.

From Figure 9 we can see that, in general, people who were more experienced with VR felt less VR sickness. This was in spite of them having chosen higher speeds on average. It is unlikely for this to mean that higher speed causes less VR sickness. Many test users explicitly told that they felt or would have felt, more VR sickness had they set the walkways faster. Instead, the people who are experienced with VR feel less VR sickness and, in turn, are okay with faster speeds.

There are a few possible reasons why people with no prior experience with VR felt less sick than people with 1 – 3 times of VR experience. One reason was that the biggest outlier in the total VR sickness data was in the 1 – 3 times group. This person experienced around double the VR sickness compared to the person with the second strongest VR sickness experienced and triple the average of the group. They were the person who commonly felt motion sickness when using escalators and MWs. Another reason was that the group with no prior VR experience only had two people. It might be that these two people naturally experience less VR sickness than the average person. They might also be better at knowing their limitations and preferences, as they set comparatively low speeds of 0.77 m/s and 1.00 m/s.

4.2 Controller movement vs MWs

Figure 10 shows the average total sickness experienced during the test with each of the locomotion techniques. On average, the test users experienced VR sickness symptoms that resulted in a 43% greater total sickness score using controller movement than when using MWs. When this is divided further into the starting locomotion techniques in Figure 11, we see that on average, the test users who started with controller movement reported stronger VR sickness with MWs than controller movement, while the test users who started with MWs reported drastically stronger VR sickness when using controller movement. This disparity is most likely caused by the longer exposure to VR that the test users had on the second test. Length of exposure to VR is correlated with the VR sickness experienced. In other words, when the test users took the headset off after the first test and answered the first SSQ, they did not have enough time to completely reset their motion sickness. Instead, their newer VR sickness built up on the earlier motion sickness. Another reason for greater total sickness scores on the second test could be that having read the SSQ once, the test users were more conscious of their state during the second test and were thus more sensitive to the symptoms of VR sickness.



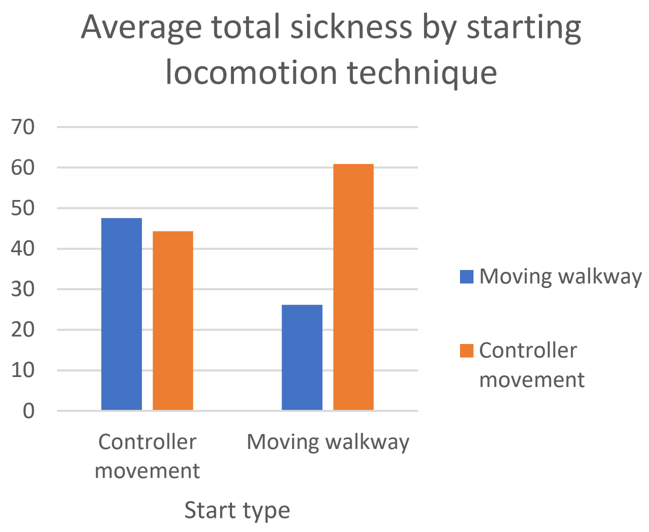


Figure 10. Average of total sickness calculated for each participant.

Figure 11. Average of total sickness divided to starting locomotion techniques.

One person said they preferred controller movement to MWs while most people explicitly said it felt much worse. However, this is partly due to controller movement not having the typical FoV reduction.

Both of the test users with no prior experience with VR started with controller movement which might explain why they experienced more VR sickness on MWs on average than with controller movement (see Figure 9). Although that is the case on average, one of the two still experienced more VR sickness with controller movement.

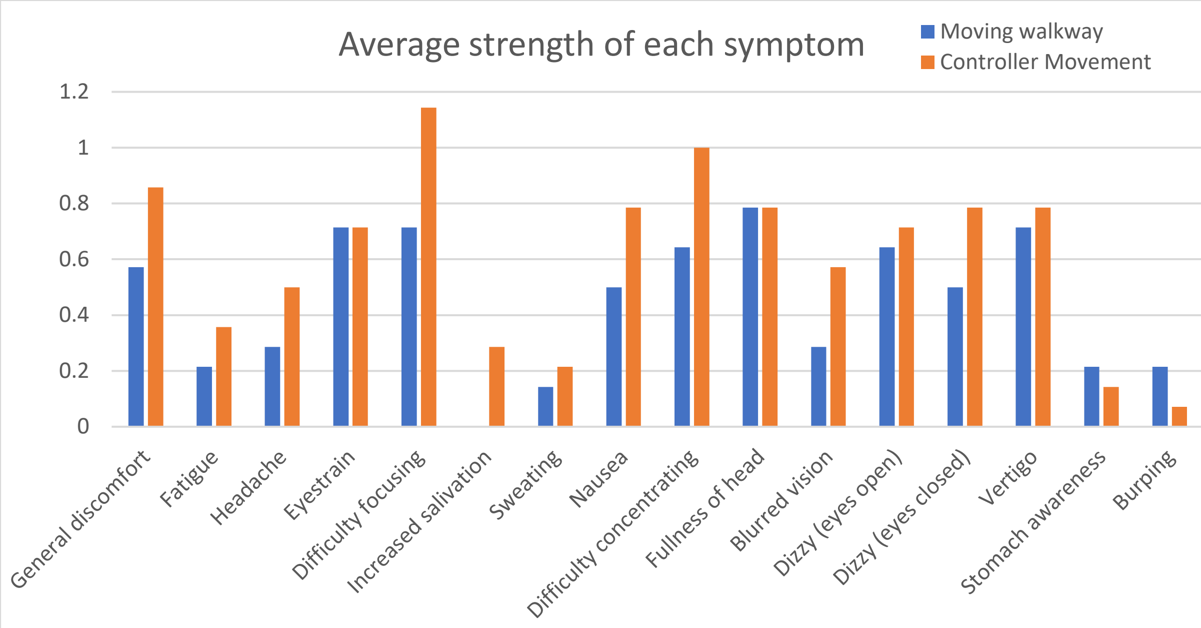


Figure 12. Average strength of each symptom in SSQ. Values 0, 1, 2, and 3 correspond to answers "none", "slight", "moderate", and "severe" respectively.

Figure 12 shows the average strength of each symptom in SSQ. Other than stomach awareness and burping, every symptom was stronger or as strong with controller movement than with MWs. The reason why stomach awareness and burping were stronger on MWs might be simply due to the small sample size, as both of these symptoms were uncommon and only reported by three test users. Another reason could be that MWs give more leisure for users for introspection, making them notice these rarer symptoms more easily.

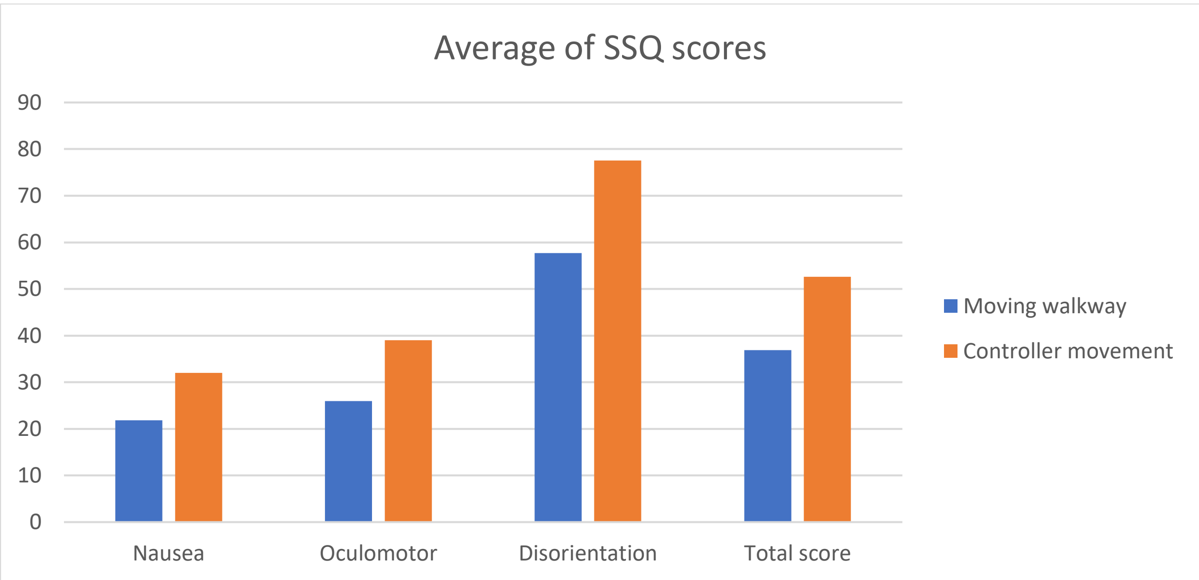


Figure 13. Key figures calculated from the SSQ.

Figure 13 shows every key figure of SSQ. We can see that controller movement causes each of the categories of VIMS more strongly than MWs. Both of the locomotion techniques cause disorientation much more strongly than nausea or oculomotor-related motion sickness. Symptoms related to disorientation in the simulator sickness questionnaire are difficulty focusing, nausea, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), and vertigo.

4.3 Virtual walkway model

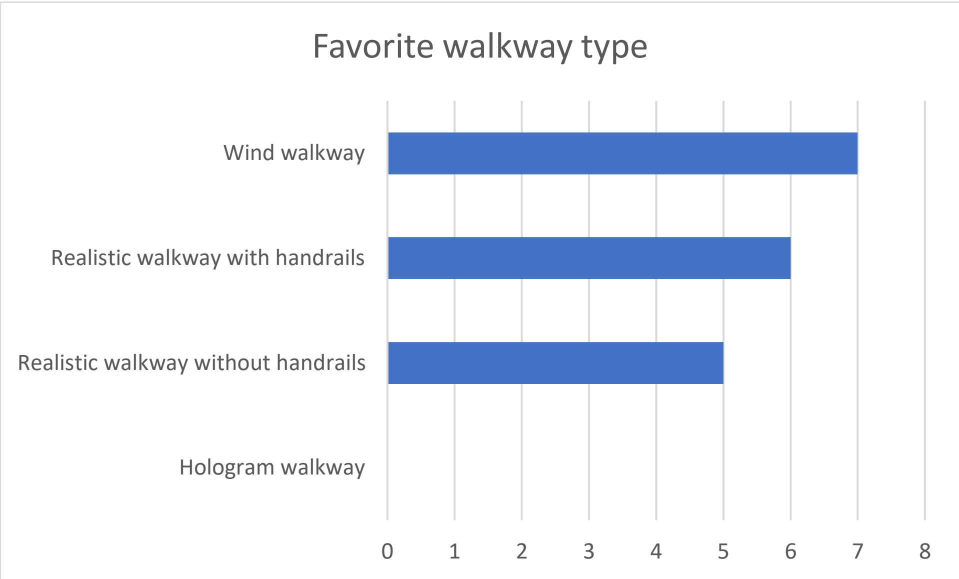


Figure 14. Preferred walkway type. The question was a multiple-choice question.

Figure 14 shows the preferred walkway types of the test users. We can see that the hologram walkway did not gain favour with the test users. Some test users said they thought the hologram walkway did not fit the environment while others said that the pattern caused them to feel stronger motion sickness. The pattern causing discomfort likely has something to do with it being transparent. The pattern is shown in more detail in Figure 15. Several test users had to ask to verify which walkway type “hologram walkway” referred to, so some test users might not have made a connection between the walkway and holograms. The hologram walkway was meant to look decidedly more digital than the other MWs, which, in hindsight, was not obvious to the users. When we take a look at how VR sickness on the hologram walkway compared with the realistic walkway without handrails in Figure 16, we can see that half of the test users felt more VR sickness while only one felt less VR sickness on the hologram walkway. Apart from the pattern, another reason that might have caused VR sickness with the hologram walkway was that there are no actual holograms that can move people, which might have broken their suspension of disbelief and thus caused a greater disparity between their expected and actual movement.

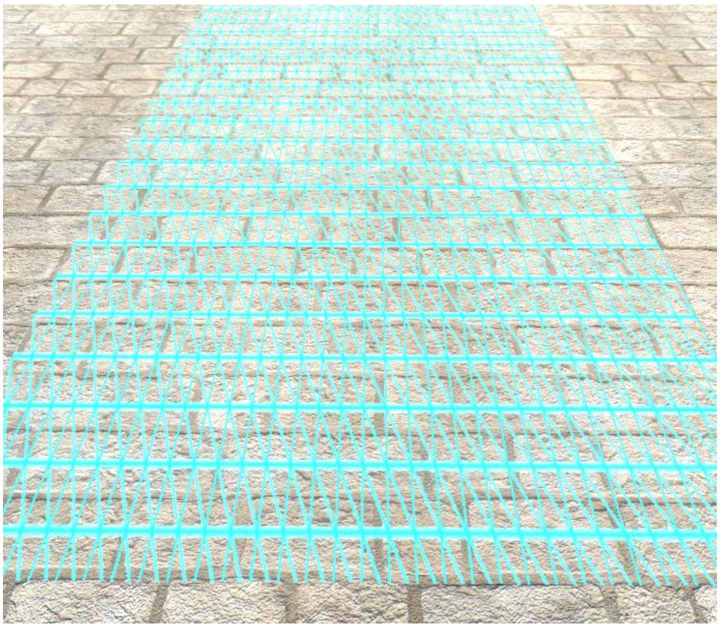


Figure 15. Close-up of hologram walkway pattern.

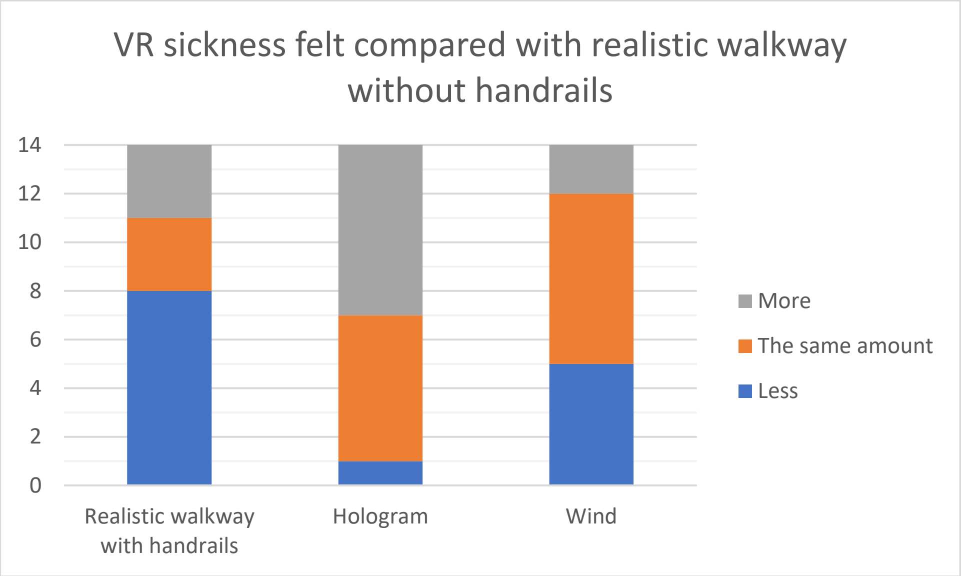


Figure 16. VR sickness of different MW models compared with realistic walkway without handrails.

Surprisingly, wind was the most popular model in the tests despite it not being an actual walkway. It is uncommon to be blown forward due to wind, so it would not have been weird if wind was observed to cause more VR sickness, as the disparity between what is expected and what is experienced should have been larger. One participant described the reason why they liked wind the most and felt the least VR sickness on it as being due to it being easy to focus eyes on something. The wind walkway did not require one to look downwards to have a static frame of reference, which is likely the reason why it caused relatively little VR sickness. It was easier to keep the frame of reference in view while looking around.

The realistic walkway with handrails was slightly more popular than one without handrails. The version with handrails also caused noticeably less VR sickness, with over half of the participants stating so. When looking at the written answers for whether virtual walkways should have handrails, three people felt like having or not having handrails does not make a difference, three people felt like walkways should not have handrails, and 8 people felt like the virtual walkways should have handrails. Among the answers as to why virtual walkways should have handrails, four people said that they made them feel safer, three said it felt more realistic, one of the three saying that the realism helped with their VR sickness, and one person said “I think it's easier to have a sense of control if you have something to hold on to (simulated by the controllers) “. The three answers against handrails each gave different reasons for why they did not like the handrails. One stated that handrails made it harder to focus their eyes due to the increased stimulus, one said that handrails made them feel dizzy or claustrophobic, and one simply said that the model with handrails was the most uncomfortable for them.

One reason why a realistic walkway with handrails and wind may have caused less VR sickness than a realistic walkway without handrails might be due to there being more distractions for the user, so they focused less on the movement itself. Three test users tried resting their hands on the handrails while one test user tried touching the leaves that were blown in the wind. One test user clearly followed a leaf with their gaze in the wind model, whereas it was difficult to say what the rest of the test users focused on while looking around on the wind MW.

There was no specific order the test users had to follow when testing each walkway model, although in hindsight there likely should have been one. Still, everyone tested the models in the order that they appeared on the menu. The order from first to last was a realistic walkway with handrails, a realistic walkway without handrails, a hologram walkway, and finally a wind walkway. This made it easy for the test users to use the wind walkway. The wind walkway did not have a walkway on the ground (or the one it had was made invisible), so should the test users have tried it first it might have taken them some time to understand how to get onto it. Since everyone tested it last, they already knew that they simply need to take one step to start moving with it and thus did not need additional prompts from the testing supervisor.

4.4 General results

Some people said that the way the speed ended when stepping out of walkways felt unrealistic. Although one person stepped out of MWs, they still said that. Naturally, when a person steps out of a real MW, their momentum carries over from the walkway. This was not replicated in the application. Instead, the friction between the player collider and the ground was quite large, so unless one set the speed of a walkway high, one was unlikely to notice any skidding. This means that the sensation replicated in the application was one where a person stops immediately after stepping out of a walkway. Stopping like that requires a person to lean backwards when stepping out of a walkway, which is likely the reason why three test users swayed at the end of several MWs.

When asked about whether the MWs in VR felt different from actual MWs, five test users reported the virtual MWs feeling the same as actual MWs. One of them even felt acceleration describing the feeling as being similar to a lucid dream. Of the people who answered they felt differences in virtual walkways, one reported the difference being the lack of sounds, and one said the difference was that they needed to do something before entering one (teleport instead of walking up to one). One mentioned the difference being that a virtual one caused motion sickness, while one found the difference to be that there were no other moving objects apart from oneself. The remaining five people reported some differences in the movement, which were: the inability to feel the walkway under their feet, lack of sensation of movement or incorrect sensation, and the end of the MW feeling difficult and unlike a physical MW.

When asked, five test users reported that they noticed some problems with the application or hardware, which were: cords slightly breaking immersion, the resolution not being good, latency in movement, and shadows glitching once. The shadow glitch most likely refers to the level of detail changing on a shadow, which is commonly done with games to reduce GPU usage. When asked whether the problems affected the strength of VR sickness symptoms experienced, everyone answered no. One person answered “maybe” on whether they believe their health affected the results. When asked if there are other factors that they believe affected the strength of VR sickness they experienced, one answered that their having to wear glasses under the headset made their vision slightly blurry which affected the results.

4.5 Analysing research questions and hypotheses

From the results obtained in this study, we can try to draw some conclusions to our research questions. For Q1, we find that MWs can likely be used to reduce VR sickness compared to controller movement. On average, participants reported a 43% higher score for total sickness when using controller movement than when using MWs in accordance with H1. Still, this test did not have the typical reduction in FoV in place that usually exists when using controller movement. However, there was not a reduction in FoV on the MWs either. In and of itself, a reduction in FoV takes away from the user experience. It is due to its effect on VR sickness that it is still a net positive to the user experience. Having a locomotion technique that does not require a reduction in FoV to reduce VR sickness will most likely lead to a better user experience. Thus, utilizing more MWs in VR might lead to a better user experience, as long as they are used mindfully.

Answering Q2 is a bit more difficult. While every speed set for MWs was higher than the typical physical MW, half of the speeds set were slower than the typical walking speed of an adult. 7 of the 14 test users set the walkways to a modest speed between 0.76 m/s and 1.12 m/s. Five test users set the walkways between the speeds of 2.24 m/s and 2.52 m/s. Only two participants set the speed to something in between. While this makes the average speed of MWs out at 1.56 m/s, which is close to the average walking speed, it is hard to take this as affirmation for H2. These polarized speeds suggest that there does not exist a middle ground for the speed of MWs that would suit most users. If the walkways were to move at a speed of 1 m/s, the test users who set the walkways to fast speeds would likely get bored if exposed to MWs for a longer period of time. Similarly, if the walkways were set to around 2.4 m/s, the test users who chose a slower speed for the walkways during the test would likely feel strong VR sickness on them. It should also be noted that the experiment did not allow the test users to use other locomotion techniques while on an MW, which might have influenced the speed the test users ended up setting for MWs.

When selecting a speed for MWs, several things should be considered. Firstly, how will the MWs be used? If MWs will be a major mechanic in a VR application users should most likely be able to set the speed themselves. If MWs in an application will not be a major mechanic, so that adding the ability to change their speed is deemed unnecessary complexity, the speed set for MWs should probably be up to around 1 m/s so that most users can use it without feeling VR sickness. Secondly, can users use other locomotion techniques while on an MW? There will most likely be users with a need for speed, so if the MWs are set to a relatively low speed of around 1 m/s, being able to use e.g. controller movement while on an MW can help alleviate boredom of such users. When users can not set the speed of MWs themselves, allowing them to use another locomotion technique while on top of one helps the speed set for MWs to cater to more users. Then, there are several factors that were not studied in this experiment, such as how the virtual environment affects the speed. It might be sensible to set the speed of MWs higher if the users need to use them for long distances at a time. Conversely, when the distances are small or there is a lot to take in in the environment, the MWs should likely move slower.

For Q3, we can try to extract some guidelines for a good virtual MW from the results. Firstly, the MW should not feel out-of-place in the environment. While the hologram walkway might have had a bad pattern, it also did not suit the environment of a park in the middle of the day. The other three models did suit the environment which likely plays a big part in why the realistic models and the wind model got all the votes for the favourite walkway model. Had the VE of the experiment been a virtual sci-fi space station instead of a park, the answers on the favourite walkway model would have likely been different. Although the experiment did not include any open questions about why a model was their favourite, in comments after the test and the written answers about handrails, four people in total cited realism when describing their likes or dislikes of a walkway model.

Another thing we see from the experiment is that a virtual MW does not need to look like a traditional MW. Only the realistic walkway with handrails looked like a traditional MW. Four test users out of fourteen answered with a realistic walkway with handrails as their sole answer when asked about their favourite walkway model in the experiment. The rest of the test users had either the realistic walkway without handrails or the wind walkway as part of their answer. These two models imply that the most important thing for a virtual MW is that there is something that moves along with the user in their FoV during their movement, even if it does not look like a traditional MW.

One thing to keep in mind with these results is that the sample size of 14 test users was quite small. While the average total sickness score was around 45, the individual answers ranged from 0 to 168. With such a high variance in results, the results did not reach statistical significance. Nonetheless, statistical significance was not the purpose of this research, but rather to analyse virtual MWs and find some good guidelines for designing them, therefore the results shown here can be considered to be within the scope of this research.

5 Discussion

While MWs can contribute to reducing the VR sickness experienced, overuse of them can make the users feel like they lose their ability to move freely in the VE. They may also become more conscious of the FoV reduction with controller movement if both are used in tandem. Using another locomotion technique in conjunction with MWs might give the best user experience. This ensures that the user has the freedom to go wherever they want and can use MWs when they feel like it. Also, if an MW does not have handrails, the user can step out of an MW partway through, giving the user more freedom.

Then, should a virtual MW have handrails? If it makes the VE or the MW feel more realistic, likely yes. Eight people said they felt less VR sickness with handrails than without while three thought the opposite. Many of the voices for handrails stated that they made them feel safer. This feeling of safety, however, is false as the user cannot actually lean on the handrails, nor does it protect the user from the mechanisms of an MW as there is nothing to be protected from. Although virtual handrails might provide a sense of safety in the VR, they do not contribute to the user's safety in real life. If one gets too immersed in a VE, they might even try to lean on a virtual handrail causing them to fall over.

Although not a research question of this study, we can also take a look at the physics of a virtual MW and how it should behave. The implementation of an MW used in this study was fairly simple with friction being really high everywhere. This makes up for quite a blocky movement since the acceleration and deceleration of stepping on an MW and out of an MW was instant. Even then, the MW felt realistic for the test users. Perhaps if the friction was slightly smaller when stepping out of an MW, so that the user would slide a little after a walkway, the physics could have matched slightly better with a real MW. One test user said explicitly that the end of an MW felt difficult and different from a real walkway. A couple of test users also swayed at the ends of nearly every MW, so perhaps that could have been alleviated with some sliding. On the other hand, this likely contradicts with one's physical environment. Thus, figuring out good physics for a virtual MW would likely require its own research. If allowing the use of other locomotion techniques as well, maybe they can be implemented in a way that allows for a seamless experience when stepping out of an MW.

As were noted in the differences test users felt with virtual MWs compared to physical MWs, virtual MWs should have sounds implemented as well. If possible, weak haptic feedback should also be enabled for feet to further replicate the feeling of a physical MW.

A typology for virtual locomotion techniques has been introduced in [41] and further expanded in [42] (see Figure 17) . Trying to place virtual MWs into this typology proves to be a challenge. Stepping onto an MW is a physical interaction while moving onto one with controller movement is artificial, so it seems that stepping onto one and out of one needs to be left out of consideration. Being on top of an MW is continuous artificial interaction, and the space for the interaction depends on whether the user can place MWs themselves. If one can place MWs oneself, the interaction space is open, whereas if the MWs cannot be placed oneself, the interaction space is limited. Even if MWs were placed with a controller, the movement is unlikely to be controlled with a controller while on top of an MW, so it would still be problematic to categorise MWs as a controller-based locomotion technique, as the controller would not be used for any locomotion. Ignoring the categories already found in [42], if MWs were to be placed in a new category, the category would probably be named along the lines of “predetermined locomotion.”

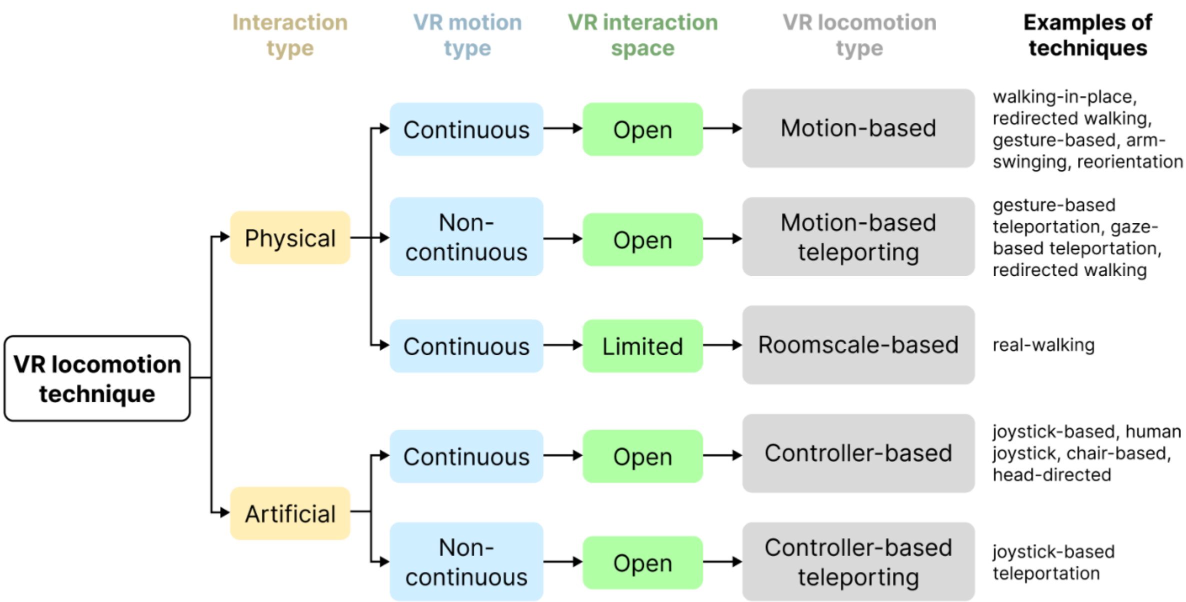


Figure 17. The VR locomotion typology, presented in a homologous manner to [42].

A couple of ways of implementing a locomotion technique that uses only MWs would be to allow the user to place MWs with their controller wherever they want, or even construct their own MW by placing starting, middle, and end points of walkways with the controller.

Alternatively, the users could be allowed to use a map to place a destination marker, which would then make an MW appear that connects the user with their destination.

6 Conclusion

While there are numerous locomotion techniques developed for VR, they all seem to have their own problems. Thus, there is still demand for new ways of moving inside VR. This paper introduced virtual MWs as a new virtual locomotion technique, and studied how much they cause VR sickness, how their speed should be set, and what shape they should have. A virtual environment and several models of different MWs were created to find answers to these questions.

14 people with varying experience with VR were recruited for the experiment. Using SSQ, virtual MWs were found to result in a total sickness score of 70% of the score of controller movement. Controller movement had a total sickness score of 52.6 while virtual MWs had 36.9.

For the speed of a virtual MW, we found that it should be faster than the average physical MW. Many people wanted it to be significantly faster on the premise that they need to use them often in VR and they cannot use other locomotion techniques while on top of them. Despite there being a flaw in the experiment, with the MWs having a default speed and thus three test users not changing the speeds (although confirming they were satisfied with the speed), we can make several other deductions from the results. 5 people set the speed between 2.4 m/s and 2.52 m/s, while 7 people set the speed between 0.76 m/s and 1.12 m/s. If one were to select one speed for virtual MWs that would suit most people, the speed should be around or below 1.0 m/s. Still, if the MWs will be used a lot in an application, this speed is likely to bore many users. This needs to be factored in by e.g. making the speed adjustable or allowing the user to use another locomotion technique while on top of an MW.

For the shape of a virtual MW, we find that one has a lot of freedom when designing one. Although a hologram version of an MW did not gain favour, a wind version of an MW was highly popular despite there not being any visible MW on the ground. The most important things for a virtual MW are that there is a static frame of reference for the user, and that the MW fits the environment.

Further research into MWs in VR could include e.g. research into virtual escalators, side-by-side comparison of a virtual MW with a physical MW, research into realistic physics of a virtual MW, further research into the relationship between the speed of an MW and VR sickness, or research into locomotion techniques that are made completely with MWs while still giving the user freedom to move wherever they want. Verifying the results of this study is also important, as the study had a relatively small sample size.

References

[1] 'Virtual reality', *Merriam-Webster.com*, 2021. https://www.merriam-webster.com/dictionary/virtual%20reality (accessed Dec. 20, 2021).

[2] T. Alsop, 'Topic: Virtual reality (VR)', *Statista*, Nov. 04, 2021. https://www.statista.com/topics/2532/virtual-reality-vr/ (accessed Dec. 28, 2021).

[3] 'Virtual Reality (VR) Market Share, Growth | Research Report, 2028', *Fortune Business Insights*. https://www.fortunebusinessinsights.com/industry-reports/virtual-reality-market-101378 (accessed Dec. 28, 2021).

[4] P. Graham, 'VR Growth to Outstrip All Other Media by 2025', *VRFocus*, Jul. 16, 2021. https://www.vrfocus.com/2021/07/vr-growth-to-outstrip-all-other-media-by-2025/ (accessed Dec. 28, 2021).

[5] 'Global Entertainment & Media Outlook 2021–2025', *PwC*. https://www.pwc.com/gx/en/industries/tmt/media/outlook.html (accessed Dec. 28, 2021).

[6] J. T. Reason and J. J. Brand, *Motion sickness*. Oxford, England: Academic Press, 1975, pp. vii, 310.

[7] M. H. Fischer and A. E. Kornmüller, 'Optokinetisch ausgelöste Bewegungswahrnehmungen und optokinetischer Nystagmus [Perception of motion based on the optokinetic sense and optokinetic nystagmus]', *Journal für Psychologie und Neurologie (Leipzig)*, vol. 41, pp. 273–308, 1930.

[8] B. Keshavarz, B. E. Riecke, L. J. Hettinger, and J. L. Campos, 'Vection and visually induced motion sickness: how are they related?', *Frontiers in Psychology*, vol. 6, p. 472, 2015, doi: 10.3389/fpsyg.2015.00472.

[9] A. S. Fernandes and S. K. Feiner, 'Combating VR sickness through subtle dynamic field-of-view modification', in *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, Mar. 2016, pp. 201–210. doi: 10.1109/3DUI.2016.7460053.

[10] J.-R. Chardonnet, M. A. Mirzaei, and F. Merienne, 'Visually Induced Motion Sickness Estimation and Prediction in Virtual Reality using Frequency Components Analysis of Postural Sway Signal', presented at the International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments, Oct. 2015, p. 9. Accessed: Jan. 30, 2023. [Online]. Available: https://hal.science/hal-01229880

[11] R. H. Y. So, W. T. Lo, and A. T. K. Ho, 'Effects of navigation speed on motion sickness caused by an immersive virtual environment', *Human Factors*, vol. 43, no. 3, p. 452, Fall 2001.

[12] A. Prithul, I. B. Adhanom, and E. Folmer, 'Teleportation in Virtual Reality; A Mini-Review', *Frontiers in Virtual Reality*, vol. 2, 2021, Accessed: Jan. 31, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frvir.2021.730792

[13] C. G. Christou and P. Aristidou, 'Steering Versus Teleport Locomotion for Head Mounted Displays', in *Augmented Reality, Virtual Reality, and Computer Graphics*, Cham, 2017, pp. 431–446. doi: 10.1007/978-3-319-60928-7_37.

[14] 'Omni by Virtuix - The leading and most popular VR motion platform', *Virtuix*. https://www.virtuix.com/ (accessed Dec. 29, 2021).

[15] 'KAT VR Omni-Directional VR Treadmills | VR Locomotion Technologies', *KATVR*. https://www.kat-vr.com/ (accessed Dec. 29, 2021).

[16] 'Virtual Reality Locomotion - Cyberith Virtualizer VR Treadmills', *Cyberith*. https://www.cyberith.com/ (accessed Dec. 29, 2021).

[17] J. N. Templeman, P. S. Denbrook, and L. E. Sibert, 'Virtual Locomotion: Walking in Place through Virtual Environments', *Presence*, vol. 8, no. 6, pp. 598–617, Dec. 1999, doi: 10.1162/105474699566512.

[18] A. S. Muhammad, S. C. Ahn, and J.-I. Hwang, 'Active panoramic VR video play using low latency step detection on smartphone', in *2017 IEEE International Conference on Consumer Electronics (ICCE)*, Jan. 2017, pp. 196–199. doi: 10.1109/ICCE.2017.7889284.

[19] S. Razzaque, Z. Kohn, and M. C. Whitton, 'Redirected Walking', in *Eurographics*, 2001. doi: 10.2312/egs.20011036.

[20] N. C. Nilsson *et al.*, '15 Years of Research on Redirected Walking in Immersive Virtual Environments', *IEEE Computer Graphics and Applications*, vol. 38, no. 2, pp. 44–56, Mar. 2018, doi: 10.1109/MCG.2018.111125628.

[21] J. J.-W. Lin, H. Abi-Rached, D.-H. Kim, D. E. Parker, and T. A. Furness, 'A "Natural" Independent Visual Background Reduced Simulator Sickness', *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 46, no. 26, pp. 2124–2128, Sep. 2002, doi: 10.1177/154193120204602605.

[22] H. B.-L. Duh, H. Abi-Rache, D. E. Parker, and T. A. Furness, 'Effects on balance distubance of manipulating depth of an independent visual background in a stereographic display', *Proceedings of the Human Factors and Ergonomics Society ... Annual Meeting*, vol. 2, p. 1882, 2001.

[23] 'TransitMaster 165 Moving Walkway / Autowalk', *KONE GB*. https://www.kone.co.uk/new-buildings/moving-walkways-and-autowalks/transitmaster-165-185-autowalk/ (accessed Dec. 20, 2021).

[24] 'TK Elevator UK moving walks: Reliable quality', *TK Elevator*. https://www.tkelevator.com/uk-en/products/moving-walks/ (accessed Dec. 20, 2021).

[25] 'ACCEL - Urban mobility solution by TK Elevator', *TK Elevator*. https://www.tkelevator.com/kr-en/products/accel/ (accessed Dec. 20, 2021).

[26] P. E. di Prampero, 'The energy cost of human locomotion on land and in water', *Int J Sports Med*, vol. 7, no. 2, pp. 55–72, Apr. 1986, doi: 10.1055/s-2008-1025736.

[27] R. C. Browning, E. A. Baker, J. A. Herron, and R. Kram, 'Effects of obesity and sex on the energetic cost and preferred speed of walking', *Journal of Applied Physiology*, vol. 100, no. 2, pp. 390–398, Feb. 2006, doi: 10.1152/japplphysiol.00767.2005.

[28] 255 pixel studios, 'Parking Garage - Complete | 3D Urban | Unity Asset Store', *Unity Asset Store*. https://assetstore.unity.com/packages/3d/environments/urban/parking-garage-complete-104909 (accessed Apr. 07, 2022).

[29] Avionx, 'Skybox Series Free | 2D Sky | Unity Asset Store', *Unity Asset Store*. https://assetstore.unity.com/packages/2d/textures-materials/sky/skybox-series-free-103633 (accessed Apr. 11, 2022).

[30] A. Wentz, 'VR hands for Unity3D'. Dec. 31, 2019. Accessed: Apr. 28, 2022. [Online]. Available: https://github.com/awentzonline/UnityVRHands

[31] adam127, 'Lowpoly leaf set | 3D model', *CGTrader*. https://www.cgtrader.com/free-3d-models/plant/leaf/lowpoly-leaf-set (accessed Mar. 29, 2022).

[32] E. Chang, H. T. Kim, and B. Yoo, 'Virtual Reality Sickness: A Review of Causes and Measurements', *International Journal of Human–Computer Interaction*, vol. 36, no. 17, pp. 1658–1682, Oct. 2020, doi: 10.1080/10447318.2020.1778351.

[33] B. K. Jaeger and R. R. Mourant, 'Comparison of Simulator Sickness Using Static and Dynamic Walking Simulators', *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 45, no. 27, pp. 1896–1900, Oct. 2001, doi: 10.1177/154193120104502709.

[34] S. Davis, K. Nesbitt, and E. Nalivaiko, 'Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters', in *Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015)*, 2015. Accessed: Sep. 13, 2022. [Online]. Available: https://ogma.newcastle.edu.au/vital/access/manager/Repository/uon:25146

[35] 'KONE TravelMaster™ 115 Escalator', *KONE GB*. https://www.kone.co.uk/new-buildings/moving-walkways-and-autowalks/travelmaster-115.aspx (accessed Sep. 09, 2022).

[36] 'Orinoco: Impressive capabilities', *TK Elevator*. https://www.tkelevator.com/uk-en/products/moving-walks/orinoco/ (accessed Sep. 09, 2022).

[37] 'Schindler 9500 inclined moving walks', *Elevators, Escalators & Moving Walks*. https://us.schindler.com/en/escalators-moving-walks/moving-walk/schindler-9500-inclined (accessed Sep. 09, 2022).

[38] C.-L. Liu and S.-T. Uang, 'A study of sickness induced within a 3D virtual store and combated with fuzzy control in the elderly', in *2012 9th International Conference on Fuzzy Systems and Knowledge Discovery*, May 2012, pp. 334–338. doi: 10.1109/FSKD.2012.6234149.

[39] K. M. Stanney, K. S. Hale, I. Nahmens, and R. S. Kennedy, 'What to Expect from Immersive Virtual Environment Exposure: Influences of Gender, Body Mass Index, and Past Experience', *Human Factors*, vol. 45, no. 3, pp. 504–520, Fall 2003.

[40] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, 'Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness', *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.

[41] C. Boletsis, 'The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology', *Multimodal Technologies and Interaction*, vol. 1, no. 4, Art. no. 4, Dec. 2017, doi: 10.3390/mti1040024.

[42] C. Boletsis and D. Chasanidou, 'A Typology of Virtual Reality Locomotion Techniques', *Multimodal Technologies and Interaction*, vol. 6, no. 9, Art. no. 9, Sep. 2022, doi: 10.3390/mti6090072.

List of abbreviations

FoV = Field of Vision

MW = Moving Walkway

SSQ = Simulator Sickness Questionnaire

VE = Virtual Environment

VIMS = Visually Induced Motion Sickness

VR = Virtual Reality

Appendix: Questionnaire

Table 1. Questionnaire used in the experiment.

Originally made with Google Forms, the questionnaire is presented in the following form for conciseness. Answer options in italics describe an answer format. Answers separated by slashes are options for multiple-choice questions with a single answer unless otherwise noted. SSQ is shown in the second table. Additional text such as a description of the privacy notice is omitted.

Question	Answer options
Privacy notice	
I consent to videos being taken of me for research purposes. They will not be published.	Yes / No
I consent to photographs being taken of me for research purposes. The photographs may be published with the research, but they have been processed in such a way that I cannot be identified.	Yes / No
Background questions	
Please state your age	*Text answer*
Please state your sex	Male / Female / Other or prefer not to say
Are you in your normal state of health?	Yes / No
If not, what problems do you have with your health?	*Text answer*
How many times have you used VR before?	None / 1 – 3 times / 4 – 10 times / 11+ times
Have you experienced VR sickness before (motion sickness due to VR)?	Yes / No
Have you used a moving walkway in real life before?	Yes / No
How often have you felt motion sickness when using a moving walkway?	Never / Rarely / Sometimes / Often / Always
Have you used an escalator in real life before?	Yes / No
How often have you felt motion sickness when using an escalator?	Never / Rarely / Sometime / Often / Always
Test 1 & 2	
How severely did you experience the following symptoms while using **moving walkways**? Tick the most suitable severity for each symptom.	*SSQ*
How severely did you experience the following symptoms while using **controller movement**? Tick the most suitable severity for each symptom.	*SSQ*
Test 3	
Did you feel more, less, or the same amount of VR sickness when using a **realistic moving walkway with handrails** as when using one without handrails?	More / Less / The same amount
Do you think having handrails on a moving walkway in VR is better than not having handrails? Why?	*Text answer*

Question	Answer options
Did you feel more, less, or the same amount of VR sickness when using a **hologram moving walkway** as when using a realistic moving walkway without handrails?	More / Less / The same amount
Did you feel more, less, or the same amount of VR sickness when using a **wind moving walkway** as when using a realistic moving walkway without handrails?	More / Less / The same amount
Which walkway type(s) did you like the most?	*(multiple)* Realistic walkway without handrails / Realistic walkway with handrails / Hologram walkway / Wind walkway
General questions	
Did the moving walkways in VR feel different from actual moving walkways? How?	*Text answer*
Did you notice any problems with the application or hardware? If yes, what kinds of problems?	*Text answer*
Did the problems affect the strength of VR sickness symptoms you experienced?	Yes / No / Maybe
Do you believe your health affected the results?	Yes / No / Maybe
Are there other factors not related to the experiment that you believe affected the strength of VR sickness symptoms you experienced?	Yes / No
If yes, what?	*Text answer*
General comments about the test	*Text answer*
Administrator notes (filled by test administrator)	
Date	*Date*
Which locomotion technique did the user start with?	Controller movement / Moving walkway
What speed did the user set? (m/s)	*Text answer*
Participant number	*Text answer*

Table 2. Simulator sickness questionnaire.

Symptom	Answer options
General discomfort	None / Slight / Moderate / Severe
Fatigue	None / Slight / Moderate / Severe
Headache	None / Slight / Moderate / Severe
Eyestrain	None / Slight / Moderate / Severe
Difficulty focusing	None / Slight / Moderate / Severe
Increased salivation	None / Slight / Moderate / Severe
Sweating	None / Slight / Moderate / Severe
Nausea	None / Slight / Moderate / Severe
Difficulty concentrating	None / Slight / Moderate / Severe
Fullness of head	None / Slight / Moderate / Severe
Blurred vision	None / Slight / Moderate / Severe
Dizzy (eyes open)	None / Slight / Moderate / Severe
Dizzy (eyes closed)	None / Slight / Moderate / Severe
Vertigo	None / Slight / Moderate / Severe
Stomach awareness	None / Slight / Moderate / Severe
Burping	None / Slight / Moderate / Severe