The Effect of Interaction Fidelity on User Experience in Virtual Reality Locomotion

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ABSTRACT

In virtual worlds, designers often consider “real walking” to be the gold standard when it comes to locomotion, as shown by attempts to incorporate walking techniques within tasks. When real walking is not conceivable due to several different limitations of virtual interactions (space, hardware, tracking, etc.) a walking simulation technique is sometimes used. We call these moderate interaction fidelity techniques and based upon literature, we can speculate that they will often provide an inferior experience if compared to a technique of high or low fidelity. We believe that there is an uncanny valley which is formed if a diagram is created using interaction fidelity and user effectiveness. Finding more points on this graph would help to support claims we have made with our hypothesis.

There are several studies done previously in the field of virtual reality, however a vast majority of them considered interaction fidelity as a single construct. We argue that interaction fidelity is more complex involving independent components, with each of those components having an effect of the actual effectiveness of an interface. In addition, the intention of the designer can also have influence on how effective an interface can be. In this study we are going to be doing a deeper look into devices which attempt to overcome the limitations of physical space which we will call semi-natural interfaces. Semi-natural interfaces are sometimes difficult to use at first due to mismatch of cues or possibly due to a lack of fidelity, but training has been shown to be beneficial to overcome this difficulty. As of today, designers have not yet found a fully general solution to walking in large virtual environments. The experiments in this document attempt to add merit to the previously defined uncanny valley thesis by comparing devices of varying levels of fidelity, including one invented by our team.

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GENERAL AUDIENCE ABSTRACT

When a user enters a virtual world, they expect it to be as realistic as possible. They expect to be able to move around an interact with objects exactly how they would in real life. This expectation is, at times, met with dismay when there are limitations between what the user expects to be able to do and what is possible for the experience to achieve. The level of realism in a virtual world is something that we call fidelity, and this comes in different levels ranging from low to high. An interaction in virtual reality which is far from how you would make that same interaction in the real world is called a low fidelity technique and this can be compared to a standard game controller being used to move a character forward. On the other spectrum, a technique in virtual reality with high similarities to the real-world interaction is call high fidelity. An example of a high-fidelity technique would be similar to having a user physically walk from one point to another to move the virtual character. In several studies it has been said that both high fidelity and low fidelity techniques have a positive effect on users and they perform well using them, but if the fidelity of the technique falls in between, it will have a negative effect on user experience. The studies in this document test several different fidelity levels of techniques in an attempt to add evidence to the hypothesis that medium fidelity devices currently do not improve user experience and in fact, are creating a negative one.

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1 Introduction

1.1 *Definitions and Key Terms*

Fidelity- The degree to which a system accurately reproduces an effect and experience when compared to its real-world counterpart (Gerthewohl, 1969)

Locomotion- The repetitive motion or action which results in character propulsion and controls movement in a virtual environment (Hollerbach J. M., 2002)

Travel- the motor component of navigation (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017)

User Interface (UI)- The medium through which the communications between the machines and the users take place (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017)

Input Device- The physical device which communicates actions to a computer from a user

Interaction Fidelity- the objective degree of exactness with which real-world interactions can be reproduced in an interactive system (McMahan, 2011)

Interaction Technique- A given method to allow a user to complete a task in a UI

Virtual Environment (VE)- A synthetic world (usually 3D) which has its real time view controlled by a user (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017)

Virtual Reality (VR)- An attempt using displays, tracking and various other technologies to immerse a user into a VE

Effectiveness- A high-level description of the usability, usefulness, and emotional impact provided by a system, technique, or interface

Head-Worn Display (HWD)- A head-coupled display device used for 3D applications (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017)

Degree of Freedom (DOF)- a specific, independent way that a body moves in space. A rigid body has three position values (x, y, z) and three orientation values (yaw, pitch, roll) for a total of six DOF (Nabiyouni, 2016)

1.2 *Motivation*

One of the many goals of virtual reality is to increase the realism and believability of its presented VE. Immersive VR systems combine interactive 3D graphics, 3D visual display devices, and 3D input devices to create the illusion that the user is inside a virtual world (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017). Designers use haptic feedback, spatial sound, and 3D imagery to attempt to replace real-world sensory information in a user's mind in order to make a more compelling experience. Another way to make VR more realistic, however, is to allow users to interact with the virtual world in the same ways they interact with the real world. In particular, there have been several advancements in realistic travel techniques for moving through a VE.

Locomotion is one of the fundamental tasks in VR systems (McMahan, Lai, & Pal, 2016). Real, physical walking is considered to be the "gold standard" technique for VR locomotion, because it provides improved spatial orientation (Ruddle, Volkova, & Bülthoff, 2011) higher levels of presence (Slater, Usoh, & Steed, Depth of Presence in Virtual Environments, 1994), and less simulator sickness (Nabiyouni & Bowman, 2015) as compared to less natural techniques. A locomotion technique which has high realism can provide the user with enhanced distance judgement while also increasing the sense of presence (Hollerbach J. M., 2002). However, it is not yet fully understood how the effectiveness of a locomotion technique is influenced by its level of realism. This uncertainty makes understanding the relationship between effectiveness and fidelity level is an important topic in research.

Unfortunately, real walking is not feasible in a VE unless it is smaller than the physical tracked workspace, so locomotion fidelity is limited by the shortcomings of technology in that respect. This has motivated the development of various simulations of real walking, ranging from techniques such as redirected walking (Razzaque, Kohn, & Whitton, 2001), human joystick (McMahan, Bowman, Zielinski, & Brady, 2012), and walking in place (Usoh, et al., 1999), to devices such as omni-directional treadmills (Darken, Cockayne, & Carmein, 1997), walking pad systems (Bouguila, Florian, Courant, Hirsbrunner, & Richard, 2004) rolling devices (Fernandes, Raja, & Eyre, 2003) and so on. These techniques and devices do not simulate real walking perfectly, so we consider them to have lower interaction fidelity (McMahan, Lai, & Pal, 2016) than real walking, and call them "semi-natural" locomotion techniques. Interactions classified as semi-natural have often been shown to have a lower effectiveness when compared to the real-life counterpart (McMahan, 2011; McMahan, Lai, & Pal, 2016; Sibert, et al., 2008).

1.3 Problem Statement

Semi-natural locomotion techniques try to be as close to real walking as possible, but they compromise naturalness to keep users inside a defined boundary while simultaneously allowing them to explore a large virtual environment. It is not yet fully understood how effectiveness is affected by the design of semi-natural devices, but it has been hypothesized (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015) that semi-natural techniques will have lower effectiveness and an inferior user experience compared not only to real walking (high interaction fidelity) but also to well-designed non-natural techniques (low interaction fidelity). This is because semi-natural techniques present themselves as being like real walking, but in fact require users to move and act in non-natural ways, meaning a user must first train in order to effectively use the given technique. This "uncanny valley" (Mori, 1970) of interaction fidelity suggests that VR locomotion techniques need to be very similar to real walking before the benefits of real walking will be seen. The research presented in this thesis aims to clarify the relationship between interaction fidelity and effectiveness. In particular, we hope to learn how much locomotion fidelity is necessary to achieve effectiveness close to that of real walking.

1.4 Research Questions and Hypothesis

1.4.1 RQ1: Is there a clear and consistent relationship between the interaction fidelity and the effectiveness of VR locomotion techniques?

It is a common belief that an increase in realism pretty much guarantees an increase in how effective a technique will be. It is from this idea where most of our research has been focused and why there is a belief that devices which fall in between have the potential to be beneficial to user experience over a technique of a lower fidelity. However, despite this, it has been theorized and there has been evidence to show that well designed low fidelity interaction technique as well as high fidelity interaction techniques will both have an edge as far as performance when compared to a technique of moderate fidelity. The hypothesis is that the relationship between the level of interaction fidelity and effectiveness forms an uncanny valley as indicated in Figure 1 Hypothesized Interaction Fidelity-Effectiveness Relation. The chart indicates that low-fidelity interaction techniques have the potential to be very ineffective (e.g., mapping a forward joystick movement on an Xbox controller to left strafing in the VE) or very effective (e.g., a standard game controller mapping). It also indicates that high-fidelity techniques will almost always be effective due to the close imitation of real world actions. The “uncanny valley” is seen in the middle of the chart, where moderate-fidelity techniques can only achieve moderate levels of effectiveness.

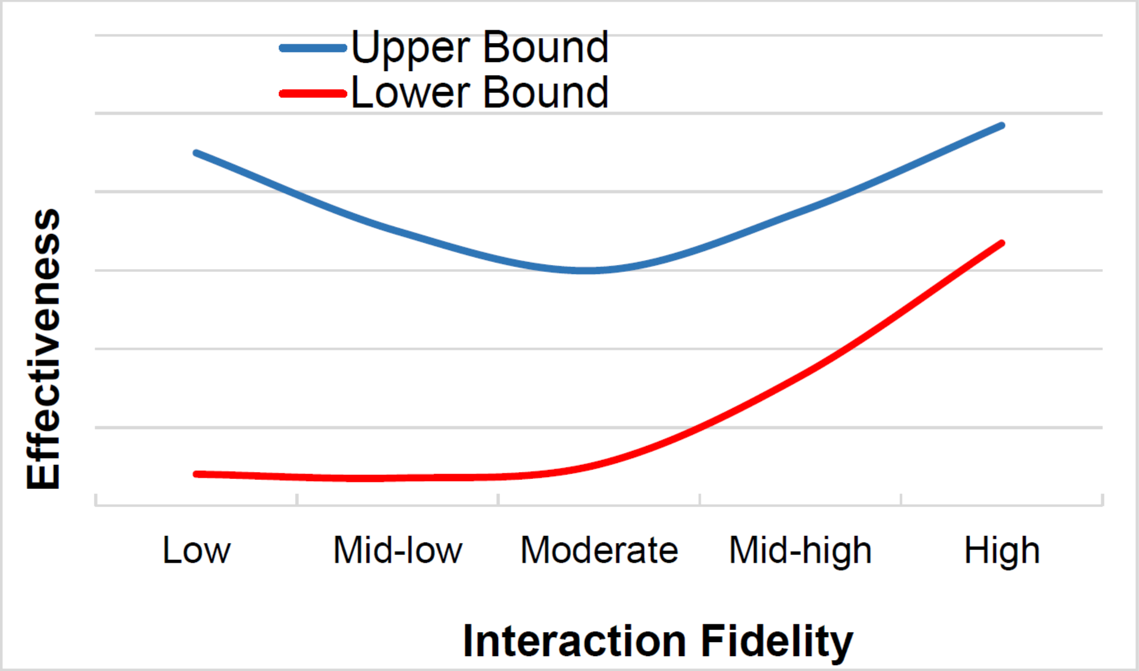


Figure 1 Hypothesized Interaction Fidelity-Effectiveness Relation.

1.4.2 RQ2: Can we create a semi-natural technique which can improve the level of effectiveness of a standard semi-natural device?

Many people and companies are interested in the semi-natural approach, especially for VR gaming, where physical movement might improve presence and realism and solve many issues of space limitations in VR. That being said there are still areas to improve upon and things that can be tweaked in order to maximize the effectiveness. We believe that even the proposed market leaders have room for improvement and are not increasing user effectiveness as of yet.

1.5 Approach

To address our first research question, we are going to delve further into the hypothesis first discussed by McMahan (McMahan, 2011) and further iterated on by Nabiyouni (Nabiyouni, 2016). This hypothesis states that moderate fidelity interfaces often have inferior effectiveness comparing to high- and well-design low-fidelity interfaces. We cannot “prove” this hypothesis; however, we can add to the existing evidence for it. We can also do a more thorough study than Nabiyouni et al. (who had some limitations including a poor moderate-fidelity device and a very limited physical walking area). We can also try to verify this relationship for state-of-the-art moderate-fidelity devices.

To address the second research question, we built a prototype of a device we believe addresses some of the fidelity limitations of the commercial Virtuix Omni device. Based on a design written in the dissertation of Nabiyouni (Nabiyouni, 2016), we built a working locomotion device. We enlisted the help of some industrial engineers for the design of the support structure and used an infrared grid over a Plexiglas floor to create a device we call A Walking Experience Simulator (AWESim). It is our belief that this device will provide a user with a more realistic experience because of the added level of control given the user. Utilizing the infrared grid, we believe that a user will feel more as if they are walking naturally based on visual feedback.

1.6 Contributions

During this study there were several things to which we made a contribution. We contributed a better understanding of the relationship between interaction fidelity and effectiveness. We went more in-depth about the main components of interaction fidelity. We also created a novel device based on a design of our own to directly compare a new approach. Through our user studies we have shown a difference between interaction fidelity when it comes to effectiveness.

2 Related Work

In this chapter, we review the literature on interaction fidelity and locomotion techniques for VR. Note that this work is a continuation of previous work done by Nabiyouni, so our literature review is similar to his own (Nabiyouni, 2016).

2.1 FIFA Analysis

McMahan et al. (2011) stated that the overall level of interaction fidelity depends on a combination of the actual characteristics of that system and that each element has the ability to fall on separate places in the interaction fidelity spectrum. This belief brought about the Framework for Interaction Fidelity Analysis (FIFA), which compares interaction techniques to their real-world counterparts across several dimensions.

We use FIFA in our work to compare locomotion techniques and where they fall on the fidelity spectrum. In particular, we use it to classify the techniques we study and develop as low-, moderate-, or high-fidelity. We also use FIFA to understand the various ways in which the realism of moderate-fidelity techniques can be increased, and to compare the subtle differences among moderate-fidelity techniques.

FIFA describes interaction fidelity with three primary factors: biomechanical symmetry, control symmetry and system appropriateness (McMahan, 2011). In a more recent study done by McMahan the system appropriateness category is replaced by input veracity which more directly defines the degree of exactness which the system captures a user's movements (McMahan, Lai, & Pal, 2016). However, to maintain consistency with our prior work on locomotion fidelity, we still refer to it as system appropriateness.

2.1.1 Biomechanical Symmetry

Biomechanical symmetry describes the degree of correspondence between the body movements used in the interaction technique and the body movements used while performing the same task in the real world. It has three sub-components: kinematic symmetry, which concerns body motions and trajectories; kinetic symmetry, which is about the forces applied to cause body movement; and anthropometric symmetry, which refers to the part of the body which was used.

2.1.2 Control Symmetry

Control symmetry describes how the control provided through the interaction technique compares to control in the real-world task. This category is also divided into three sub-components: dimensional symmetry, which compares the similarity between the control dimensions between the real-world task and the interaction technique; transfer function symmetry, which is how an interaction technique interprets and transforms input data into an output; and termination symmetry, which is how interaction is initiated and stopped.

2.1.3 System Appropriateness

System appropriateness is used to characterize how suitable a system is for performing the interaction and is divided into four sub-components: input accuracy, input precision, latency, and form factor. Input accuracy is mainly about how close the measurements of the input are to ground truth while input precision is about how repeatable these measurements are. Latency references the amount of delay between the input of a user and the feedback of the system, while form factor deals with the shape, size, and other physical attributes of the actual device.

2.2 Locomotion Techniques

A locomotion technique is defined by the type of interface it uses to perform its duty. In this review, we divide these techniques into three different levels of fidelity; high, medium, and low (based on FIFA analyses of the techniques). A high-fidelity technique, otherwise known as a natural technique, is one which creates an experience utilizing physical walking while keeping a user within the boundaries of the physical tracked space (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017). A medium-fidelity technique, also known as a semi-natural technique, is one which is not quite real because it attempts to alter natural walking in some way. This is done by one of several different techniques including gait alteration, mechanical readjustment, and metaphor application. A low-fidelity technique, otherwise known as a non-natural technique, is one which is more common to users. They are usually based on handheld controllers but there are a few exceptions to that description.

2.2.1 High-Fidelity Techniques

2.2.1.1 Real Walking

There have been several studies done on the effects of high-fidelity interaction on travel, Usoh et al. compared real walking, walking in place, and flying and found that walking afforded the greatest sense of presence compared to the other techniques (Usoh, et al., 1999). It was also found by Chance et al. that when compared to gaze-based steering and joystick-based steering to navigate to locations within a maze, real walking turned out to provide much better spatial orientation than either of the others (Chance, Gaunet, Beall, & Loomis, 1998). Nabiyouni et al. compared the effects of all three levels of fidelity techniques, including real walking, and found evidence to support the hypothesis that high- and low-fidelity locomotion techniques often perform better than medium-fidelity ones (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015). However, real walking was combined to very small physical spaces in all of these studies due to tracking area limitations. Further work is needed to characterize the effectiveness of real walking in more expansive spaces.

2.2.1.2 Redirected Walking

Redirected walking was a concept first introduced by Razzaque et al. and has the benefit of being able to extend the size of a virtual environment but incorporates all of the proven benefits of physical walking. This addresses the size limitation mentioned in real walking by interactively and imperceptibly rotating the virtual scene about the user. The rotation causes the user to walk continually toward the furthest wall of the lab without noticing the rotation (Razzaque, Kohn, & Whitton, 2001). One important aspect of redirected walking is not to let the user notice the rotations applied to their movements which is done by altering figures called gains. There are three types of gains: translation, rotation, and curvature. These effect the proportion of the mapped VE translation to the user's physical translation, the proportion of the amount in the VE to the user's physical rotation, and the radius of the curvature on which user is physically walking to virtually walk straight respectively (Bruder, Steinicke, Wieland, & Lappe, 2012). The main goal of redirected walking is to make the user rotate away from the boundaries of tracking space. This is accomplished by generalized steering algorithms which make the user move toward collision free locations.

It would seem redirection is the answer to making the most out of a tracked area for a VE, however, redirection can have an effect of spatial orientation. In a study conducted by Suma et al. participants were observed that when using certain of redirection, pointing to targets became difficult (Suma, Krum, Finkelstein, & Bolas, 2011). In addition, redirected walking needs either a larger tracker space than any of the other techniques or must have predetermined waypoints to guide user motion (Razzaque, Kohn, & Whitton, 2001). This technique also must have a terrain which is mostly flat and even which limits creative design within a VE.

2.2.2 Medium-Fidelity Techniques

2.2.2.1 Pressure Boards

Many people can remember owning or knowing someone who owned the original Nintendo Entertainment System (NES) and one of the first games many people played was a trio of games which included Mario Bros, Duck Hunt, and Stadium World Class Track Meet. In order to play World Class Track Meet you had to have a device called a Power Pad which was a grey mat with 12 colored circles (Figure 2). Under those circles were pressure sensors which you had to interact with in order to move your character. It was many people's first introduction to one of the earliest forms of a medium fidelity technique known as a pressure board. These devices allow for navigating through virtual game environments by standing on top of a flat surface and by shifting one's weight toward different parts of the surface. A more recent example of this type of device is Wii Balance board (Figure 3), which has been used by researchers for navigation in VR (de Haan, Griffith, & Post, 2008) & (Valkov, Steinicke, Bruder, & Hinrichs, 2010).

When compared to walking in real life, this technique is far from what would be considered natural. Yes, in some ways pressure boards can be considered as a walking in place technique, but the difference is this technique needs the user to "step" in a specific place. Even the best pressure board does not see a difference between a shift in weight and an actual foot lifted.

Figure 2 Nintendo Power Pad

Figure 3 Wii Balance Board

2.2.2.2 Rolling Sphere

In 2003 Kiran Fernandes described the idea of walking inside a sphere for locomotion and training. In this system a user would walk inside a sphere rolling on casters, and virtual imagery is projected to the sphere using the projectors mounted outside and surrounding the sphere (Fernandes, Raja, & Eyre, 2003).

The most recent iteration is known as the Virtusphere (Figure 4) and is a large hollow sphere mounted on casters, in which a user wearing a HWD can walk in any direction to move through a VE (Latypov, 2018). A study has been done measuring the effectiveness of this device against other levels of fidelity (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015) during which the Virtusphere had significantly worse performance than the gamepad and real walking techniques, which would suggest that the device which presents itself as being able to simulate natural walking may not be living up to its claims.

Figure 4 The Virtusphere

The main drawback of this device is initiation and termination of motion. The Virtusphere has a certain mass and in order to start walking you have to exert a certain amount of force in the desired direction. The same principle applies to terminating the action and the inertia of the Virtusphere must be overcome in order to change directions or come to a stop, which has an effect on the time it takes to come to a complete stop.

2.2.2.3 Sliding in Place

Sliding on a surface seems to be a promising, as well as popular solution for infinite locomotion. From the idea of the Virtual Perambulator (Iwata & Fujii, Virtual perambulator: a novel interface device for locomotion in virtual environment, 1996) came devices such as the Wizdish (Williams, King, & Bridgland, 2017), which has a user slide their feet backward and forward, and the Virtuix Omni (Goetgeluk, 2017) which has special shoes and holds you in place while you walk on a low-friction floor (Figure 5). The addition of a harness to hold a user in place is an improvement on previous implementations of such devices since sliding on a surface while the user was not able to see their own feet, caused them to lose balance. Devices such as the OmniWalker (Figure 5) use ball bearings instead of a low friction surface to allow movement in various directions (Suryajaya, et al., 2010).

Figure 5 WizDish; Virtuix Omni; Omni Walker

When compared to real walking this technique is considered a good emulation. It generally allows a more “natural” walking feeling and instead of learning a metaphor or technique, a gait manipulation structure is usually implemented in combination with some variation of a walk-like action. Changing the gait of natural walk however does create a situation where a user needs to be supported which means that the comfort of the support structure is a factor. Comfort is subjective and varies between users so this makes it a difficult task when you consider every variation of body structure which has to be considered.

2.2.2.4 Stepping Systems

If you have been to almost any fitness gym you would recognize a Stairmaster machine, which is similar to stepping devices used for VR locomotion. A good example of this device would be the Sarcos Biport which uses hydraulic arms to provide a force feedback to a user (Hollerbach J. M., 2002). Walking with this technique is usually very close to how walking would be in real life but this technique has one fatal flaw, changing direction. Another kind of stepping system was created by Iwata et al. called the Gait Master. This device uses foot pads which carry the user’s foot backward in an attempt to cancel forward movement. The pads are on a turntable which allow movement in different directions and newer iterations include elevated pads to show a difference in surface height (Iwata, Yano, & Nakaizumi, 2001).

One of the main problems with this technique is that it requires bulky equipment and a large area to work within. The space needed does not compare with the amount of area which can be walked suing the device, however, having a vast VE does not make a difference if you can only walk in one direction with ease.

2.2.2.5 Cycling Systems

Cycling systems are essentially exercise bikes which are being used as controllers. This idea was proposed by Sarcos Robotics in 1994 but described in a study done by Darken et al. and was called the Uniport (Figure 6). A user saw the VE through an HWD and changed direction using thighs to turn the seat while the pedals controlled forward movement (Darken, Cockayne, & Carmein, 1997). The Uniport was thought of as mainly a training device for soldiers, but the concept was redesigned and used as an immersive environment for exercise purposes as the VirZoom (Figure 6) (Janszen, 2018). It places the user in a VE which they need to use the pedals to go through and interact with.

Figure 6 Uniport; VirZoom

These systems are very task specific and are not great when it comes to closeness to real walking. If the simulation is about riding a bike, then these have the potential to be excellent if designed well but applying this motion to walking can be troublesome when changing direction.

2.2.2.6 Treadmills

A treadmill is probably one of the most recognizable pieces of equipment, even if you have never used one. Using a treadmill does not inherently create balance problems which made it an easy choice for use in some VR applications. Using a CAVE display and a tilting treadmill, Hollerbach et al. created the Sarcos Treadport (Figure 7). It is a relatively large 6X10-foot treadmill surrounded by a three sides cave with a six-axis tracking system which is attached to the ceiling and also to a body harness. As the user moves around, the treadmill is used to re-center them and has a speed which is directly proportional to the distance the user is from the center (Hollerbach, Xu, Christensen, & Jacobsen, 2000).

Figure 7 Sarcos Treadport walking up a hill

In 1996 the concept of an omni-directional treadmill was patented by David Carmein who later helped to design and develop the Omni-Directional Treadmill (ODT) (Darken, Cockayne, & Carmein, 1997). The ODT was a 4.2x4.2 ft. active surface with a top velocity of 3 m/sec. It had two orthogonal belt arrays which rotated to allow the user to turn in various directions. The ODT is composed of five subsystems that form a unique mobility interface device: belts that form the active surface, a position-sensing system, a control computer, a drive system, and a safety system. When the inner belt rotates, it provides motion in the y direction by engaging the rollers of the upper belt and causing them to roll. While standing at its center, a user has approximately .635 meters of active surface to move on in any direction. As the system tracks the user's position on its surface, that information is passed to an algorithm that determines how to adjust the treads in order to re-center the user. Later, Iwata improved on the idea by using two sets of belts to enable rotation in two directions and called it the Torus (Figure 8). The first set of belts comprises an array of twelve small treadmills in parallel, rotating in the same direction. These belts connected side-by-side, form a large belt which rotates in the orthogonal direction to make the arbitrary planar motion possible (Iwata, 1999).

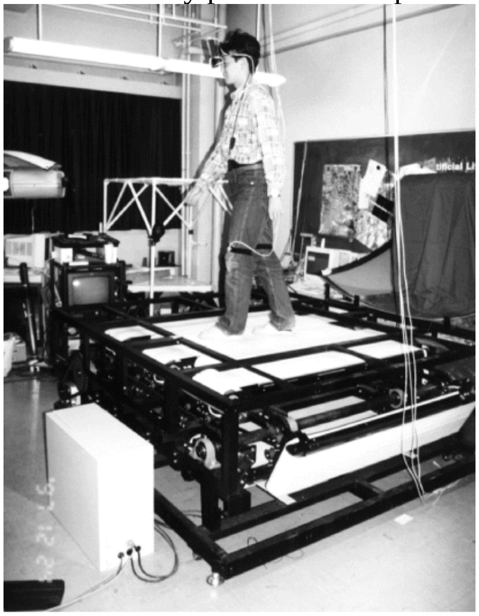


Figure 8 Torus Treadmill

In these techniques not only is precise tracking required, but the related communications, filtering, calculated response, and actual response must occur correctly with essentially no lag in order to adequately simulate the real world. Turning and changing directions is still a big issue in this technique as many times the lag is too great and stumbles occur. The majority of problems observed in these devices relate directly to how the system senses its user and how the system's response affects the way in which the corrections occur. Current spatial tracking technology is mediocre at best and it have a huge effect on how this device works. Its biggest limitation is the advancement of the tracking technology.

2.2.2.7 Human Joystick

As an input device, there is no better-known device than the joystick. It is in every arcade machine which has controlled motion as well as every home console gaming system. A more natural method in which a user is to perceive their entire body as a joystick was proposed by Bourdot et al. and a full 6 DOF navigation framework was created (Bourdot & Touraine, 2002). In this technique, the velocity of travel is based on the distance a user moves from a perceived neutral point around a user. This kind of technique was also used by McMahan et al. to enable a user to travel through a VE in a CAVE (McMahan, Bowman, Zielinski, & Brady, 2012). They used the tracked head position to figure out her distance from a neutral zone and activated the technique to increase the velocity in the linear direction indicated.

This technique does not use physical walking usually so it is far from real walking. There are some body motions but not to do a repeated action as expected when walking. A gesture or leaning motion has no gait and therefore cannot be thought of as realistic system.

2.2.2.8 Walking in Place

Slater et al. developed a technique which allowed the user to "walk in place" to travel through a VE (Slater, Usoh, & Steed, 1995). In order to use this technique a user was asked to march in place and the virtual character was moved in the direction of the gaze. Slater et al. used a neural network to analyze the stream of coordinates received from the HWD and whenever it determined the act of walking, the user was moved. In this study they observed that users had a higher sense of presence with the technique of walking-in-place when compared to a flying technique. This study was replicated by Usoh et al. and added another later by comparing both techniques to real walking (Usoh, et al., 1999). Usoh observed that the real walking was significantly better than the walking in place and the flying technique. Usoh et al. also found out that the users' degree of association with their virtual avatars was a factor of presence so they believe tracking more body parts will have a considerable increase in presence.

2.2.3 Low-Fidelity Techniques

2.2.3.1 Game Controller

A game controller is one of the most common techniques and because of its easily mappable button configuration, has been used by many users and researchers (Whitton, et al., 2005). The game controller technique has high accuracy and precision, low latency, and high dimensional symmetry. The most recent iteration of a game controller has two joysticks for translation and rotation and both are used in unison to change the viewpoint in an environment. Game controllers employ good HCI design principles and it is believed that even users who tries it for the first time can learn it quickly and use it effectively. This technique was compared in several studies including Nabiyouni et al. who compared this technique with the Virtusphere and real walking (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015), and found that the game controller compared favorably to real walking in terms of task performance.

2.2.3.2 Finger Walking

Finger Walking is a scaled down version of walking in place in which a user slides their fingers across a multitouch surface (Kim, Gracanin, Matkovic, & Quek, 2010). This technique enables users to translate and rotate the view point by moving their fingers in-place. Although this interface might be convenient and low cost, there have been expressed difficulties with precisely detecting finger motions. Most notably this technique observed improvements on accuracy of replicating a given route (Kim, Gracanin, Matkovic, & Quek, 2010).

2.2.3.3 Flying

A flying technique is a super natural technique which gives a user freedom of movement in all three dimensions. If you imagine as if you were a bird or an actual airplane then you have the basis of this idea (Whitton, et al., 2005). This technique is not limited to walking and can be applied to a wide range of VEs and gives more freedom of motion than a typical game controller technique.

2.2.3.4 Teleportation (with walking)

The idea of teleportation has been discussed by several VR researchers as a beneficial method of transportation. One of the best-known implementations of this concept would be the portal technique used in several popular video games. A game called Portal and Portal 2 developed by Valve is one of these implementations where the user moves objects (including themselves) around using a handheld device. This device creates doorways through which things can move in and out to places which normally are not reachable. Cloudhead games created a system in 2015 called Blink which allows a user to move around vast spaces in VR while promising to decrease motion sickness. This technique has a user look where they would like to go in the VE and after a button press there is a fade out sequence and then it fades back in with the user in the space they selected. This technique also gives users the option of having visual effects to show the limitations of the physical space they are using as to avoid injury and to allow proper mapping to include the desired area of interaction. A study performed by Bowman et al. (Bowman, Koller, & Hodges, 1997) found that teleportation can result in a decrease in spatial orientation awareness.

2.2.4 Fidelity Summary

There are several different approaches to the design of a locomotion technique and although there are many different designs, all are limited in various ways. In particular, there are no moderate-fidelity techniques that provide a highly effective simulation of real walking. That being said there are spatial limitations to the design of a VE which utilizes real walking so that is also a deficit. Low fidelity techniques are easy to deploy and can be easy to use, but they are the furthest thing from reality and thus are inherently limited in producing a realistic experience of moving through a virtual environment.

3 Experiment 1

3.1 Goal

Our first experiment was designed to partially address RQ1: Is there a clear and consistent relationship between the interaction fidelity and the effectiveness of VR locomotion techniques? We compared the effectiveness of an industry-leading semi-natural locomotion device (the Virtuix Omni) and a well-known low-fidelity technique (a game controller). Based on prior research, we expected the game controller technique to be more effective overall than the semi-natural Omni device, but we were interested to know whether the Omni was an improvement over earlier semi-natural device such as the Virtusphere.

3.2 Research Questions

This experiment addressed three specific research questions of its own:

RQ1.1. How does the user experience (including speed, accuracy, spatial orientation, game experience, simulator sickness, presence, and user preference) with the semi-natural Virtuix Omni compare to a traditional non-natural VR locomotion interface?

RQ1.2. Do these results support the uncanny valley hypothesis of McMahan et al. (McMahan, Lai, & Pal, 2016)?

RQ1.3. Compared to earlier semi-natural VR locomotion techniques, does the Omni provide higher interaction fidelity and correspondingly higher levels of user experience?

3.3 Design

Visual feedback in our experiment was provided by an Oculus Rift CV1 head-worn display (HWD) with three sensors surrounding the Omni, which allowed 360° tracking. The virtual scene was rendered by an MSI G-series laptop with an Intel core i7-6700, 16GB of RAM, and a Nvidia GTX 1060, running the Unity game engine v5.5.0. For the game controller condition, we used an Xbox One wireless controller.

The Virtuix Omni (Figure 9) is a commercial VR locomotion device. Users strap into a harness which supports the lower body inside a ring. Users stand on a low-friction curved floor and wear special low-friction shoes (Figure 9Figure 9 The Virtuix Omni shoes and platform). The harness can turn freely within the ring, and the ring contains sensors to provide information about the direction the user is facing. Bluetooth sensor units snap onto the top of the shoes to track foot movements.

In both conditions, users stood inside the Omni while wearing the Oculus Rift HWD. The HWD cables were attached to an overhead clamp that kept users from becoming entangled when they turned in the Omni. In the controller condition, the Omni's harness was removed so that users could stand and turn naturally, and users did not wear the low-friction shoes in this condition.

Figure 9 The Virtuix Omni shoes and platform

3.4 *FIFA Analysis*

Interaction fidelity is defined as the objective degree of exactness with which a system reproduces real world interactions. To interpret the results of our study with respect to the effects of interaction fidelity on user experience, we need to analyze the levels of interaction fidelity provided by the locomotion techniques in our experiment.

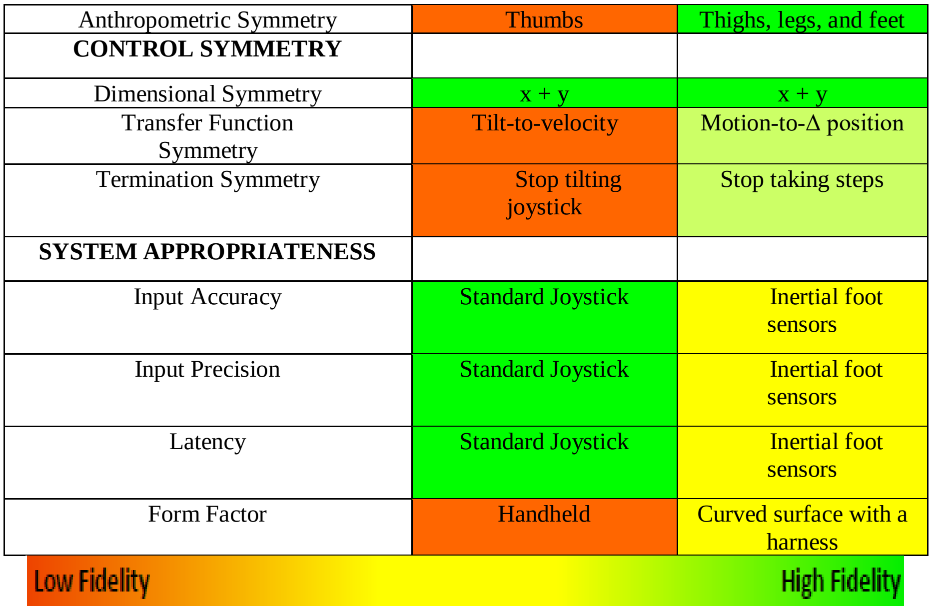
McMahan et al. introduced the Framework for Interaction Fidelity Analysis (FIFA) for this purpose (McMahan, 2011). FIFA compares interaction techniques to their real-world counterparts using three different dimensions: system appropriateness, control symmetry, and biomechanical symmetry.

Table 1 summarizes our analysis of a traditional game controller-based technique using two analog joysticks to translate and rotate the user in the VE, and the Virtuix Omni device. The legend on the bottom shows the level of interaction fidelity for each component, from red (low fidelity) to green (high fidelity). The table only shows our analysis of the translation aspects of locomotion, but not the turning aspects.

Clearly, the Omni has higher locomotion fidelity than the game controller technique; however, the Omni falls short of high locomotion fidelity in several ways. The lack of friction when walking results in moderate kinetic symmetry. The Omni's IMU-based foot sensors can only detect step-like motions, which means that the transfer function is different than that of real walking, and the accuracy/precision/latency is less than ideal. Finally, the curved walking surface and the harness are both form factor issues that decrease the fidelity of the Omni.

Table 1 FIFA Analysis Controller vs Omni

	Game controller	**Virtuix Omni**
BIOMECHANICAL SYMMETRY		
Kinematic symmetry	Move thumb to translate	Move thighs, legs, feet and to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and low shear ground forces



Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
CONTROL SYMMETRY		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	Tilt-to-velocity	Motion-to-Δ position
Termination Symmetry	Stop tilting joystick	Stop taking steps
SYSTEM APPROPRIATENESS		
Input Accuracy	Standard Joystick	Inertial foot sensors
Input Precision	Standard Joystick	Inertial foot sensors
Latency	Standard Joystick	Inertial foot sensors
Form Factor	Handheld	Curved surface with a harness

Low Fidelity High Fidelity

3.5 *Interfaces*

The experiment compared two different locomotion interfaces: the Virtuix Omni and a game controller technique.

The Omni was used in "decoupled mode," in which the forward direction is determined by the orientation of the user's torso as detected by the ring and is independent of head orientation. In other words, users could walk in one direction while looking in another, as in the real world. The Omni needed to be calibrated at the beginning of each session, because when enabling the decoupled mode, the device has to be told which direction in the virtual world is forward.

For the game controller technique, we mapped one of the analog sticks on the controller to forward, backward, and sideways movements. Rather than using the other analog stick to control viewpoint rotation, as many games do, we used the head orientation to rotate the view. The forward direction of movement was defined by the forward direction of the head. In this way, we limited the differences between the techniques to the method of translation, keeping the method of rotation constant.

With both techniques, users were informed of how to walk forward and backward, and how to strafe. Users had a few minutes to practice with the techniques in an empty VE before any of the tests started. Each user had the chance to practice the Omni with and without the headset to ensure they were somewhat proficient.

3.6 *Participants*

Ten participants were recruited on a voluntary basis for our study. All were males between the age of 18-24. Also, due to the limitations of the Omni, participants had to be shorter than six feet (1.8 meters) tall, weigh less than 270 lbs. (122 kg), and have a maximum waist size of 42 inches (106 cm). None of the participants had prior experience with the Omni. All but one participant had experience with games in general, but only about half of them had experience with VR. The selection of participants was completely coincidental and was not selected intentionally for the purpose of this study.

3.7 Tasks

We used the tasks from an existing locomotion testbed (Nabiyouni & Bowman, 2015). The testbed includes tasks emphasizing accuracy, speed, and spatial orientation, and uses a variety of measures to get a comprehensive view of locomotion user experience.

3.7.1 Path Following

In the path following task, the participant had to navigate from a start point to an end point along a path marked on the ground (see Figures 10 and 11). This task emphasized accuracy; participants were instructed to move as accurately as possible along the path without worrying about moving quickly. The initial path was a simple straight line, and subsequent paths became more complicated. There were six total path following tasks that each participant had to complete. Visual and auditory feedback was provided to indicate the start and end of each task.

For all of the path following tasks we used path deviation as a measure of accuracy. We defined this deviation as the perpendicular distance between the user's position in the VE and the indicated line which was recorded every 50ms (Nabiyouni, 2016). We took measures of both total deviation (the sum of all deviation measurements over the entire path) and max deviation (the maximum distance the user deviated from the specified track at any given time during the course).

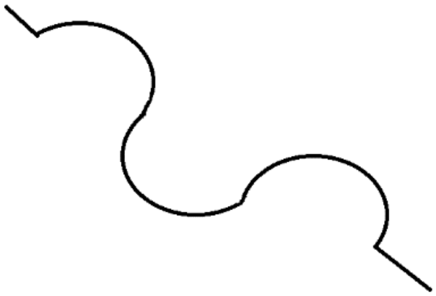


Figure 10 A top down view of the 2m curved path following task

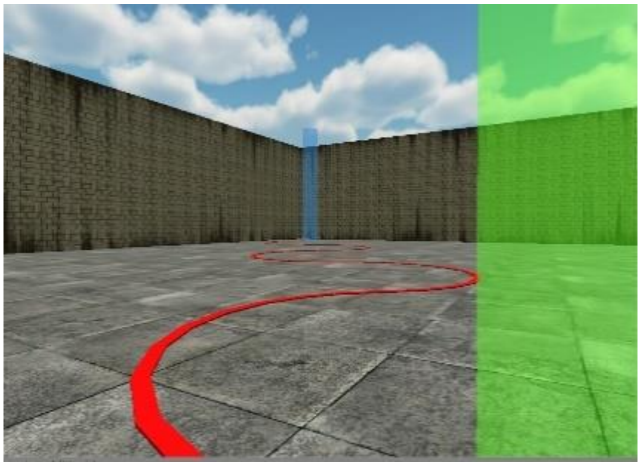


Figure 11 A view from the user's perspective of the 2m curved path following task

3.7.2 Speed Path

In the speed path task, users stood on a roughly oval track enclosed by walls (Figure 12) and were told to complete two laps as quickly as possible while also avoiding collisions with the walls. Auditory feedback was provided when a wall collision was made. Participants were informed that each collision would result in a penalty on their score.

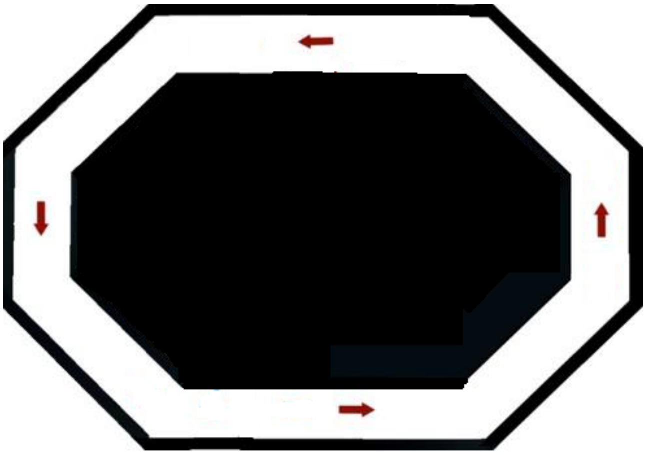


Figure 12 A top down view of the speed path

Even though we told participants we were measuring time for this task, we made sure to emphasize the importance of avoiding wall collisions, because that was a more accurate measure of the differences between the Omni and the controller (it is not possible to go faster than the maximum velocity in the controller technique).

3.7.3 Spatial Orientation Task

In the spatial orientation task, users had to remain aware of the location of markers in the world. Upon reaching a numbered location along the path, users were asked to turn and face in the direction of the previous numbered location and press a button on the controller. The path was shaped like a maze (Figure 13) with walls in between the various parts of the path so the user could not see the actual markers or any signs of the markers once they were no longer standing on them.

We measured the user's position, the marker's position, and the user's orientation for each button press, allowing us to calculate the absolute value of the difference between the user's heading and the true direction to the marker. This was calculated at each of the six locations to give each user five data points with each condition.

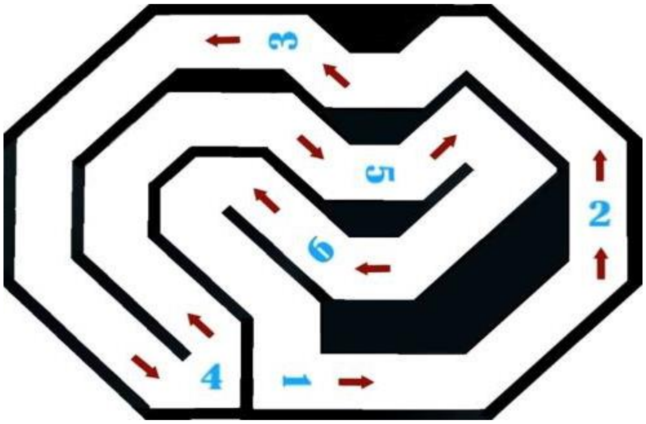


Figure 13 . A top down view of the orientation task

3.8 *Procedure*

We received approval from the university's Institutional Review Board for our study. Upon arrival, participants were asked to read and sign an informed consent form. They next completed a background questionnaire that asked for their age, gender, occupation, eyesight, and experience of playing video games. After that, they were given an introduction to our experiment background, facilities to be used, study procedures and locomotion interfaces. Participants had a short training session before using each locomotion interface, in which they were introduced to the 3D environment and were asked to perform a simple straight-line locomotion task. Two different techniques (standard game controller and the Omni) were used to complete the tasks and every user experienced both techniques in a counterbalanced order.

To measure subjective aspects of user experience, we administered questionnaires after each condition. We used a modified Game Engagement Questionnaire (GEQ) (IJsselsteijn, de Kort, & Poels, 2013) for overall game experience. For usability and preferences, we developed our own usability questionnaire consisting of seven-point Likert-scale items. Finally, we used the simulator sickness questionnaire (SSQ) (Kennedy R. S., Lane, Berbaum, & Lilienthal, 1993). At the conclusion of the experiment, we asked users to rank the techniques for overall preference, comfort, ease of use, and fun.

3.9 *Results*

In this section, we present the statistically significant results in our study. Path deviation, wall collisions, and angle metrics are of a numeric continuous type while subjective variables in the questionnaires are numeric ordinal type. Our primary analyses were one-way analyses of variance (ANOVAs) for collisions, total deviation, max deviation, and angular error, and Wilcoxon signed ranks tests for questionnaire responses.

3.9.1 Deviation

In the path following task, we did not detect a difference between the Omni and controller for most of the paths (Figures 14-16). For example, Figure 14 shows the deviation for the curved path with 2m radius curves (this is the path shown in Figures 10 and 11). On the most difficult path, however (curved path with 1m radius curves, the Omni was significantly worse than the controller for both deviation measures (p_{total}<.003 and p_{max}<.0005), as shown in Figure 17.

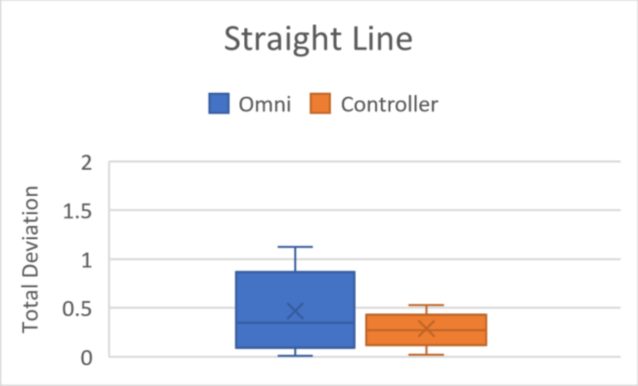


Figure 14 Straight Line results

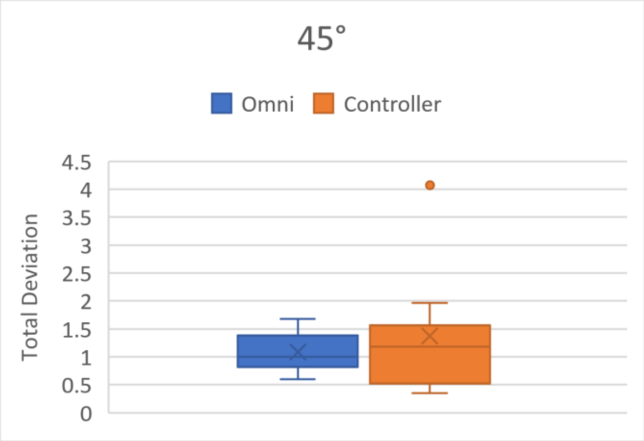


Figure 15 45° Results

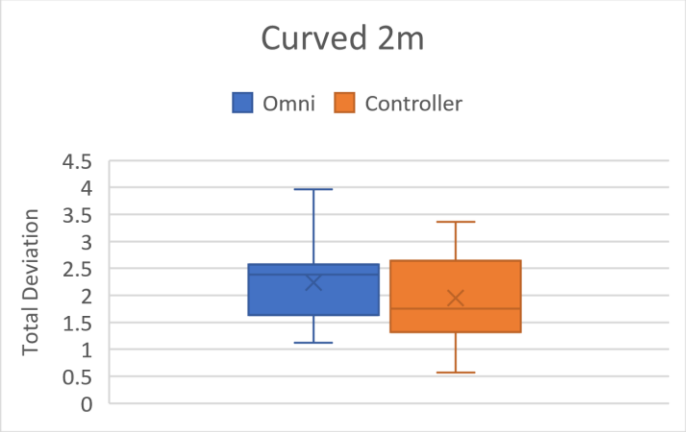


Figure 16 2m Semi Circle Results

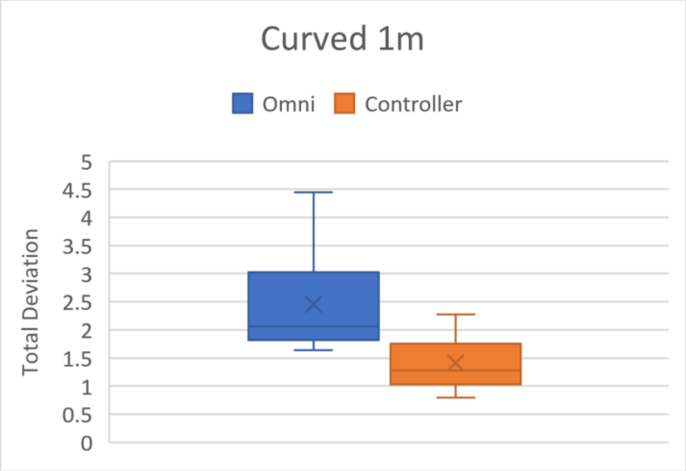


Figure 17 1m Semi-Circle Results

3.9.2 Collisions

In the speed path task, we did not find a statistical difference between the conditions for the measure of collisions with the wall. In absolute terms, the controller resulted in slightly more collisions (Figure 18). However, more testing would be needed to see if this trend is significant (p>.18).

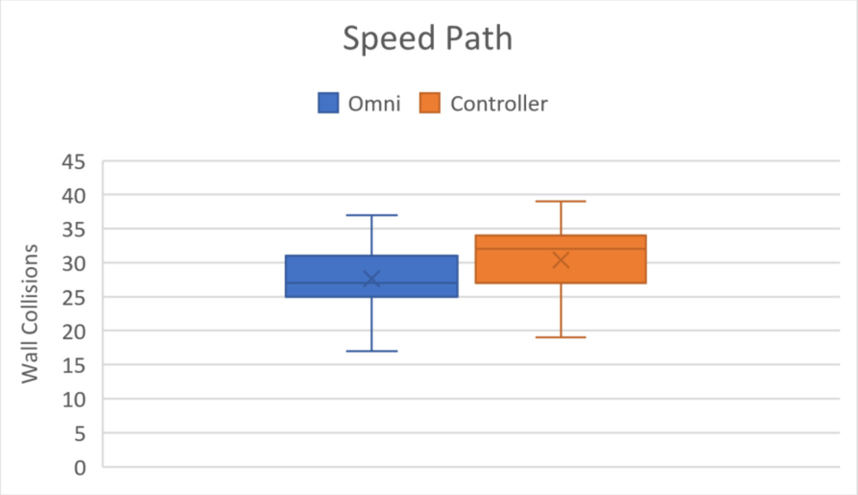


Figure 18 Number of collisions on speed path

3.9.3 Spatial Orientation

The spatial orientation task did not reveal any significant results (Figure 19). However, we did note that there were three times as many outliers (data values more than two standard deviations away from the mean) with the use of the controller when compared with the Omni.

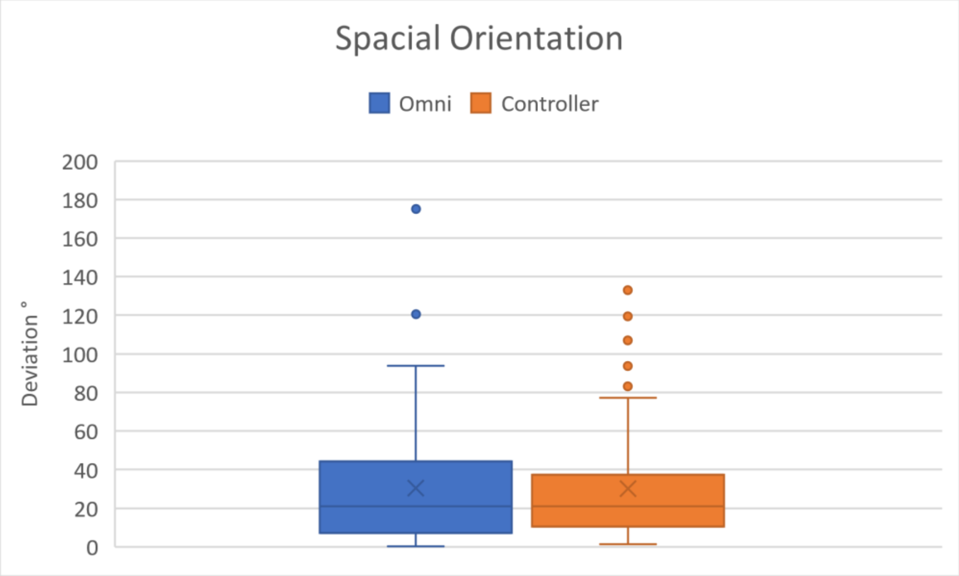


Figure 19 Spatial Orientation Deviation

3.9.4 Questionnaire results

At the midpoint of the study five of the participants expected the Omni to perform better than the controller across the board (the same question was asked regardless of which technique was used first). At the end of the study, however, six of the users said the controller was better for reasons varying from the difficulty of turning the Omni around sharp curves, to the amount of fatigue which was created in the legs during the tasks. Despite this, users said they felt like with more practice, they would become better with the Omni, and even though it was more difficult, it was also more fun.

3.9.4.1 Game Experience Questionnaire

As expected, the Omni scored higher in negative affect, as shown in Figure 20. Judging by the results of the survey, flow did not show a statistical difference despite the closer to natural nature of the Omni ($p<0.22$). In the end however, if given a choice of devices the users voted to use the controller overall and the Omni showed no statistical difference in tension/annoyance (see Figure 21) when compared to the controller ($p<0.2$). Since we suspected that the questionnaire results might be biased by the order in which participants experienced the two techniques, we performed a second analysis that only considered data from the technique that participants experienced first. In this analysis, there showed no statistical significance in tension/annoyance ($p<0.2$) but did show it in negative affect ($p<0.03$).

3.9.4.2 Simulator Sickness Questionnaire

Nausea was the only result to stand out in this portion of the questionnaire according to the individual user survey but showed no statistical significance ($p<0.2$). There were 2 users whose data could not be used as they did become unable to complete the trials. One ended due to a head ache caused by wearing the headset too tight who used the controller as the initial technique while the other had to quit during the final phase of the controller after completing the Omni portion of the course.

3.9.5 Discussion

Overall, we found few objective differences in task performance between the Omni and the controller. Only the most difficult path following task resulted in significantly more deviation when using the Omni. In addition, we saw a trend that the game controller produced more wall collisions during the speed path task. Participants tended to “hug the wall” with the controller, which led to more wall collisions, while with the Omni, users consciously took steps to avoid hitting the walls.

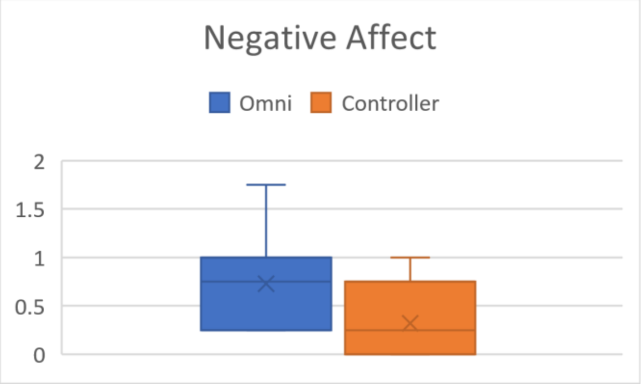


Figure 20 GEQ Negative Affect Results

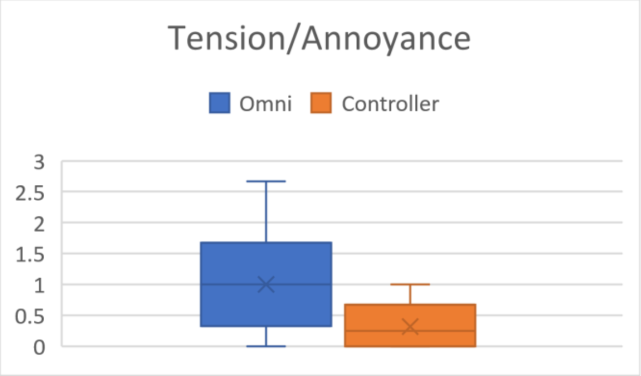


Figure 21 GEQ Tension Annoyance

Considering the subjective measures, however, we conclude that the game controller still provides a better user experience than the Omni overall. While the Omni was seen as more natural and more fun from the user preference survey, the requirement to wear an uncomfortable harness, the difficulty in turning while walking, and the sense of fatigue after only a short usage session caused more participants to prefer the game controller. These results provide additional evidence in support of McMahan’s uncanny valley hypothesis (McMahan, Lai, & Pal, 2016).

We did not compare the Omni directly to other semi-natural techniques or to real walking but based on prior results (some of which were based on the same testbed as the one we used), we can speculate about how the Omni stacks up.

We are confident that the Omni provides a much better user experience than the Virtusphere. A prior comparison of the Virtusphere to a game controller technique found highly significant differences in user experience in favor of the controller (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015). The Omni feels more like real walking (the Virtusphere is significantly different from real walking in terms of forces), and it takes less time to “learn to walk” with the Omni. This is reflected in our FIFA analysis (section 3.4), which showed that the Omni has a higher level of interaction fidelity than the Virtusphere. The increase in interaction fidelity is reflected by a better overall user experience.

At the same time, there are still important differences between the Omni and real walking. Our FIFA analysis still classifies the Omni as a moderate fidelity technique, differing from real walking on kinetic symmetry, transfer function symmetry, termination symmetry, and all aspects of system appropriateness. If the position of the feet were tracked directly, and mapped directly to movement in the VE, the level of interaction fidelity would be much closer to real walking.

Comparing our results to results with the real walking technique used in a previous study with the same testbed (Nabiyouni & Bowman, 2015), we see the impact of these differences in interaction fidelity (see Figure 22). Thus, we suggest that the Omni represents an improvement in UX design for semi-natural locomotion devices, but that even higher fidelity is needed to escape the uncanny valley.

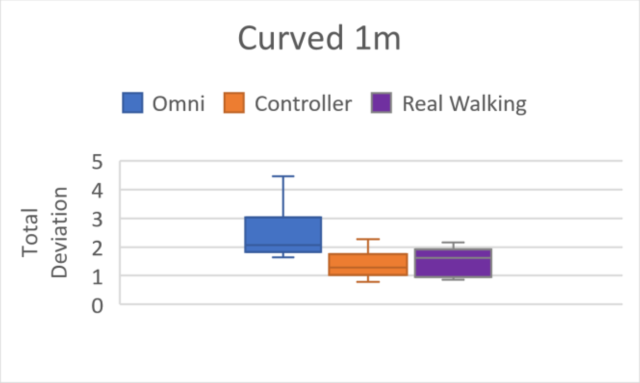


Figure 22 Comparison of real walking results from prior study (Nabiyouni & Bowman, 2015) with Omni and controller results from this study.

4 Experiment 2

4.1 Goals

Designers are working diligently in order to create an answer for overcoming space limitations in the environments they create in VR. Walking metaphors, motion devices, movement techniques, and are all being implemented and created in order to maximize user experience, enjoyment, and effectiveness. Moderate fidelity devices have been a sought-after answer to several issues facing virtual reality but how effective are they when it comes to user experience? Are devices which mimic real walking worth pursuing at this time or are the negative effect too great to create an enjoyable experience for a user? These are all questions which have to be considered by designers whenever they consider how a user is going to move around within whatever environment they are going to dream up. The real question that needs to be answered is will devices which mimic real walking ever be good enough to be on par with real walking which has been proven to be the gold standard when it comes to locomotion in virtual reality.

The first goal of experiment 2 was to more fully address RQ1 (Is there a clear and consistent relationship between the interaction fidelity and the effectiveness of VR locomotion techniques?) by comparing moderate-fidelity techniques to the gold standard of real walking. We hypothesized that real walking would be significantly more effective than moderate-fidelity techniques but were interested to see how close moderate-fidelity devices could come to real walking for different tasks and different measures of effectiveness.

Secondly, experiment 2 was designed to address RQ2: Can we create a semi-natural technique which can improve the level of effectiveness of a standard semi-natural device? We designed and developed a semi-natural device called AWESim that aimed to address some of the fidelity limitations of the Virtuix Omni. The experiment compared the Omni, AWESim, and real walking to study the influence of our design decisions on effectiveness.

4.2 Design

Visual feedback in our experiment was provided by an Oculus Rift CV1 head-mounted display (HWD) with three sensors surrounding the Omni as well as the AWESim, which allowed 360° tracking. The virtual scene was rendered by computers which each had Intel core i7 processors with a Nvidia GTX 1070 and 16GB RAM, running the Unity game engine v2017.1.1f1. The Omni and the AWESim used a desktop configuration while the Real walking condition used an MSI VR backpack of similar configuration.

The Virtuix Omni is a commercial VR locomotion device. Users strap into a harness which supports the lower body inside a ring. Users stand on a low-friction curved floor and wear special low-friction shoes. The harness can turn freely within the ring, and the ring contains sensors to provide information about the direction the user is facing. Bluetooth sensor units snap onto the top of the shoes to track foot movements.

The AWESim (Figure 23) is a device created by our lab based on a design initially described by a previous group member (Nabiyouni, 2016). AWESim is a sliding-based locomotion device is designed to address the primary fidelity limitations of the Virtuix Omni:

- It tracks the relative position of the feet on the surface during sliding motions and applies these directly to camera motions (both distance and direction), rather than simply detecting step-like motions and moving the camera in the direction of leaning as the Omni does. This should give users more control and make the system feel more responsive.
- Its form factor does not require a harness or complicated don/doff procedure, while still providing support to keep the user from falling as they slide their feet.
- Its form factor includes a flat walking surface, rather than the curved surface used in the Omni.

A user mounts the AWESim device and sits on a structure similar to a horse saddle on top of a bar stool-like pole while their feet come in contact with a plexiglass floor. There are also crutch-like structures which provide a bit more support while the user is seated on the device. The floor has an infrared grid that was intended to be a large touch screen from PQMT Labs which detects when and where the grid had been intersected. As the user slides their feet, the distance and direction of motion is applied to the motion of the camera in VR. The support structure of the device did not have the limitations seen in many other techniques due to its not using a harness to support the user's body weight. The AWESim also was only limited to how high the stool could be raised so we were able to accommodate a wider range of users for testing.

The AWESim algorithm looks for clusters of touch points that represent the user's feet. Each cluster is treated independently. The centroid of each cluster is considered to be the foot's position. As the foot position changes from frame to frame, the relative motion is directly applied to the virtual camera. Thus, sliding one foot backwards along the surface by six inches moves the virtual camera forward six inches.

Challenges in implementing this algorithm included foot detection and tracking (making sure that a foot identified in one frame was the same as a foot identified in the next frame), handling situations where one or both feet were touching the surface, gracefully handling cases where a foot exited or entered the surface (to ensure that this did not affect the virtual camera), and decrease turning motions from translating the virtual camera.

Ideally, we would like users to raise the stool so that the feet are barely touching the touch surface, so that they are in an upright posture but still supported by the stool and can make natural walking movements. On the other hand, our foot tracking algorithm works best if a user can manage to use only the tips of the toes, as more foot surface contacting the touch surface results in more points and a displaced foot centroid due to extra points being calculated into the foot object. In addition, the algorithm works best if the user does not have their feet on the ground while turning, to avoid unwanted motions while rotating.

These caveats result in a tradeoff between natural walking movements and accurate locomotion.

In the end, movement with AWESim was very responsive and allowed precise control over walking distance and direction, but still sometimes felt too sensitive. In addition, when users moved/turned their feet on the surface to turn their bodies in a different direction, this sometimes still resulted in unintended movements of the camera.

Figure 23 Side View of the AWESim

For the real walking element, we used the Cube in the Moss Arts Center at Virginia Tech. The Cube is a four-story facility with a 50x40-foot floor area. A Qualisys optical tracking system with 24 cameras tracks passive reflective markers in a 36x28-foot area. The tracking data was streamed via Wi-Fi from the Qualisys server PC, directly connected to the tracking system, to the rendering MSI VR backpack. The virtual environment was designed to fit completely inside the tracking area so that real, 1:1-scale walking could be used to traverse all of the paths used in the various locomotion tasks.

4.3 FIFA Analysis

Table 2 summarizes our analysis of the real walking condition in the cube, the Virtuix Omni and the AWESim. The legend on the bottom shows the level of interaction fidelity for each component, from red (low fidelity) to green (high fidelity). The table only shows our analysis of the translation aspects of locomotion, but not the turning aspects.

As seen in the table, we claim the AWESim increases fidelity through a more-realistic transfer function, more responsive termination, a more accurate/precise/low-latency sensor, and an improved form factor. Overall, AWESim has a higher interaction fidelity than the Virtuix Omni.

Table 2 FIFA Analysis of new device

	Cube Walking	Virtuix Omni	AWESim

BIOMECHANICAL SYMMETRY			
Kinematic symmetry	Move thighs, legs, feet and to translate entire body	Move thighs, legs, feet and to translate entire body	Move thighs, legs, feet and to translate entire body
Kinetic Symmetry	Large vertical and shear ground forces	Large vertical and low shear ground forces	Large vertical and low shear ground forces
Anthropometric Symmetry	Thighs, legs, and feet	Thighs, legs, and feet	Thighs, legs, and feet
CONTROL SYMMETRY			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 position-to-position	Motion-to-Δ position	Δ position-to-Δ position
Termination Symmetry	Stop taking steps	Stop taking steps	Stop taking steps
SYSTEM APPROPRIATENESS			
Input Accuracy	Tracking system camera	Inertial foot sensors	Touch Surface
Input Precision	Tracking system camera	Inertial foot sensors	Touch Surface
Latency	Tracking system camera	Inertial foot sensors	Touch Surface
Form Factor	Slightly different sensory cues	Curved surface with a harness	Flat surface with a saddle

We believe this to be true because the Omni uses inertial sensors on the feet which do not immediately register stopping or starting, nor do they actually track the foot position or direction of motion, whereas the AWESim uses a direct relation between where the foot moves and where the virtual character is moved in the world. We also observed that curved surfaces disrupt a user's natural walking pattern and causes balance loss which is the reason we chose to use a flat surface.

4.4 Interfaces

The experiment compared three different locomotion interfaces: the Virtuix Omni, a real walking tracked space, and a device of our own creation called the AWESim (A Walking Experience Simulator).

The Omni was used in "decoupled mode," in which the forward direction is determined by the orientation of the user's torso as detected by the ring and is independent of head orientation. In other words, users could walk in one direction while looking in another, as in the real world. The Omni needed to be calibrated at the beginning of each session, because when enabling the decoupled mode, the device has to be told which direction in the virtual world is forward.

In the real walking condition, we attempted to minimize latency so most of the interactions did not need influence from the researcher. The VR backpack was controlled using a remote desktop software which allowed the user to be hands free during the tasks and the tasks were designed so that in all three tasks there would be minimum interaction.

The AWESim uses a flat, low friction surface and a saddle structure to keep the user in place while using the device. As the user walks and slides their feet on the surface, the feet movement is detected and creates virtual movement. The stool-like base is able to rotate, therefore, to rotate in the VE the user will be rotating similar to real world.

4.5 Participants

Twenty-seven participants were recruited on a voluntary basis for our study. Six of them were females while the rest were males while the age ranged with twenty-one of them being age eighteen to twenty-four, three were age twenty-five to thirty-one, and three were over thirty-two years of age. Also, due to the limitations of the Omni, participants had to be shorter than six feet (1.8 meters) tall, weigh less than 270 lbs. (122 kg), and have a maximum waist size of 42 inches (106 cm). None of the participants had prior experience with the Omni or the AWESim and few had been inside of the cube for a tracked walking session. The selection of participants was completely coincidental and was not selected intentionally for the purpose of this study.

4.6 Tasks

We used the tasks from an existing locomotion testbed (Nabiyouni & Bowman, 2015). The testbed includes tasks emphasizing accuracy, speed, and spatial orientation, and uses a variety of measures to get a comprehensive view of locomotion user experience.

4.6.1 Path Following

In the path following task, the participant had to navigate from a start point to an end point along a path marked on the ground. This task emphasized accuracy; participants were instructed to move as accurately as possible along the path without worrying about moving quickly. The initial path was a simple straight line, and subsequent paths became more complicated. There were six total path following tasks that each participant had to complete. Visual and auditory feedback was provided to indicate the start and end of each task.

For all of the path following tasks we used path deviation as a measure of accuracy. We defined this deviation as the perpendicular distance between the user's position in the VE and the indicated line which was recorded every 50ms (Nabiyouni, 2016). We took measures of both total deviation (the sum of all deviation measurements over the entire path) and max deviation (the maximum distance the user deviated from the specified track at any given time during the course).

4.6.2 Speed Path

In the speed path task, users stood on a roughly oval track enclosed by walls and were told to complete two laps as quickly as possible while also avoiding collisions with the walls. Auditory feedback was provided when a wall collision was made. Participants were informed that each collision would result in a penalty on their score.

Even though we told participants we were measuring time for this task, we made sure to emphasize the importance of avoiding wall collisions, because that was a more accurate measure of the differences between the Omni and the controller (it is not possible to go faster than the maximum velocity in the controller technique).

4.6.3 Spatial Orientation Task

In the spatial orientation task, users had to remain aware of the location of markers in the world. Upon reaching a numbered location along the path, users were asked to turn and face in the direction of the previous numbered location and press a button on the controller. The path was shaped like a maze with walls in between the various parts of the path so the user could not see the actual markers or any signs of the markers once they were no longer standing on them.

We measured the user's position, the marker's position, and the user's orientation for each button press, allowing us to calculate the absolute value of the difference between the user's heading and the true direction to the marker. This was calculated at each of the six locations to give each user five data points with each condition.

4.7 Procedure

We received approval from the university's Institutional Review Board for our study.

Our plan was to run this study completely within-subjects (i.e., to have each participant use all three locomotion interfaces, with order counterbalanced. We also planned to include a maze exploration task (Figure 24), where users had to find statues and collect them from various places in the area which would allow users to interact with each device before being inside of the measured tasks. When we began the study with this procedure, however, we had five out of six participants quit due to motion sickness. This was initially believed to be because of the instability of the AWESim, so we made changes to how the algorithm worked and improved its functionality. We tried to run the study again and we had four out of seven participants quit.

We realized that having participants run through a maze in a medium fidelity device, essentially has each user spinning around in place until they complete the task, which may account for the high volume of motion sickness. Participants removed themselves from the study regardless of which technique (Omni or AWESim) was used first.

Therefore, we removed the maze task from the study and abandoned the idea that we could run the entire study within-subjects. Then we had to think of how to get both subjective views from users who experience all the techniques as well as quantitative data directly comparing the two semi-natural devices.

To address these issues, we broke the study into three separate sub-studies:

- one which had a user use one device picked for them (between subjects),
- one where the user used both semi-natural devices (within subjects) but not real walking, and

- one where each user was given only a simple task on all three devices (within subjects, qualitative data only). The task was to walk to five marked points in the environment in any order.

Upon arrival, participants were asked to read and sign an informed consent form. They next completed a background questionnaire that asked for their age, gender, occupation, eyesight, and experience of playing video games. After that, they were given an introduction to our experiment background, facilities to be used, study procedures and locomotion interfaces. Participants had a short training session before using each locomotion interface, in which they were introduced to the 3D environment and were asked to perform a simple straight-line locomotion task.

To measure subjective aspects of user experience, we administered questionnaires after each condition. We used a modified Game Engagement Questionnaire (GEQ) (IJsselsteijn, de Kort, & Poels, 2013) for overall game experience. For usability and preferences, we developed our own usability questionnaire consisting of seven-point Likert-scale items. For presence we used a questionnaire developed by Witmer & Singer (Witmer & Singer, 1998). Finally, we used the simulator sickness questionnaire (SSQ) (Kennedy R. S., Lane, Berbaum, & Lilienthal, 1993). At the conclusion of the experiment, we asked users to rank the techniques for overall preference, comfort, ease of use, and fun.

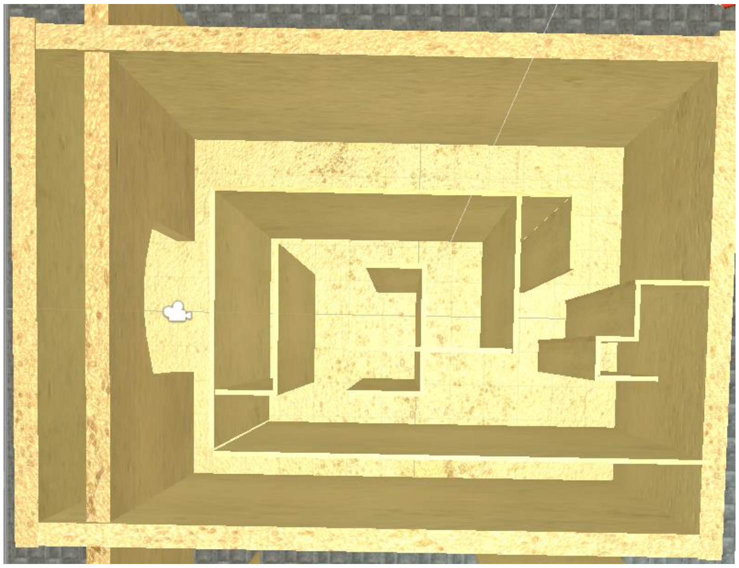


Figure 24 Top-down view of Maze Task

4.8 Results

In this section, we present the statistically significant results in our study. Path deviation, wall collisions, and angle metrics are of a numeric continuous type while subjective variables in the questionnaires are numeric ordinal type. Our primary analyses were one-way analyses of variance (ANOVAs) for collisions, total deviation, max deviation, and angular error, and Wilcoxon signed ranks tests for questionnaire responses.

4.8.1 Deviation

For all of the path following tasks we only found a statistical difference for the 135° path following task for maximum deviation in the within subjects testing phase (see Figure 25). In the between-subjects analysis, we found a difference in the straight line max deviation shown in Figure 26 (p<0.037), and the 135° path task shown in **Error! Reference source not found.** & Figure 28 ($p_{total} < 0.048$ and $p_{max} < 0.03$) this was mostly due to the difference in the real walking results which were far superior to both the Omni and the AWESim (there is no statistical difference between either the Omni and the AWESim when compared together). For the max deviation there was more variance in the Omni data in 5 out of the 6 tasks given, even though the total deviation overall had both the Omni and the AWESim on par with each other.

Figure 25 135° max deviation Within Subjects

Figure 26 Straight line max deviation

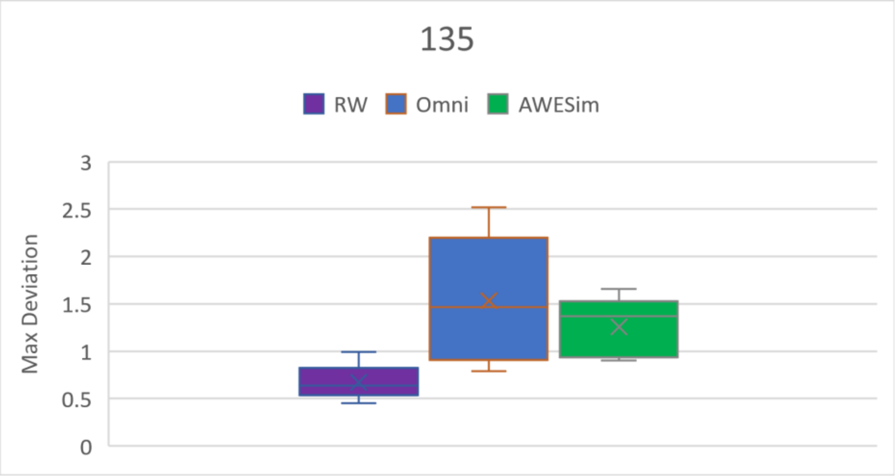


Figure 27 135° max deviation Between Subjects

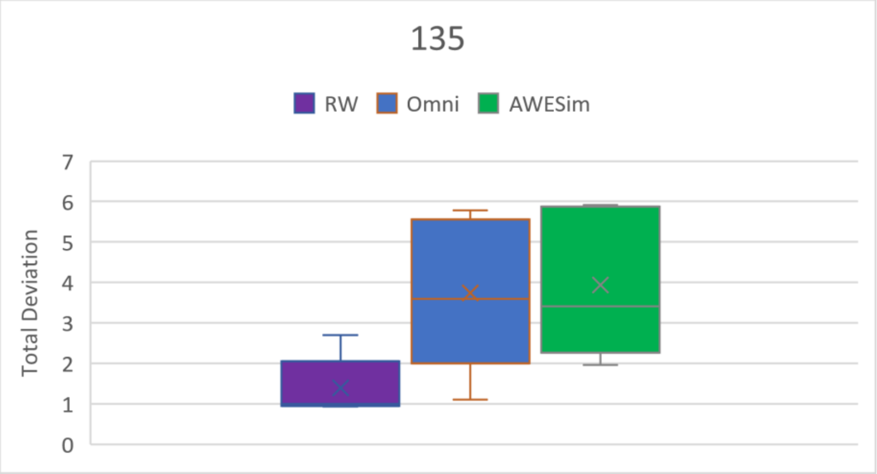


Figure 28 135° Total deviation Between Subjects

4.8.2 Wall Collisions and Speed

In the speed path task, we did not find a statistical difference between the conditions for the measure of collisions with the wall nor a statistical difference in the time taken to finish the task (Figure 29 & Figure 30). This was the consistent result across both the between-subjects and within-subjects results.

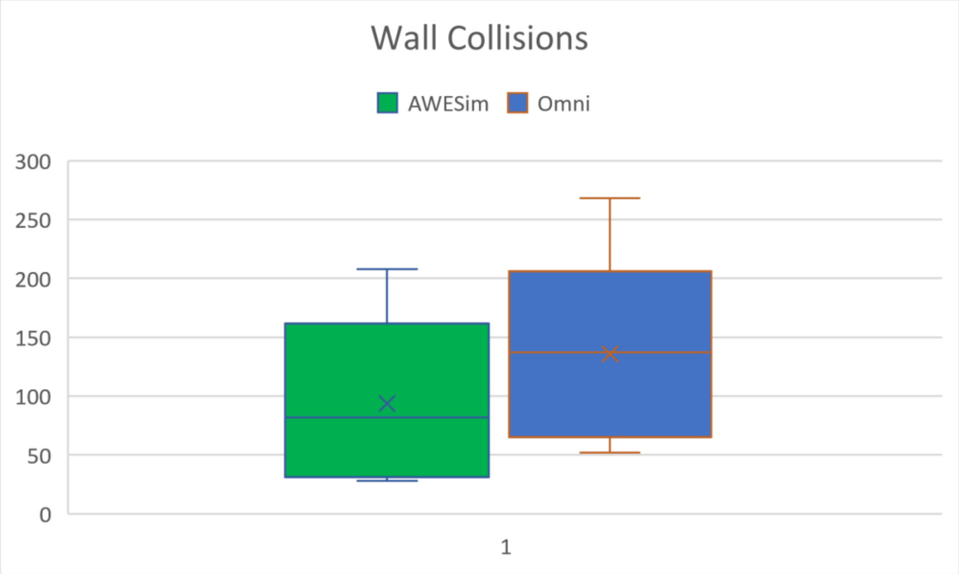


Figure 29 Wall collisions within subjects

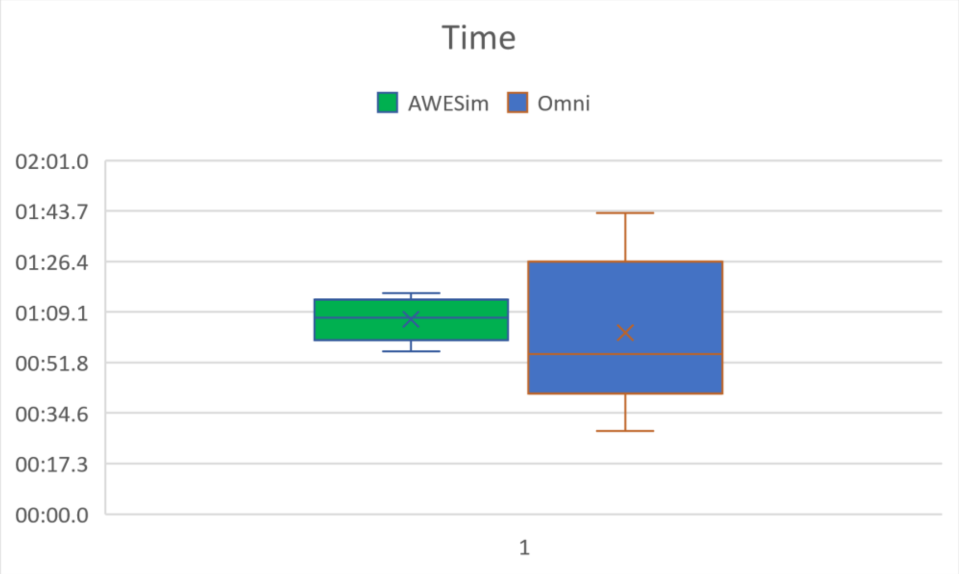


Figure 30 Time taken to complete the course within subjects

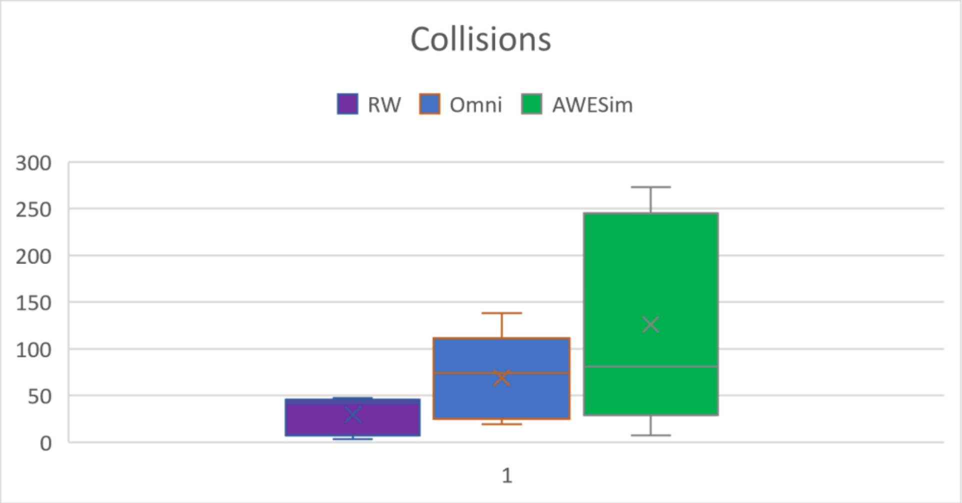


Figure 31 Collisions between subjects

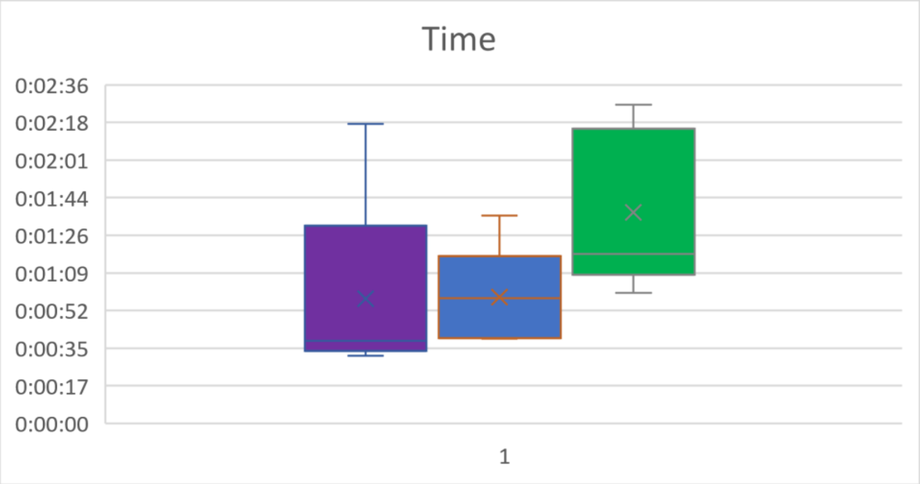


Figure 32 Time to complete course between subjects

4.8.3 Spatial Orientation

The spatial orientation task also did not reveal any significant results in the between subjects study but did find a statistical difference in the within subjects study ($p < 0.013$). Interestingly enough all of the devices had around the same level of variance in the between subjects study.

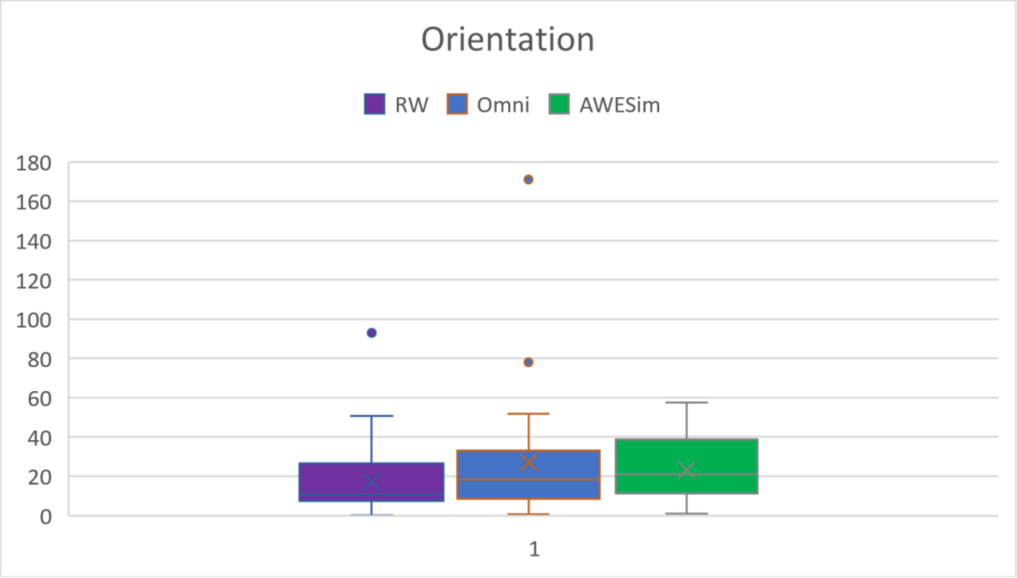


Figure 33 Spatial Orientation between subjects

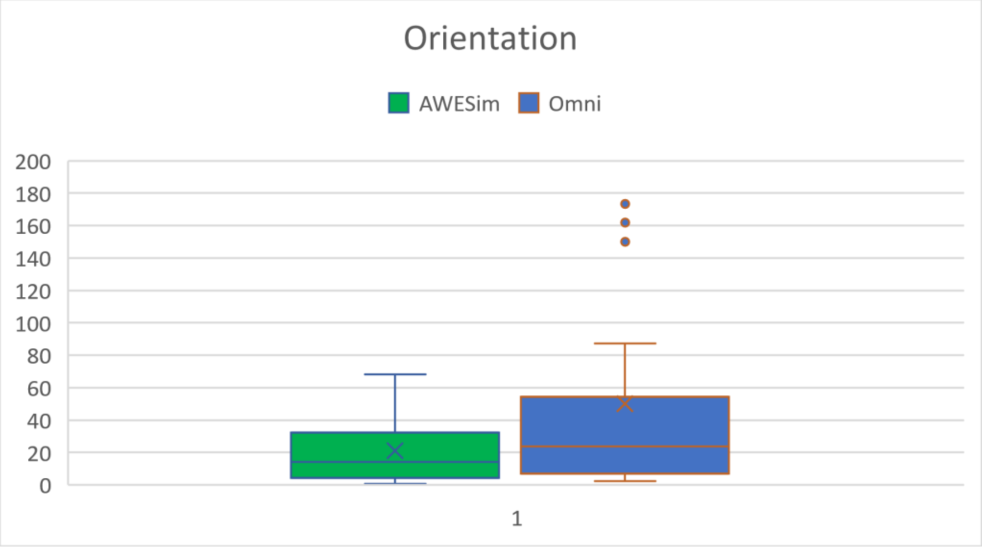


Figure 34 Spatial Orientation within subjects

4.9 Questionnaire Results

The results for the within subjects study was almost unanimous on which device they preferred to use, Omni won 4:1. The majority of the complaints about the device were about the saddle structure and the comfort of it. The limitation of the structure made the users feel uncomfortable to a point where it had a negative effect on their performance.

4.9.1 Game Experience Questionnaire (GEQ)

Tension/annoyance scored the highest significant difference in this study ($p < 0.051$) but only for the between subjects portion of the study as shown in Figure 37. There were no statistical significant differences in the user preference data for the within subjects study. There was almost significant difference in the third set of data in the area of Flow (p<0.09) which only used the simple task.

4.9.2 Simulator Sickness Questionnaire (SSQ)

For simulator sickness there was only one value which went below 0.1 which was disorientation (p<0.083) during the within subjects study. I will attribute this fact to there being no disorientation being recorded from the users during this portion of the study meanwhile the AWESim had a couple instances. The rest of the data did not have a significant difference.

4.9.3 Presence Questionnaire

There were no significant data results given during this portion of the study. We believe it is in part due to the questionnaire we selected but we will look for a better one in the future.

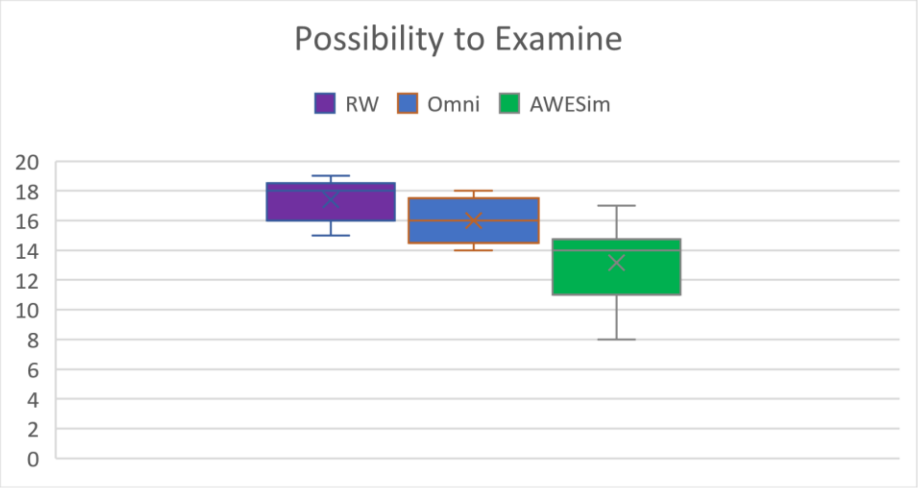


Figure 35 From Presence Questionnaire Between Subjects

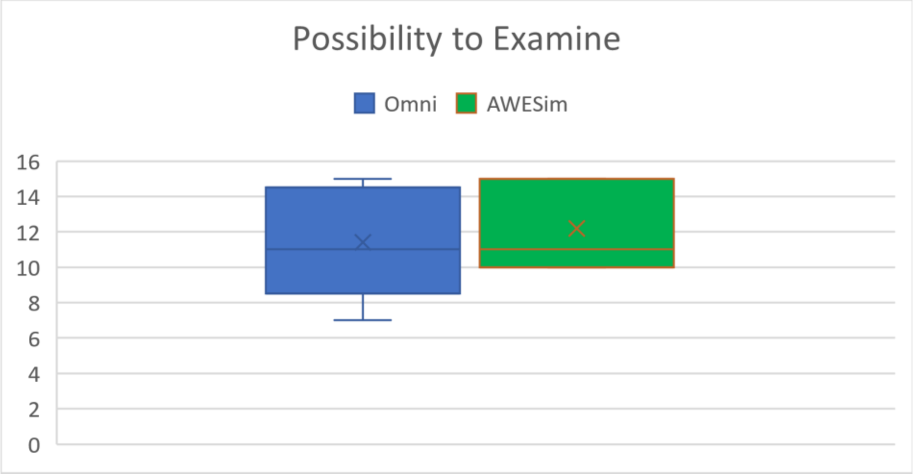


Figure 36 From Presence Questionnaire Within Subjects

4.10 Discussion

Overall, we did not find very many significant differences in the Omni and the AWESim but did find places where the real walking condition shone as the obvious winner. Two out of five participants from the observation portion of the study selected the AWESim as their favorite method of travel while two more selected the real walking condition. Only one participant during the within-subjects test selected the AWESim as the favorite even though all but four of those participants selected the AWESim as the more accurate device. The main complaint listed was discomfort involving the saddle support structure and the amount of pressure it put on sensitive areas. In addition, the crutches we placed on the device to alleviate a few pressure issues ended up creating issues for participants who did not have a long enough torso to comfortably use them. They forced shorter users to raise up their arms uncomfortably high which causes even more fatigue in the upper arm area.

There was a great deal of variance when observing the max deviation on the Omni when compared to real walking and the AWESim had instances which had consistently less variance than the Omni and was almost on par with real walking in that aspect. This suggests that the AWESim provides a more consistent experience for novice users.

The majority of complaints about the AWESim came from the construction of the saddle structure. The added movement control given the users with the AWESim was promising but seemed to be too sensitive to effectively give a user consistent results without long training sessions and careful foot motions.

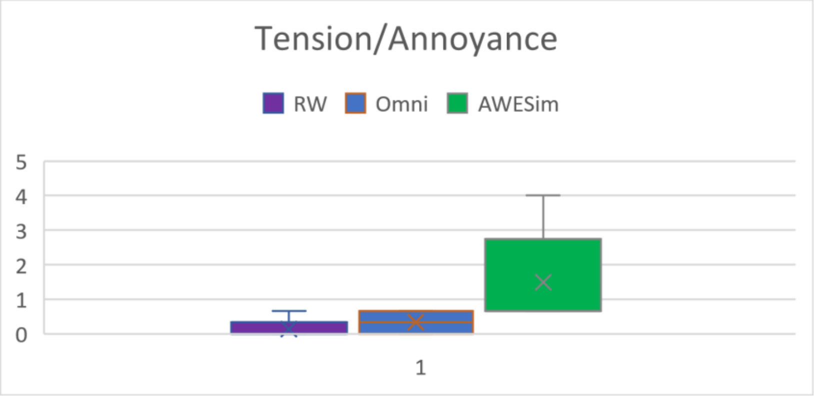


Figure 37 Between subjects tension and annoyance

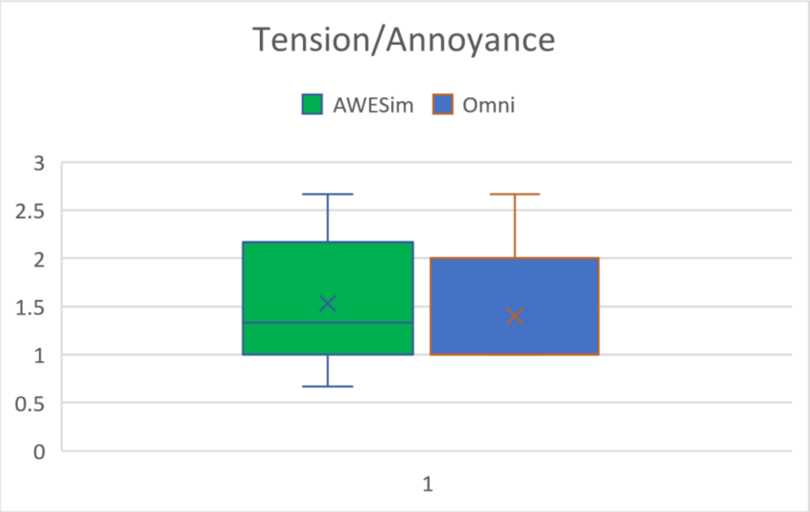


Figure 38 Within Subjects tension/annoyance

We are confident that both the Omni and the AWESim provide a much better user experience than the Virtusphere. The Omni feels more like real walking (the Virtusphere is significantly different from real walking in terms of forces), and it takes less time to "learn to walk" with the Omni. The design of the AWESim support structure prevented extended use of the device for several users. Although our FIFA analysis (section 4.3) showed that the AWESim has a higher level of interaction fidelity than the Omni, the increase in interaction fidelity is not reflected by a better overall user experience, in theory because of poor support structure design.

At the same time, there are still important differences between the AWESim and real walking. Our FIFA analysis still classifies the AWESim as a moderate fidelity technique, differing from real walking on kinetic symmetry, transfer function symmetry, termination symmetry, and slightly all aspects of system appropriateness. The position of the feet was tracked directly, and mapped directly to movement in the VE, so we feel the level of interaction fidelity much closer to real walking than the Omni, but poor design does not allow extended use and effected results.

Comparing the results with those of our previous study we can see that more testing will need to be done in order to find out if the AWESim is a definitive winner. Thus, we cannot suggest that the AWESim represents an improvement in UX design for semi-natural locomotion devices but can still conclude that even higher fidelity is needed to escape the uncanny valley due to the closeness of the relation of results from the Omni which has not escaped the either.

5 Conclusions and Future Work

The relationship between the level of interaction fidelity in a technique and its effectiveness is not a simple “more is better.” This study adds evidence to support the hypothesis that semi- natural techniques can result in an inferior user experience compared to both high-fidelity and well-designed low-fidelity techniques. At the same time, our results suggest that newer semi-natural devices with increased fidelity have the potential to climb out of the uncanny valley.

When it comes to the device we created, with a few alterations to the support structure I believe that it has the potential to be a market leader in semi-natural devices because several of the complaints about the device involved comfort and I believe this had a negative effect on user performance. The movement algorithm of the Omni does not simulate the feet so, at times, movement can be inaccurate, but the system is polished so even though it is a cumbersome device to get in, it is comfortable to be in for long periods of time.

Semi natural devices are still beneficial in many ways. They overcome space limitations, are lower cost than a large tracked area, and do not have the issues of techniques such as redirected walking while giving the feeling of walking which you cannot get with low fidelity techniques. As beneficial they may be, this study adds to the believe that they still negatively affect the user experience.

In our first study (presented in chapter 3) we compared a semi-natural technique with a non-natural technique. The non-natural technique was a game controller and the semi-natural technique was the Virtuix Omni. During this study we found evidence to support our original hypothesis and the controller performed better than the Omni on several different aspects.

In our second study (presented in chapter 4) we compared two medium fidelity techniques (the Virtuix Omni and a device of our own creation called the AWESim) in a within-subjects test and did a between-subjects study comparing the results of a high-fidelity technique and both of the semi-natural devices used in the within subjects study. From the results it seems that in the transfer function and form factor components, AWESim was actually lower fidelity than we thought. The transfer function was lower fidelity when turning (because physical turning sometimes got mapped to virtual translation) and the form factor was lower fidelity in terms of discomfort that doesn’t exist during real walking. The approach of supporting the user on a narrow seat can be very uncomfortable when one and sometimes both feet are not supporting the user’s weight on the ground when walking. The crutch support which we added to help alleviate some of the pressure coming from the saddle actually contributed to other serious issues of discomfort. These issues are not seen in the current setup of the FIFA analysis and we believe as a result of these finding, certain aspects of the analysis should be expanded.

Form factor once was a place to put any addition issues which were not listed in the other points such as new encumbering weight, sensations which normally would not be felt, places of discomfort, or anything else. We believe that form factor should be broken down into more direct categories as form factor has been realized as a significant component of the experience with a device. Even though the AWESim was seen to have more accuracy, the ergonomics issues kept it from providing a better user experience. This implies that designers of locomotion devices must make ergonomics (especially distribution of weight and methods of turning) a primary issue.

The next iteration of work I believe should be focused on adjusting the saddle structure for the AWESim and making slight adjustments to the walking algorithm to refine the motions in the perceived view. The Omni is not a device which will change much more since it is already on the market, but there is a more recent update to the software which we did not use because it is not optimized for use with the Oculus Rift. Due to the configuration of the real walking condition, the Oculus Rift had to be used so we could not have a software which was not optimized for that system. I would propose that the next step should be comparing a new variation of the AWESim with both a high fidelity and a low fidelity interaction technique until there is a clear improvement in the performance of the semi-natural interaction technique.

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Appendix A: The Game Experience Questionnaire (GEQ)

The Game Experience Questionnaire
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1. Introduction

This document contains the English version of the Game Experience Questionnaire. The development and testing of the Game Experience Questionnaire is described in project Deliverable 3.3.

The Game Experience Questionnaire has a modular structure and consists of :

1. The core questionnaire
2. The Social Presence Module
3. The Post-game module.

In addition to these modules, a concise in-game version of the GEQ was developed.

All three modules are meant to be administered immediately after the game-session has finished, in the order given above. Part one and two probe the players’ feelings and thoughts while playing the game; Part 3, the post-game module, assesses how players felt after they had stopped playing.

Part 1 is the core part of the GEQ. It assesses game experience as scores on seven components:
Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge. For a robust measure, we need five items per component. As translation of questionnaire items, no matter how carefully performed, sometimes results in suboptimal scoring patterns, we have added a spare item to all components. After the first use of the translated GEQs, scale analyses will be performed to check whether any item should be discarded or replaced.

Part 2, the social presence module, investigates psychological and behavioural involvement of the player with other social entities, be they virtual (i.e., in-game characters), mediated (e.g., others playing online), or co-located. This module should only be administered when at least one of these types of co-players were involved in the game.

Part 3, the post-game module, assesses how players felt after they had stopped playing. This is a relevant module for assessing naturalistic gaming (i.e., when gamers have voluntarily decided to play), but may also be relevant in experimental research. The In-game version of the GEQ is a concise version of the core questionnaire. It has an identical component structure and consists of items selected from this module. The in-game questionnaire is developed for assessing game experience at multiple intervals during a game session, or play-back session. This should facilitate the validation of continuous and real-time indicators some of the partners in the FUGA project are developing.

2. Game Experience Questionnaire – Core Module

Please indicate how you felt while playing the game for each of the items,
on the following scale:

not at all	slightly	moderately	fairly	extremely
<0>	<1>	<2>	<3>	<4>

1 I felt content
2 I felt skilful
3 I was interested in the game's story
4 I thought it was fun
5 I was fully occupied with the game
6 I felt happy
7 It gave me a bad mood
8 I thought about other things
9 I found it tiresome
10 I felt competent
11 I thought it was hard
12 It was aesthetically pleasing
13 I forgot everything around me
14 I felt good
15 I was good at it
16 I felt bored

17 I felt successful
18 I felt imaginative
19 I felt that I could explore things
20 I enjoyed it
21 I was fast at reaching the game's targets
22 I felt annoyed
23 I felt pressured
24 I felt irritable
25 I lost track of time
26 I felt challenged
27 I found it impressive
28 I was deeply concentrated in the game
29 I felt frustrated
30 It felt like a rich experience
31 I lost connection with the outside world
32 I felt time pressure
33 I had to put a lot of effort into it

3. In-game GEQ

Please indicate how you felt while playing the game for each of the items, on the following scale:

not at all	slightly	moderately	fairly	extremely
<0>	<1>	<2>	<3>	<4>

1 I was interested in the game's story GEQ Core – 3
2 I felt successful GEQ Core – 17
3 I felt bored GEQ Core – 16
4 I found it impressive GEQ Core – 27
5 I forgot everything around me GEQ Core – 13
6 I felt frustrated GEQ Core – 29
7 I found it tiresome GEQ Core – 9
8 I felt irritable GEQ Core – 24
9 I felt skilful GEQ Core – 2
10 I felt completely absorbed GEQ Core – 5
11 I felt content GEQ Core – 1
12 I felt challenged GEQ Core – 26
13 I had to put a lot of effort into it GEQ Core – 33
14 I felt good GEQ Core – 14

4. GEQ - Social Presence Module

Please indicate how you felt while playing the game for each of the items, on the following scale:

not at all	slightly	moderately	fairly	extremely
<0>	<1>	<2>	<3>	<4>

1 I empathized with the other(s)
2 My actions depended on the other(s) actions
3 The other's actions were dependent on my actions

4 I felt connected to the other(s)
5 The other(s) paid close attention to me
6 I paid close attention to the other(s)
7 I felt jealous about the other(s)
8 I found it enjoyable to be with the other(s)
9 When I was happy, the other(s) was(were) happy
10 When the other(s) was(were) happy, I was happy
11 I influenced the mood of the other(s)
12 I was influenced by the other(s) moods
13 I admired the other(s)
14 What the other(s) did affected what I did
15 What I did affected what the other(s) did
16 I felt revengeful
17 I felt schadenfreude (malicious delight)

5. GEQ – post-game module

Please indicate how you felt after you finished playing the game for each of the items, on the following scale:

not at all	slightly	moderately	fairly	extremely
<0>	<1>	<2>	<3>	<4>

1 I felt revived
2 I felt bad
3 I found it hard to get back to reality
4 I felt guilty
5 It felt like a victory
6 I found it a waste of time
7 I felt energised
8 I felt satisfied
9 I felt disoriented
10 I felt exhausted
11 I felt that I could have done more useful things
12 I felt powerful
13 I felt weary
14 I felt regret
15 I felt ashamed
16 I felt proud
17 I had a sense that I had returned from a journey

6. Scoring guidelines

Scoring guidelines GEQ Core Module

The Core GEQ Module consists of seven components; the items for each are listed below.

Component scores are computed as the average value of its items.

Competence: Items 2, 10, 15, 17, and 21.
Sensory and Imaginative Immersion: Items 3, 12, 18, 19, 27, and 30.
Flow: Items 5, 13, 25, 28, and 31.

Tension/Annoyance: Items 22, 24, and 29.
Challenge: Items 11, 23, 26, 32, and 33.
Negative affect: Items 7, 8, 9, and 16.
Positive affect: Items 1, 4, 6, 14, and 20.

Scoring guidelines GEQ In-Game version

The In-game Module consists of seven components, identical to the core Module. However, only two items are used for every component. The items for each are listed below.

Component scores are computed as the average value of its items.

Competence: Items 2 and 9.
Sensory and Imaginative Immersion: Items 1 and 4.
Flow: Items 5 and 10.
Tension: Items 6 and 8.
Challenge: Items 12 and 13.
Negative affect: Items 3 and 7.
Positive affect: Items 11 and 14.

Scoring guidelines GEQ Social Presence Module

The Social Presence Module consists of three components; the items for each are listed below.

Component scores are computed as the average value of its items.

Psychological Involvement – Empathy: Items 1, 4, 8, 9, 10, and 13.
Psychological Involvement – Negative Feelings: Items 7, 11, 12, 16, and 17.
Behavioural Involvement: Items 2, 3, 5, 6, 14, and 15.

Scoring guidelines GEQ Post-game Module

The post-game Module consists of four components; the items for each are listed below.

Component scores are computed as the average value of its items.

Positive Experience: Items 1, 5, 7, 8, 12, 16.
Negative experience: Items 2, 4, 6, 11, 14, 15.
Tiredness: Items 10, 13.
Returning to Reality: Items 3, 9, and 17.

Appendix B: Simulator Sickness Questionnaire (SSQ)

SIMULATOR SICKNESS QUESTIONNAIRE
Kennedy, Lane, Berbaum, & Lilienthal (1993) ***
Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort
None Slight Moderate Severe
2. Fatigue
None Slight Moderate Severe
3. Headache
None Slight Moderate Severe
4. Eye strain
None Slight Moderate Severe
5. Difficulty focusing
None Slight Moderate Severe

6. Salivation increasing

None Slight Moderate Severe

7. Sweating

None Slight Moderate Severe

8. Nausea

None Slight Moderate Severe

9. Difficulty concentrating

None Slight Moderate Severe

10. « Fullness of the Head »

None Slight Moderate Severe

11. Blurred vision

None Slight Moderate Severe

12. Dizziness with eyes open

None Slight Moderate Severe

13. Dizziness with eyes closed

None Slight Moderate Severe

14. *Vertigo

None Slight Moderate Severe

15. **Stomach awareness

None Slight Moderate Severe

16. Burping

None Slight Moderate Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version: March 2013

***Original version: Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

Simulator Sickness Questionnaire***

Kennedy, Lane, Berbaum, & Lilienthal (1993) ***

Validation of the French-Canadian version of the SSQ developed by the UQO Cyberpsychology Lab:

Total: items 1 to 16 (scale of 0 to 3).

« Nausea »: items 1 + 6 + 7 + 8 + 12 + 13 + 14 + 15 + 16.

« Oculo-motor »: items 2 + 3 + 4 + 5 + 9 + 10 + 11.

Appendix C: Presence Questionnaire (PQ)

PRESENCE QUESTIONNAIRE

(Witmer & Singer, Vs. 3.0, Nov. 1994)*

Revised by the UQO Cyberpsychology Lab (2004)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?
|________|________|________|________|________|________|________|
NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?
|________|________|________|________|________|________|________|
EXTREMELY BORDERLINE COMPLETELY ARTIFICIAL NATURAL

4. How much did the visual aspects of the environment involve you?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?
|________|________|________|________|________|________|________|
EXTREMELY BORDERLINE COMPLETELY ARTIFICIAL NATURAL

6. How compelling was your sense of objects moving through space?
|________|________|________|________|________|________|________|
NOT AT ALL MODERATELY COMPELLING VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?
|________|________|________|________|________|________|________|
NOT CONSISTENT MODERATELY CONSISTENT VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?
|________|________|________|________|________|________|________|
NOT COMPELLING MODERATELY COMPELLING VERY COMPELLING

11. How closely were you able to examine objects?
|________|________|________|________|________|________|________|

NOT AT ALL PRETTY CLOSELY VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT EXTENSIVELY

13. How involved were you in the virtual environment experience?
|________|________|________|________|________|________|________|
NOT INVOLVED MILDLY ENGROSSED COMPLETELY INVOLVED

14. How much delay did you experience between your actions and expected outcomes?
|________|________|________|________|________|________|________|
NO DELAYS MODERATE DELAYS LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?
|________|________|________|________|________|________|________|
NOT AT ALL SLOWLY LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
|________|________|________|________|________|________|________|
NOT PROFICIENT REASONABLY PROFICIENT VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
|________|________|________|________|________|________|________|
NOT AT ALL INTERFERED SOMEWHAT PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?
|________|________|________|________|________|________|________|
NOT AT ALL INTERFERED SOMEWHAT INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED SOUNDS:
20. How much did the auditory aspects of the environment involve you?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

21. How well could you identify sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

22. How well could you localize sounds?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED HAPTIC (SENSE OF TOUCH):
23. How well could you actively survey or search the virtual environment using touch?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

24. How well could you move or manipulate objects in the virtual environment?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT EXTENSIVELY

Scoring:
Total: Items 1 to 19 (reverse items 14, 17, 18)
□ « Realism »: Items 3 + 4 + 5 + 6 + 7 + 10 + 13
□ « Possibility to act »: Items 1 + 2 + 8 + 9
□ « Quality of interface »: Items (all reversed) 14 + 17 + 18
□ « Possibility to examine »: Items 11 + 12 + 19
□ « Self-evaluation of performance »: Items 15 + 16
□ « Sounds* »: Items 20 + 21 + 22
□ « Haptic* »: Items 23 + 24