How Does Interaction Fidelity Influence User Experience in VR Locomotion?

Mahdi Nabiyouni

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Doug A. Bowman, Chair
Tobias Höllerer
Chris L. North
Denis Gracanin
Nicholas F. Polys

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Abstract

It is often assumed that more realism is always desirable. In particular, many techniques for locomotion in Virtual Reality (VR) attempt to approximate real-world walking. However, it is not yet fully understood how the design of more realistic locomotion techniques influences effectiveness and user experience. In the previous VR studies, the effects of interaction fidelity have been coarse-grained, considering interaction fidelity as a single construct. We argue that interaction fidelity consists of various independent components, and each component can have a different effect on the effectiveness of the interface. Moreover, the designer's intent can influence the effectiveness of an interface and needs to be considered in the design. Semi-natural locomotion interfaces can be difficult to use at first, due to a lack of interaction fidelity, and effective training would help users understand the forces they were feeling and better control their movements. Another method to improve locomotion interaction is to develop a more effective interface or improve the existing techniques. A detailed taxonomy of walking-based locomotion techniques would be beneficial to better understand, analyze, and design walking techniques for VR.

We conducted four user studies and performed a meta-analysis on the literature to have a more in-depth understanding of the effects of interaction fidelity on effectiveness. We found that for the measures dependent on proprioceptive sensory information, such as orientation estimation, cognitive load, and sense of presence, the level of effectiveness increases with increasing levels of interaction fidelity. Other measures which depend more on the ease of learning and ease of use, such as completion time, movement accuracy, and subjective evaluation, form a u-shape uncanny valley. For such measures, moderate-fidelity interfaces are often outperformed by low- and high-fidelity interfaces.

In our third user study, we further investigated the effects of components of interaction fidelity, biomechanics and transfer function, as well as designers' intent. We learned that the biomechanics of walking are more sensitive to changes and that the effects of these changes were mostly negative for hyper-natural techniques. Changes in the transfer function component were easier for the user to learn and to adapt to. Suitable transfer functions were able to improve some locomotion features but at the cost of accuracy.

To improve the level of effectiveness in moderate-fidelity locomotion interfaces we employed an effective training method. We learned that providing a visual cue during the acclimation phase can help users better understand their walking in moderate-fidelity interfaces and improve their effectiveness. To develop a design space and classification of locomotion techniques, we designed a taxonomy for walking- based locomotion techniques. With this taxonomy, we extract and discuss various characteristics of locomotion interaction. Researchers can create novel locomotion techniques by making choices from the components of this taxonomy, they can analyze and improve existing techniques, or perform experiments to evaluate locomotion techniques in detail using the presented organization. As an example of using this taxonomy, we developed a novel locomotion interface by choosing a new combination of characteristics from the taxonomy.

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General Audience Abstract

Virtual Reality researchers have been trying to develop natural travel techniques to allow users to physically walk and move in virtual environments rather than using unnatural methods such as joysticks. Using such techniques, the user can physically move or perform actions similar to walking to navigate through virtual environments. More natural travel methods can improve various parameters such as sense of presence and spatial understanding. However, the effects of increasing naturalness of walking on the user experience have not been known for years.

In this dissertation, we have run four user experiments, performed a meta-analysis on the literature and developed a taxonomy to contribute a better understanding of how increasing levels of walking naturalness can affect user experience in Virtual Reality. Our findings can benefit designers and researchers in designing novel travel techniques, improve existing techniques or more in-depth understating of what to expect when employing a certain travel technique.

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1 Introduction

One of the goals of much virtual reality research is to increase realism. It is often assumed that more realism or immersion is better and will lead to greater effectiveness, where effectiveness is defined as "producing a result that is wanted" or "having an intended effect" (Merriam-Webster 2004) and is measured in VR by performance, usability or user satisfaction. Immersive VR replaces real-world sensory information with computer-generated stimuli such as 3D imagery, 3D interaction, haptic feedback and spatial sound. Realistic VR aims to allow users to experience a synthetic world as if it is real and to produce a sense of presence in the user's mind (Bowman and McMahan 2007). In particular, many techniques for travel in VR attempt to approximate real-world walking. VR research has shown that immersive systems in general and realistic interfaces in particular have more to offer than just an impressive and realistic demonstration. Such interfaces can improve the results in practical applications, which makes them compelling and universally sought after. Realistic interfaces have been studied for years for various tasks such as selection, manipulation, wayfinding, travel, and system control. Travel, and particularly locomotion –walking based travel–, is often a secondary and base task that enables the user to control the view point and allow her to perform other types of tasks.

Locomotion with high fidelity can provide the user with better proprioceptive cues, enhance distance judgment, and increase the sense of presence (Hollerbach 2002). However, it is not yet fully understood how the design of more realistic locomotion techniques affects user task performance and user experience. Moreover, higher fidelity typically implies higher cost and more design limitations, and there are success stories of applications with lower levels of realism. Thus, understanding the comparative levels of effectiveness and subjective preference for locomotion interfaces with different levels of fidelity is an important research topic in VR.

Designers may need to reduce the level of realism to overcome various limitations. In most VEs, real walking throughout the entire space is infeasible, due to limited size of the tracked space. Devices such as omni-directional treadmills (Darken, Cockayne et al. 1997, Iwata 1999), stepping systems (Hollerbach, Xu et al. 2000, Iwata, Yano et al. 2001, Iwata, Yano et al. 2005), rolling spheres (Fernandes, Raja et al. 2003, Latypov 2006) and sliding-in-place surfaces (Iwata and Fuji 1996, Suryajaya, Lambert et al. 2009, Goetgeluk 2013), as well as techniques such as walking-in-place (Usoh, Arthur et al. 1999, Feasel, Whitton et al. 2008), human joystick (Li 2001, McMahan, Bowman et al. 2012), and redirected walking (Razzaque, Kohn et al. 2001, Razzaque 2005) are designed to simulate real-world walking to varying degrees, with the idea that users will be able to leverage their real-world experiences and skills to move through a virtual environment (VE) effectively. However, such devices and techniques are "semi-natural" and do not provide a highly natural walking experience to the user. This can also apply to interactions other than locomotion. Using such semi-natural interfaces, users' actions are different from the real-world actions, and such interfaces often have lower effectiveness comparing to the natural counterparts (Sibert, Templeman et al. 2008, McMahan 2011, Marsh, Putnam et al. 2012, McMahan, Bowman et al. 2012, McEwan, Blackler et al. 2014, McMahan, Lai et al. 2016, Yan, Lindeman et al. 2016).

As an example, The Virtusphere (Latypov 2006), one such device, is a large hollow sphere mounted on casters, in which a user wearing a head-mounted display (HMD) can walk in any direction to move through a VE. The Virtusphere is similar to a human-sized “hamster ball,” and while it offers unlimited movement through a VE of any size, it can also be difficult for users to control and use. Although the walking motion seems natural in the Virtusphere, the inertia of the sphere makes it difficult for the user to start walking and the momentum will cause the user to struggle to turn or stop. Moreover, the curved surface does not provide same feeling as walking on a flat surface. Many other semi-natural locomotion interfaces, including the examples mentioned above, similarly have problems with usability and naturalness.

The reason behind the relatively low effectiveness of the semi-natural interfaces is still an open question for VR researchers. By far, there is no effective and realistic locomotion technique available in VR, which allows exploring unlimited or large VEs. Researchers are yet to find a general solution for natural locomotion in VR. Any effort to more clearly understand this issue can benefit the design and development of immersive interfaces and help to provide realistic and natural methods for locomotion in VR.

1.1 Definitions

Fidelity: the degree to which a system accurately reproduces a real-world experience and its effects (Gerathewohl 1969).

Display Fidelity: the objective degree of exactness with which a system reproduces real-world sensory stimuli (sensory realism) (McMahan 2011).

Interaction fidelity: the objective degree of exactness with which a system reproduces real world interactions (action realism) (McMahan 2011).

Travel: the act of controlling the user’s viewpoint in the three dimensional environment (Bowman, Koller et al. 1998).

Locomotion: repetitive limb motion, or gait, resulting in self-propulsion, which controls motion through the VE (Hollerbach 2002).

Effectiveness: producing a result that is wanted; having an intended effect (Merriam-Webster 2004). Measured in VR by task performance, usability, or user satisfaction.

Immersion: immersion is a multi-dimensional continuum and a combination of many components such as field of view (FOV), field of regard (FOR), display size, display resolution, stereoscopy, head-based rendering, etc. (Bowman and McMahan 2007).

Components of interaction fidelity: Different aspects of interaction fidelity which in combination produce the level of interaction fidelity for an interface. Interaction consists of many components such as head tracking, kinetic symmetry, kinematic symmetry, anthropometric symmetry, transfer function, input precision and accuracy, etc. (McMahan 2011).

1.2 Fidelity

As defined by Gerathewohl (Gerathewohl 1969), *fidelity* is the degree to which a system accurately reproduces a real-world experience and its effects. Fidelity has several distinct aspects, including display fidelity and interaction fidelity (Bowman, McMahan et al. 2012). *Display fidelity* is defined as the objective degree of exactness with which a system reproduces real-world sensory stimuli (McMahan 2011). Researchers have reported positive effects of increasing display fidelity on various parameters of effectiveness (Ruddle, Payne et al. 1999, Bowman and McMahan 2007). However, the effects of interaction fidelity are not as clear.

Interaction fidelity is defined as the objective degree of exactness with which a system reproduces real world interactions (McMahan 2011). Increasing interaction fidelity has been shown, in some cases, to increase effectiveness (Hinckley, Tullio et al. 1997, Pausch, Proffitt et al. 1997, McMahan, Bowman et al. 2012). For example, manipulation techniques based on six-degree-of-freedom input devices outperformed techniques based on two-degree-of-freedom mice (Hinckley, Tullio et al. 1997). However, there are also studies with the opposite result, in which lower-fidelity techniques for travel or locomotion outperformed higher-fidelity techniques (McMahan, Alon et al. 2010, McMahan, Bowman et al. 2012) (Sibert, Templeman et al. 2008, Marsh, Putnam et al. 2012, McEwan, Blackler et al. 2014, McMahan, Lai et al. 2016, Yan, Lindeman et al. 2016). For example, "natural" interaction techniques for driving a vehicle in a racing game were significantly less effective than low-fidelity ones (McMahan, Alon et al. 2010).

Although higher fidelity, in general, is believed to improve effectiveness (e.g., because it increases the sense of presence, it provides better proprioceptive cues, or it results in greater spatial awareness (Hollerbach 2002)), there is also evidence that semi-natural techniques can reduce effectiveness compared to completely non-natural interfaces (McMahan, Alon et al. 2010, McMahan, Bowman et al. 2012) (Sibert, Templeman et al. 2008, Marsh, Putnam et al. 2012, McEwan, Blackler et al. 2014, McMahan, Lai et al. 2016, Yan, Lindeman et al. 2016).

1.3 Components of Interaction Fidelity

In most of the previous studies, fidelity has been coarse-grained, considering interaction fidelity as a single construct. It has been argued that interaction fidelity consists of various independent components, described in the Framework for Interaction Fidelity Analysis (FIFA) (McMahan 2011). FIFA has been recently updated (McMahan, Lai et al. 2016) to capture the components of interaction fidelity more accurately.

Each component of fidelity can have a different level of fidelity and fall in a different location on the fidelity continuum. FIFA allows us to compare interaction techniques and where they fall on the fidelity spectrum. FIFA can be employed to better understand differences among different interfaces. FIFA describes interaction fidelity using three primary factors: biomechanical symmetry, control symmetry, and system appropriateness.

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. Sub-components of biomechanical symmetry include kinematic, kinetic, and anthropometric symmetry.

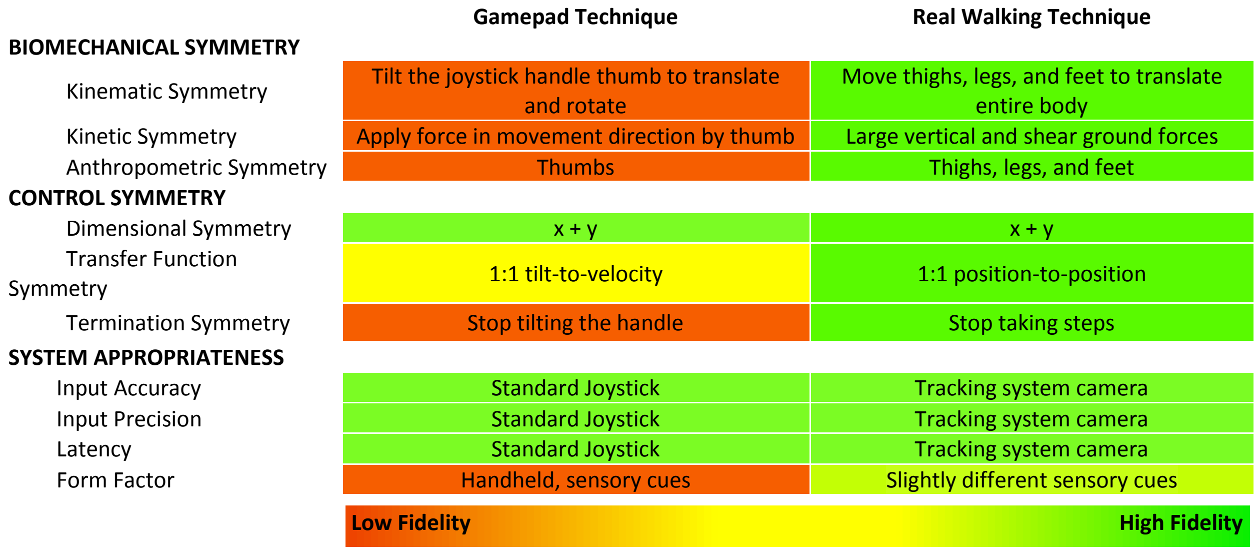
Kinematics is concerned with body motions or trajectories; kinetics refers to the forces applied to cause body movements; and anthropometry considers which body parts are used.

Control symmetry describes how the control provided through the interaction technique compares to control in the real-world task. It also has three sub-components: dimensional symmetry, transfer function symmetry, and termination symmetry. Dimensional symmetry considers the similarity between the control dimensions in a real-world task and those in an interaction technique. Transfer function symmetry refers to how interaction techniques interpret and transform input data into an output effect. Termination symmetry is concerned with how the interaction is stopped. Although not included in the original FIFA publication, we also consider initiation symmetry, relating to how the interaction is begun.

System appropriateness characterizes the suitability of the system for performing a particular aspect of the interaction, and includes four factors: input accuracy, input precision, latency, and form factor. The FIFA framework has been used to determine and compare levels of fidelity for different locomotion interfaces (Nabiyouni, Saktheeswaran et al. 2015).

Table1.1 compares a high-fidelity locomotion technique, real walking, with a low-fidelity technique, gamepad. The green color indicates high level of interaction fidelity for each specific component, the yellow color signifies a medium level of fidelity, and the orange color indicates low fidelity.

Table1.1 – Analyzing interaction fidelity for locomotion interaction techniques



	Gamepad Technique	**Real Walking Technique**
BIOMECHANICAL SYMMETRY		
Kinematic Symmetry	Tilt the joystick handle thumb to translate and rotate	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
CONTROL SYMMETRY		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-velocity	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
SYSTEM APPROPRIATENESS		
Input Accuracy	Standard Joystick	Tracking system camera
Input Precision	Standard Joystick	Tracking system camera
Latency	Standard Joystick	Tracking system camera
Form Factor	Handheld, sensory cues	Slightly different sensory cues

Low Fidelity **High Fidelity**

1.4 Design Approaches

Designers can consider various approaches to design 3D interaction based on human natural actions. The first approach is designing highly natural interfaces. Such interfaces mimic the real world actions as closely as possible and have high levels of interaction fidelity. Such interfaces provide high immersion, however, such methods often have physical limitations. As an example, highly natural locomotion methods such as real walking (Usoh, Arthur et al. 1999), physically limit the user to a tracked space and only allow users to explore a VE of similar size. Therefore, the user will not be able to explore large or unlimited VEs.

For the second approach, semi-natural interfaces are designed to overcome some physical limitations. Such interfaces have lower levels of interaction fidelity compared to natural interfaces. Although semi-natural designs try to be as close to natural interactions as possible, they often make compromises in terms of naturalness in order to reduce the limitations of natural interfaces. For example, interfaces such as Virtusphere (Latypov 2006), Omni Directional Treadmills (ODT) (Darken, Cockayne et al. 1997, Iwata 1999) or Virtuix Omni (Goetgeluk 2013) mimic real world walking movements. However, the forces applied while walking are necessarily different from real walking and can disturb the users' balance or change the way they walk. As a result, such interfaces might not be as effective as natural interfaces. Nonetheless they can allow exploring a large or unlimited VE. Therefore, semi-natural techniques can even disturb the user's real-world abilities to improve specific limitations.

Designers may therefore consider a third approach: enhancing users' real-world abilities with a hyper-natural interaction technique (Bowman, McMahan et al. 2012). For example, the Seven League Boots technique (Interrante, O'Rourke et al. 2007, Interrante, Ries et al. 2007) dynamically scales real walking movements so that the user can virtually walk great distances even in a small tracking workspace. Hyper-natural techniques use natural metaphors to extend users' interaction abilities (Bowman, McMahan et al. 2012), so while they have moderate interaction fidelity, like the semi-natural techniques described above, the "reduction" in fidelity is intentionally designed to enhance the interaction and improve effectiveness.

Evaluations of hyper-natural techniques have often shown that they outperform their natural counterparts (Poupyrev, Billinghurst et al. 1996, Interrante, Ries et al. 2007, Bowman, McMahan et al. 2012). However, these evaluations typically include only a few metrics, and the methods could possibly be detrimental to task performance in other ways. For example, a technique like Seven League Boots may reduce spatial orientation in users due to the mismatch between visual and proprioceptive cues (Hollerbach 2002). A deep understanding of hyper-natural techniques requires a thorough evaluation of a variety of performance metrics.

Finally, as the fourth approach, designers can make the choice to reject the real-world metaphor altogether and design a non-natural interaction technique with low levels of interaction fidelity. This could take the form of a technique in which the designer simply determines an efficient mapping between the input and desired output actions, such as the joystick or keyboard controls used in many video games. With non-natural techniques designers intend to provide virtual actions similar to the real world (e.g., walking) while the interaction method is far from the corresponding real world action (e.g., employing a gamepad (Feasel, Whitton et al. 2008)). On the other hand, designers can create super-natural techniques that go far beyond reality to provide users with unrealistic superpowers. In super-natural techniques, the designer typically puts a "story" around the technique and provides the user with abilities beyond real-world actions (e.g., teleportation (Wolpaw 2011, Freitag, Rausch et al. 2014)) while the corresponding physical action is not natural. In both the non-natural and super-natural approaches, developers have tremendous freedom to design effective techniques without the constraints of the real world. We summarize these approaches to VR interaction technique design in Figure 1.1.

In Figure 1.1, the interaction fidelity axis spans the interaction fidelity spectrum from low to high. Input flexibility indicates input (the actions that the user provides) design degree of freedom. Output flexibility indicates output (the response actions that occur in the VE) degree of freedom. Each bubble depicts a specific design approach and the size of the bubble implies the amount of freedom on each axis.

It is critical to understand the designer's intent for the interaction techniques. As shown in Figure 1.1, natural techniques are highly realistic and try to mimic the real world as closely as possible. Being natural adds a large amount of constraints and natural techniques do not leave room for much freedom on the input or output side, due to mimicking the read-world actions closely with respect to input and simulating adds a large amount of constraints and natural techniques do not leave room for much freedom on the input or output side, due to mimicking the read-world actions closely with respect to input and simulating the real-world motions in the VE regarding output (e.g., real-walking technique (Usoh, Arthur et al. 1999)).

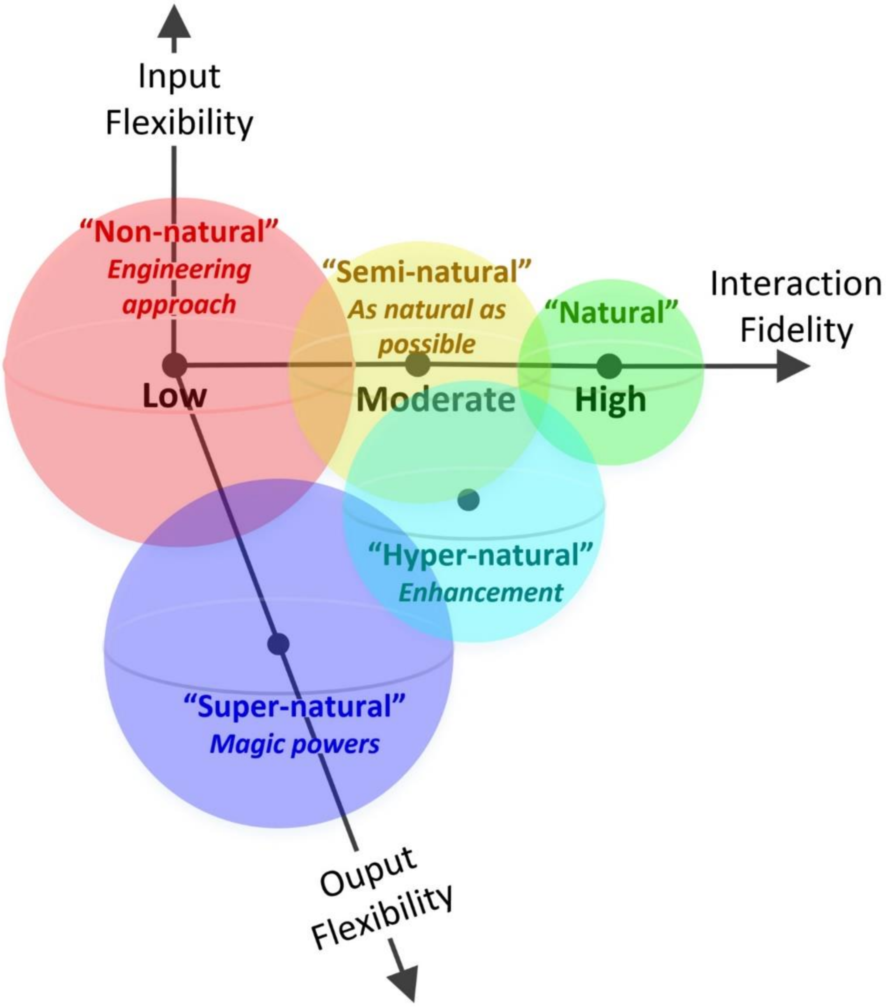


Figure1.1 – VR interaction technique design approaches

The semi-natural and non-natural techniques strive for a natural mapping but fall short due to limitations of technology/space, or reject naturalism and go for an effective but arbitrary mapping. For semi-natural interfaces, the input might be different from real-world actions by some degree, however the output closely simulates natural motions in the VE (e.g., omnidirectional treadmill (Darken, Cockayne et al. 1997), Virtusphere (Latypov 2006)). Non-natural interfaces provide high level of freedom on the input method design, while on the output they simulate the real-world motions closely (e.g., gamepad (Yan, Lindeman et al. 2016), desktop joystick (Sibert, Templeman et al. 2008)).

Hyper-natural and super-natural techniques, try to create a new reality that is better than or completely different from physical reality. Such techniques, change the natural interaction intentionally to provide users with enhancements or compensate for natural human body limitations. Hyper-natural techniques provide enhancements to the real-world abilities in the VE and have some freedom on the input design (e.g., Seven-League Boots (Interrante, Ries et al. 2007), Go-Go technique (Poupyrev, Billinghurst et al. 1996)), while super-natural techniques provide magic powers and abilities to the user in the VE and allow for high levels of freedom regarding input design (e.g., flying (Usoh, Arthur et al. 1999)).

1.5 Problem Statement

Although semi-natural locomotion techniques tend to be as close to real walking as possible, nonetheless they often unavoidably compromise naturalness to keep users inside the boundaries of the physical space, while enabling them to explore a large VE. It is not yet fully understood how the design of semi-natural locomotion techniques influences effectiveness. Based on the literature, we speculate that semi-natural locomotion techniques will often have performance inferior to both natural and non-natural techniques (McMahan, Alon et al. 2010, McMahan, Bowman et al. 2012) (Sibert, Templeman et al. 2008, Marsh, Putnam et al. 2012, McEwan, Blackler et al. 2014, McMahan, Lai et al. 2016, Yan, Lindeman et al. 2016). As a result, mental workload may increase, users may lose balance, get disoriented, or have simulator sickness (Medina, Fruland et al. 2008, McMahan, Alon et al. 2010, McMahan 2011, Marsh, Putnam et al. 2012, McMahan, Bowman et al. 2012, Marsh, Hantel et al. 2013, Skopp, Smolenski et al. 2014). Finding more evidence for this hypothesis will help us understand if such results are a general effect of interaction fidelity.

Researchers have identified that it is not essential to just go for naturalism, rather it is possible to enhance the user’s abilities in the VE with hyper- or super-natural techniques. However, the effects of hyper- and super-natural approaches on the effectiveness of locomotion are not yet clear.

A better understanding of the effects of interaction fidelity on effectiveness will assist designers to improve semi-natural interfaces or to design novel techniques with higher levels of effectiveness. Previous studies often consider interaction fidelity as a single construct and discuss it holistically. Based on the FIFA framework (McMahan 2011), interaction fidelity consists of several components. These components might have independent or correlated effects on the effectiveness. Studying the effects of individual components of fidelity in a more fine-grained manner can provide us with a deeper understanding of the effects of interaction fidelity.

Using interfaces that are not natural is often not intuitive, rather, users must acclimate to the interface before they can use it effectively. Designing quick and effective acclimation procedures for semi-natural locomotion interfaces can make them more usable and provide a better experience to the user (Marsh, Hantel et al. 2013). However, this is not the only way to improve less-than-natural interaction.

Designers may as well consider improving an interface or designing a novel interface based on various characteristics of locomotion interaction. For this purpose, a thorough taxonomy of locomotion can help designers better understand the effects of each characteristic of locomotion and help them in the decision making process for making design choices. We demonstrate this process by designing a novel locomotion interface which aims for higher level of effectiveness compared to existing interfaces.

1.6 Research Questions and Hypothesis

RQ1. How does the effectiveness of locomotion techniques change at varying levels of fidelity? Does increasing interaction fidelity "guarantee" increase in effectiveness?

It is important to understand the relationship between interaction fidelity and effectiveness to predict the result of an interface design and to contribute to designing more effective and usable interfaces. We would like to further investigate the hypothesis that high- and well-designed low-fidelity interfaces have superior effectiveness compared to interfaces with a medium level of fidelity. Additionally, we would like to further study the effectiveness of well-designed low-fidelity interfaces and investigate if the effectiveness of these interfaces depends on the task and the measure.

We theorize that high-fidelity interaction techniques will outperform medium-fidelity interfaces such as Virtusphere, and that low-fidelity standard interfaces can outperform medium-fidelity interfaces for certain tasks and measures. Semi-natural techniques will have lower effectiveness due to the illusion of realistic walking. This forms an uncanny valley indicated in Figure 1.2. Our hypothesis is illustrated by a curve relating interaction fidelity to effectiveness as shown in Figure 1.2. Different locomotion interfaces need to be studied to provide further evidence in regard to this hypothesis. We acknowledge that a low level of effectiveness can also be a result of very low-fidelity interfaces, which may include performing irrelevant actions and metaphors for virtual interactions (e.g., rubbing one's head to navigate). Moreover, moderate-fidelity interfaces might suffer from using poor design principles and thus have low effectiveness. On the other hand, a high-fidelity design

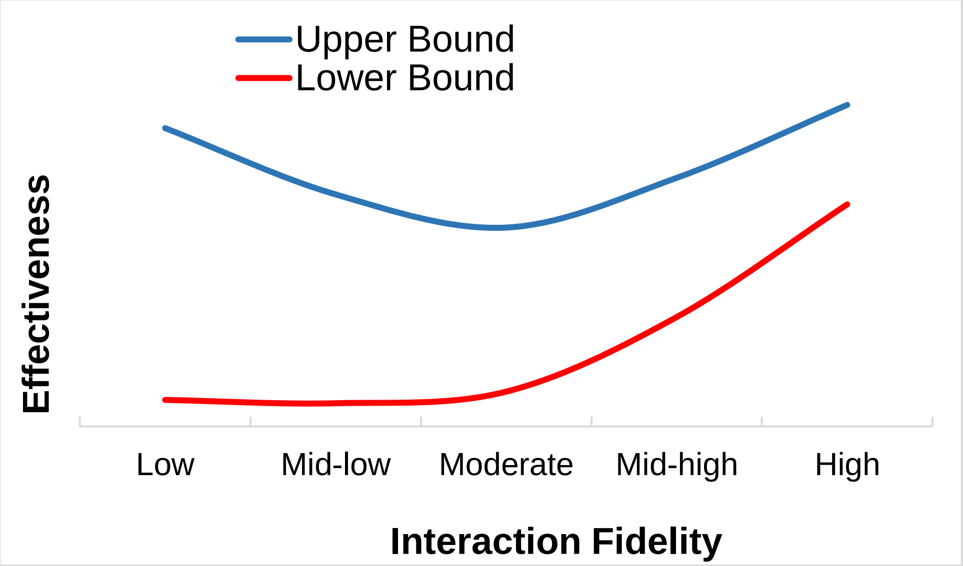


Figure 1.2 –Illustrative diagrams of the hypothesized relationship between Interaction Fidelity and Effectiveness

will always be reasonably effective, due to close imitation of real world actions. We believe that the uncanny valley graph shown in Figure 1.2 is only valid for the “non-natural,” “semi-natural,” and “natural” design approaches (Figure 1.1), and that it does not apply for hyper- and super-natural approaches.

This hypothesis is conceptual rather than quantitative. The curves in Figure 1.2 are not intended to make any prediction about absolute value of performance and the height of the curves and the distance between the curves is not meant to be meaningful. Our overall hypothesis consists of three main parts:

1. High interaction fidelity almost always leads to high level of effectiveness.
2. Moderate levels of interaction fidelity do not typically achieve high levels of effectiveness.
3. The effectiveness of the low-interaction fidelity techniques depends on the task and measurements, and on the way effectiveness is defined.

RQ2. How do various components of interaction fidelity impact the effectiveness of interaction techniques?

Among the different components described in Section 1.3, we chose to study biomechanics holistically, because its sub-components are tightly bound together for locomotion. Similarly, transfer function symmetry should be studied because of its importance in technique design (e.g., both the redirected walking (Razzaque, Kohn et al. 2001) or Seven League Boots (Interrante, Ries et al. 2007) techniques manipulate the transfer function). System appropriateness mostly depends on the system specifications, so we will use the most suitable systems available and we will aim to keep system appropriateness levels constant in all of the experiment conditions. We expect changing biomechanics symmetry to have some detrimental effects on the effectiveness. We also hypothesize that users will be able to adapt more easily to changing transfer functions, since this has been previously shown for various manipulation techniques.

RQ3. What is the effect of hyper-naturalism on the effectiveness of locomotion techniques?

Hyper-natural techniques, like semi-natural techniques, change the way users naturally interact. For example, the redirected walking (Razzaque, Kohn et al. 2001) or Seven League Boots (Interrante, Ries et al. 2007) techniques both manipulate the transfer function with different designer’s intent. Broadly, with this question, our goal is to understand how hyper-natural techniques influence the effectiveness. Although hyper-natural techniques are known to have positive effects on some effectiveness metrics for certain tasks, this may not be true in all situations. Moreover, different components of fidelity can have different effects on the effectiveness of an interface. The effects of low levels of biomechanical symmetry and transfer function symmetry in both semi-natural and hyper-natural techniques (Figure 1.1) needs to be studied to reveal any possible differences based on the designer’s intent.

Since the intent of hyper-natural techniques is to enhance the user's abilities, they may improve effectiveness for some specific metrics. However, since they change the way users naturally interact, they may negatively affect some other effectiveness metrics. For example, we expect the scaling in Seven League Boots to have a detrimental effect on accuracy in difficult path-following tasks.

RQ4. How can we improve the level of effectiveness in moderate fidelity locomotion interfaces?

Semi-natural locomotion interfaces are often not as effective and easy to use as real walking. Since such locomotion interfaces are not standard and common interfaces and typically users are not familiar with them, acclimating the user to perform gait in such devices is necessary. However, it is not clear how we can make the acclimation phase more effective. We hypothesize that providing certain visual cues to the users can help them better understand their walking using the locomotion interface and how it is different from real walking, and thus increase the effectiveness of the training. The visual cue can vary depending on the locomotion interface and its form factor.

RQ5. Considering 3D UI design principles, can we develop a meaningful design space and classification of locomotion techniques to aid a deeper understanding of the differences between the techniques and to provide a design space for new techniques to be tried?

We have planned to study various components of fidelity. We believe that some have greater effect on the effectiveness. We can use the design principles we learned in our efforts on the aforementioned research questions to extract various characteristics of locomotion interfaces. Several interfaces have been introduced by researchers. Still, none of them currently provide an effective interface and a general solution to the unlimited locomotion problem. To achieve a deeper understanding of the reasons behind this, we need to better understand various characteristics of walking-based locomotion using a taxonomy of locomotion techniques. Using this taxonomy, designers will be able to design novel locomotion interfaces, or improve the existing ones.

1.7 Approach

For RQ1:

To address the first research question, we are examining the hypothesis first discussed by Ryan P. McMahan in his PhD dissertation (McMahan 2011). The hypothesis postulates that moderate fidelity interfaces often have inferior effectiveness compared to high- and well-designed low-fidelity interfaces. To further investigate this hypothesis, we propose to run a variety of controlled experiments, comparing different levels of interaction fidelity for locomotion tasks. We carefully planned experiments to measure different parameters of effectiveness such as performance and user preference. We ran three studies, described in Chapters 4, 5.1 and 5.2, to address this question (Nabiyouni, Laha et al. 2014, Nabiyouni and Bowman 2015, Nabiyouni, Saktheeswaran et al. 2015).

We performed a meta-analysis on this hypothesis. The meta-analysis analyzes the results from the literature to further investigate the relationship between increasing levels of interaction fidelity and effectiveness. We reviewed papers that compared two or more locomotion interfaces with different levels of interaction fidelity. We normalized the data from the papers in order to be able to demonstrate and compare the results in the same scale. We compared the level of interaction fidelity for different interfaces using the FIFA framework (McMahan 2011). We characterized measures and tasks based on their behavior regarding increasing levels of interaction fidelity. This meta-analysis is presented in Chapter 8.

For RQ2 and RQ3:

To address the second question, we studied the effects of different components of interaction fidelity in controlled experiments. We developed techniques based on biomechanical and transfer function symmetry and combinations of these components for hyper natural locomotion, and we compare these techniques to real walking. We developed a locomotion interaction testbed with the ability to test different parameters of effectiveness, such as accuracy, navigation, speed control, and orientation estimation, as well as simulator sickness and user experience. We investigated the effects of kinetic and kinematic symmetry on medium-fidelity interfaces and we study the impact of changing gait forces on the effectiveness of the locomotion interfaces. To address RQ2 and RQ3, we ran an experiment and compared four techniques using a hyper-natural transfer function, hyper-natural biomechanics, a combination of these two, and natural walking. This work is described in Section 5.2 (Nabiyouni and Bowman 2015).

For RQ4:

To address this research question, we consider improving effectiveness using effective training. The literature shows a positive effect of training on improving effectiveness with 3D interfaces (Marsh, Hantel et al. 2013). We believe that informing users about the differences between the locomotion interface and natural walking will help them to learn how to walk differently using the locomotion interface, and improve their effectiveness. We planned an experiment to investigate how to improve the effectiveness of the training. This study is described in section 5.3 (Nabiyouni, Scerbo et al. 2015). This method can be applied to other locomotion interfaces as well as tasks other than locomotion.

For RQ5:

Characterization of different components of interaction fidelity contributes to a better understanding of how to design locomotion interfaces. Designing a novel and effective walking-based locomotion interface, or improving existing designs, requires an in-depth understanding of various characteristics of locomotion. By selecting from different options for each characteristic, we can make better design decisions. We characterized the components of interaction fidelity, building on top of FIFA (McMahan 2011), Bowman's (Bowman, Koller et al. 1998) and Arns's (Arns 2002) taxonomies. We considered an “application based” or “goal based” characterization of interaction techniques (Bowman, Koller et al. 1997) in our taxonomy design. We extracted various characteristics of walking-based locomotion interfaces and developed a design space and classification of locomotion techniques in this taxonomy. To present an example for using this taxonomy, we have designed and developed a novel locomotion interface. The taxonomy and the novel locomotion interface are presented in Chapter 9.

2 Related Work: Locomotion Techniques Based on Physical Body Movement

A locomotion interface is a system or device that provides users with a sense of walking and enables them to translate and rotate in a VE. A high-fidelity locomotion interface creates an experience of physical walking in exploring a large virtual environment while keeping the user in the boundaries of the physical environment (Bowman, Kruijff et al. 2004, Steinicke, Visell et al. 2013).

Common locomotion interfaces are based on handheld game controllers (or gamepads). For example, a typical technique might employ two joysticks: one for translation and one for rotation. To increase the match between proprioceptive cues and visual feedback, more natural interfaces and devices such as walking-in-place (Usoh, Arthur et al. 1999, Feasel, Whitton et al. 2008), omni-directional treadmills (Darken, Cockayne et al. 1997), the Virtusphere (Latypov 2006), and redirected walking (Razzaque, Kohn et al. 2001), have been proposed.

In this chapter, we discuss and categorize locomotion techniques that simulate "virtual" walking, based on physical body movements. The output of such techniques will be mimicking human walking in the VE.

2.1 Pressure-Based Board

One of the earliest ideas for navigating through virtual game environments was based on standing on a surface, and navigate by controlling the balance of one's weight. Users need to stand at top of a flat surface and by shifting their weight toward different parts of the surface, they can provide input to the system. The idea shown in Figure2.1-A, was patented in 1997 (Li 2001).

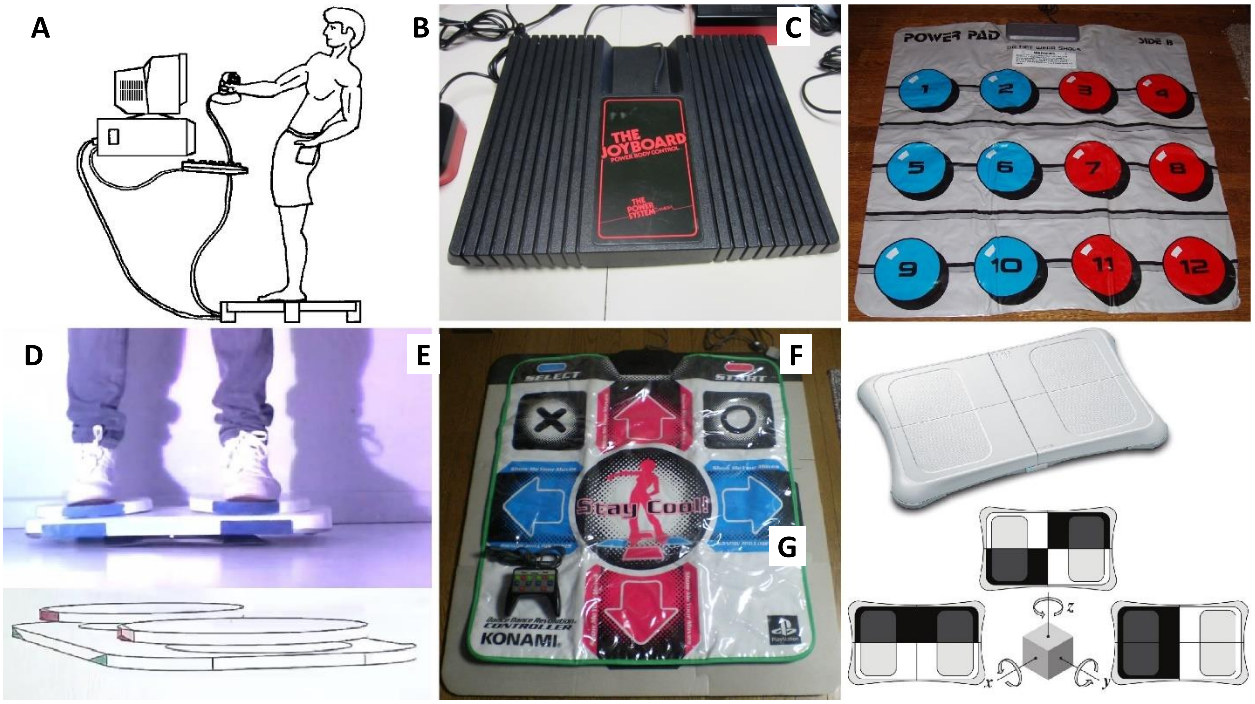


Figure2.1 – A: Human Joystick patent (Li 2001) B: Atari Joyboard, C: Nintendo Power Pad, D: Escapad omnidirectional treadmill (Plet 2016), E: Konami Dance Dance Revolution, F: Nintendo Wii balance board, G: Shifting weight on Wii balance board for navigation (de Haan, Griffith et al. 2008).

The Atari *Joyboard* (Figure2.1-B) developed in 1982 (Johnson 2008), and Nintendo *Power Pad* (Figure2.1-

C) developed in 1986 (Sinclair, Hingston et al. 2007) were two of the earliest devices based on this ideas which were used for gaming and entertainment. More recent examples include Nintendo *Wii balance board* (Figure2.1-F-G) , Konami *Dance Dance Revolution* (Figure2.1-E) (Unnithan, Houser et al. 2006) and *Escapad* Omnidirectional Treadmill (Figure2.1-D) (Plet 2016).

The *Walking-Pad* locomotion interface (Bouguila, Evequoz et al. 2004) is similarly based on the stepping in place. The user stands at the top of the flat platform and the footfall pressure caused by the stepping actions is detected by the grid of switch sensors (Bouguila, Florian et al. 2005).

Among such interfaces, *Wii balance board* is a low-cost and easily accessible device that has been used by several VR researchers. De Haan et al. (de Haan, Griffith et al. 2008) used Wii balance board for both continuous and discrete input. They found out that the continuous input, is suitable for interactions that require two or three simultaneous degrees of freedom, such as navigation and rotation. They found the discrete input more fit for providing control input, such as object selection or mode switching. Valkov et al. (Valkov, Steinicke et al. 2010) used foot gestures for navigation tasks in VEs. They have combined multi-touch hand and foot gestures for interaction with 3D data using a world-in-miniature (WIM) and a non-WIM technique. They found that the WIM technique is better in terms of easiness to orientate.

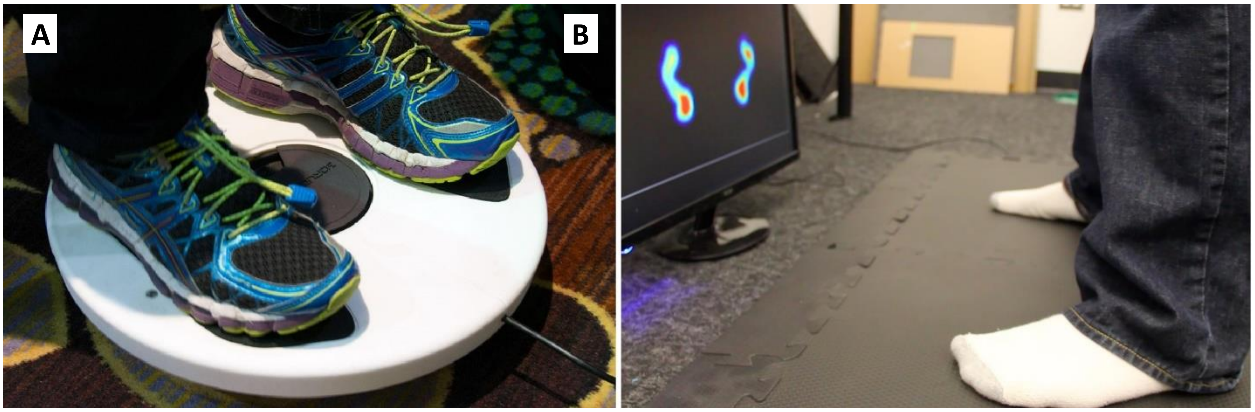


Figure2.2–A: 3D Rudder VR foot controller (Bonora 2016), B: HovrMat, the Mechanical Force Redistribution (MFR) device for surface interaction (Grau, Hendee et al. 2014)

The 3D Rudder (Bonora 2016), is a feet controlled device for 3D navigation and motion control. To move in any direction, the user needs to tile device in that direction (Figure2.2-A). To rotate the view, the user needs to rotate the device in the same direction and to move in vertical direction is performed by applying pressure to the sides of the platform. The Mechanical Force Redistribution (MFR) interface is able to sense the amount of forces applied into the surface (Grau, Hendee et al. 2014). This high accuracy force sensing surface can provide an anti-aliased image of forces applied to the floor (Figure2.2-B) and makes large-format floor tiles possible (Perlin 2015). This interface was patented by Perlin (Perlin, Hendee et al. 2015) and has been employed to develop pressure-based locomotion interfaces (Perlin 2015)

2.2 Cycling Systems

Various types of exercise bikes have been used as controllers. VirZoom Exercise Bike-Based VR Game Controller (Janszen 2015) is a more recent real world implementation of this idea, which provides an immersive experience to travel through VEs (Figure2.3-B). Using buttons user will be able to interact with the VE and by pedaling a bicycle-like device user will be able to control the velocity of view point movement.

A similar idea has been previously developed by Darken et al., (Darken, Cockayne et al. 1997) to develop a locomotion interface based on the act of cycling for training purposes. This locomotion interface, Uniport, is built by Sarcos Corporation and includes upper body mechanical tracking. The Uniport, shown in, Figure2.3-A, operates in a similar fashion to a unicycle and require users to pedal to stimulate walking. The user wears an HMD to view the VE and can move forward or backward, turn right or left and feel the haptic feedback while traversing sloped surfaces. The user can control the direction of movement changing the direction of the Uniport's seat using her thighs and waist.

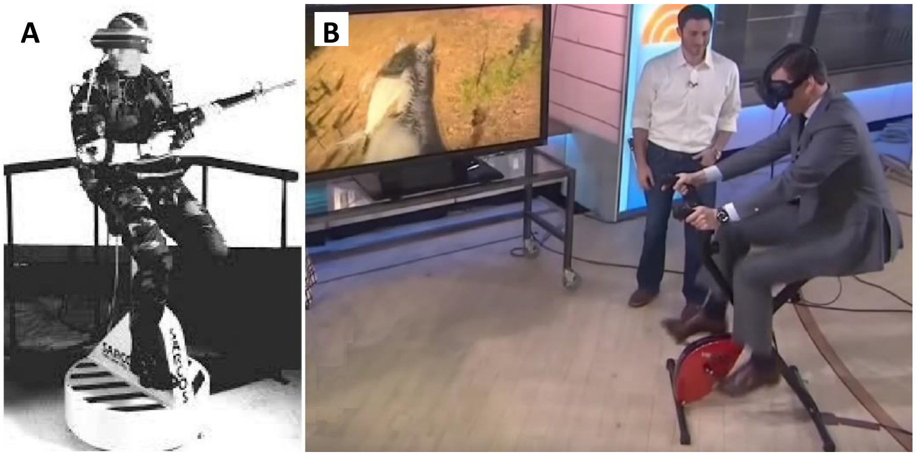


Figure2.3– Pedal-based locomotion interfaces. A: Uniport (Darken, Cockayne et al. 1997), B: VirZoom Exercise Bike-Based VR Game Controller (Janszen 2015).

2.3 Stepping Systems

Some other locomotion interfaces use the concept of a generalized stair stepper exercise machine. In such devices each foot platform can be individually programmed. Such foot platforms provide three DOF. Sarcos Biport (Hollerbach 2002), one such device, employs hydraulic arms to provide force feedback to the user (Figure2.4-B). The user's feet are attached to the hydraulic arms using releasable bindings and the force sensors positioned near the attachment points are used in force and steering control strategies. As the user lift her foot, during the swing phase of the gate, the attached arm must follow the foot without any force, to avoid dragging her foot. On the other hand, as the user steps down to contact a surface, the arm must present a rigid surface by getting firm. This interface has the potential to present both uneven and soft surface, which is not possible in most other locomotion interfaces, but it has speed limitations due to its structure. However, safety can still be an issue and safety considerations such as ceiling restraints, kill switches or harnesses seems necessary. Gait Master locomotion interface developed by

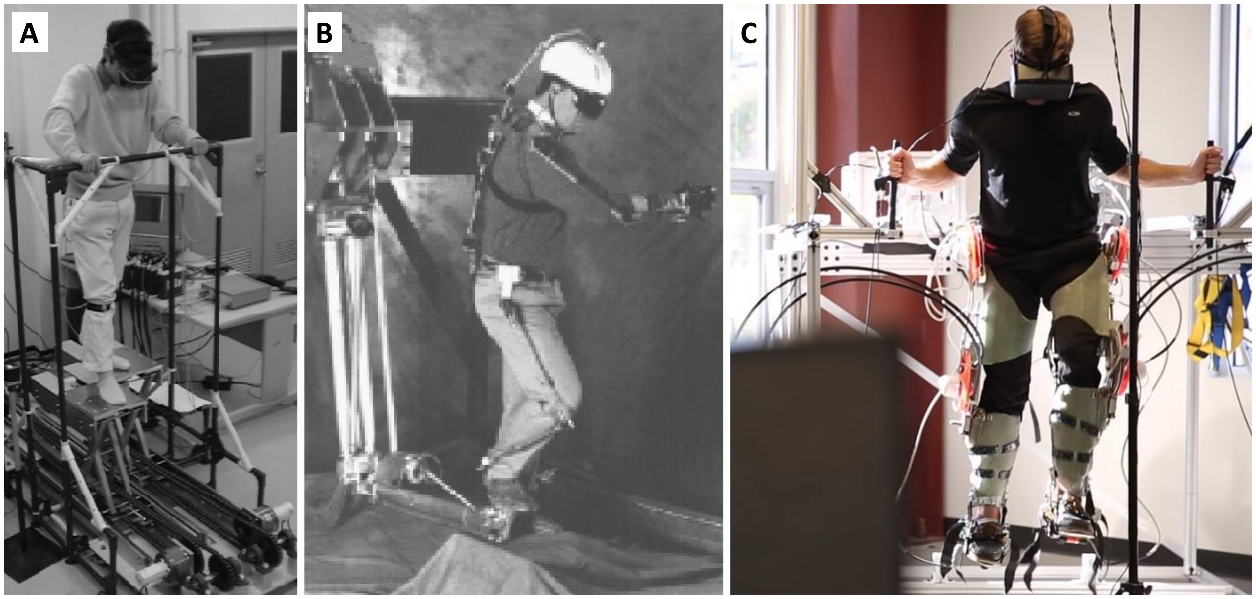


Figure2.4– Pedal-based locomotion interfaces, A: Gait Master (Iwata, Yano et al. 2001), B: Sarcos Biport (Hollerbach 2002), C: AxonVR whole body human-computer interface (Rubin 2016).

Iwata et al. (Iwata, Yano et al. 2001) is another example of such stepping systems. This interfaces, employs two foot pads for the user to step on them and at each step, footpads move backwards to carry the user's foot backward and cancel the user's forward movement (Figure2.4-A). These two motion platforms are mounted on a turn table. The turn table rotates the motion platforms to enables the user to turn in different directions. The motion platforms are able to move vertically to stimulate uneven surfaces. Gait Master employs a frame for the user to hold onto and have better balance and confidence while walking.

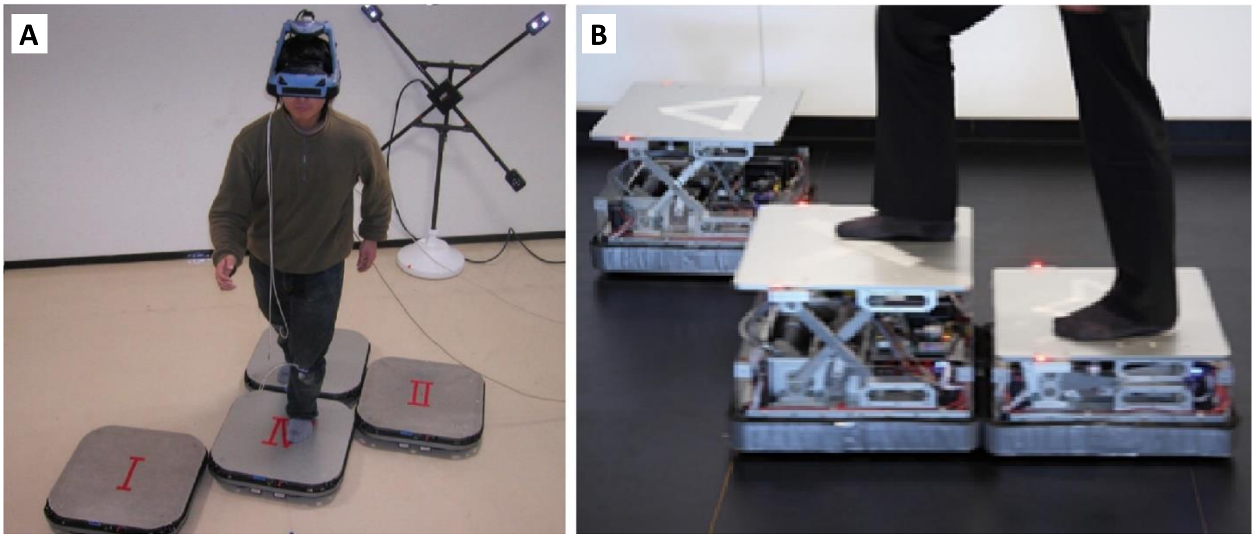


Figure2.5- A: *CirculaFloor robotic tiles (Iwata, Yano et al. 2005),* B: CirculaFloor has the potential to simulate uneven surfaces (Iwata 2004).

AxonVR (Rubin 2016) which has recently been patented (Rubin and Crockett 2016) is a whole body human-computer interface which can provide haptic feedback for the whole body including arms and legs. This interface includes an exoskeleton which applies forces intro carious body parts based on the input received from the VE (Figur2.4-C). Force feedback for the legs can simulate walking on hard surfaces and allow simulation of human walking. Although AxonVR seems to be cumbersome to use for the user, it is able to simulate uneven surfaces.

In these systems, as the user move her feet upward, the ground underneath get unconnected from her foot to some degree. As the user step down, the ground moves and become present underneath the user's foot. CirculaFloor (Iwata, Yano et al. 2005) works in a similar manner (Figure2.5A). In this system, as the user move forward the robotic tiles in the back, move forward and position in front of the user so that the user's foot can place on the tile. Meanwhile the tiles that user is standing on keep moving back so that the user always stays within a small physical space. This interface has the potential to form uneven surfaces by adding an up-and-down mechanism (Iwata 2004) as shown in Figure2.5-B.

2.4 Rolling Sphere

The idea of walking inside a sphere for locomotion interaction in VR seems to be promising and has been noticed by the VR researchers. A fully immersive spherical projection system, called Cybersphere shown in Figure 2.6-A, has been proposed by Fernandes et al. (Fernandes, Raja et al. 2003). In this system user walks inside a sphere rolling on casters, and virtual imagery is projected to the sphere using the projectors mounted outside and surrounding the sphere. The use of such system for a fully immersive VR training system has been described in (Fernandes, Raja et al. 2003). Latypov has patented the idea of walking inside a sphere in US Patents (Latypov 1998) and called it Virtusphere. The similar idea of a motion simulating device has been patented by David Carmein (Carmein 1999).

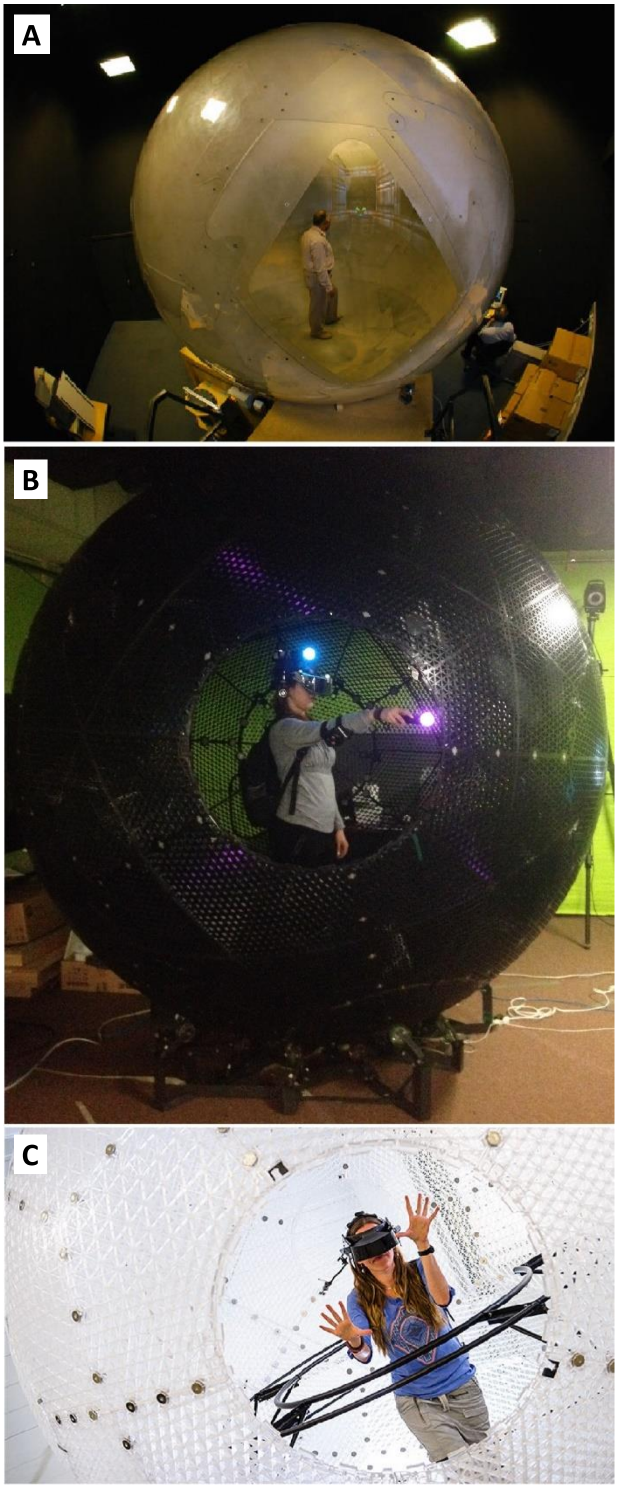


Figure2.6 – A: Cybersphere (Fernandes, Raja et al. 2003), B: An early model of the Virtusphere, C: The new Virtusphere includes a rail inside the sphere.

The Virtusphere (Latypov 2006) shown in Figure 2.6-B, is a large hollow sphere mounted on casters, in which a user wearing a head-mounted display (HMD) can walk in any direction to move through a

VE. The Virtusphere is similar to a human-sized “hamster ball,” and while it offers unlimited movement through a VE of any size, it can also be difficult for users to control and use. A new model of the Virtusphere shown in Figure 2.6-C, has a lighter sphere and includes a rail rolling inside the sphere. Users can hold onto the rail to have a better balance and confidence while walking.

Skopp et al. (Skopp, Smolenski et al. 2014), studied presence, overall involvement/control and sickness in the Virtusphere compared to a gamepad technique. Although the mean values of these metrics were better for the gamepad than for the Virtusphere, they did not observe any significant difference. Marsh et al. (Marsh, Hantel et al. 2013), performed a study on the effectiveness of training on performance and cognitive resource demands in the Virtusphere. They observed a positive effect of training on movement abilities and performance. Performance, simulator sickness and satisfaction have been studied for first-person and third person viewpoints in the Virtusphere (Medina, Fruland et al. 2008). This study found that the first-person viewpoint group performed better and enjoyed the system more, while the third-person group had less motion sickness and balance disturbance. Chapman et al. (Chapman, Nemec et al. 2013) developed a mobile tactile messaging system in a Virtusphere to assist dismounted soldier-to-soldier communication.

VR researchers has noticed that users often have difficulties to walk toward their intended direction as well as initiating and terminating the walking, while inside the Virtusphere. To improve this, Marsh et al. (Marsh and Kluss 2015) developed an interface to incorporate the orientation of the user’s body as a clue of intended movement direction. This method assumes that the user intended to travel in the direction that her torso is facing and the system set the direction of movement in the VE accordingly. They have compared this method to the baseline Virtusphere interfaces and found out that their method improved the self-reported naturalness and traversal accuracy during a blind-walking task.

2.5 Sliding-In-Place

Sliding on a surface to stimulate walking appears as a promising solution for the infinite locomotion problem. Sliding on a surface can keep the user in a limited physical space while providing an action, close enough to real walking, to stimulate walking in an infinite VE. Such devices are passive and do not require a control system, but often require a low-latency tracking system and might need a support for the user to keep her balance.

The movie “Disclosure” in 1994, featured a stationary, dish-shaped, concave platform for locomotion in VEs upon which the user stands while performing the walking motions (Figure2.7-A). Similar ideas was patented which disclose a passive locomotion interface with a concave upward facing surface with low amount of friction, which enables the user to move freely in VEs (Williams 2008, Carrell 2013). Based on this patent *Wizdish* (Swapp, Williams et al. 2010) was implemented (Figure2.7-B). Walking on a *Wizdish*, the user does not remove her foot to move forward, but rather she slides her feet back and force to simulate walking action. This model of *Wizdish* shown in Figure2.7-B, does not provide users with handles, harness or any type of support to help them with their balance.

Figure2.7 – A: Locomotion device from the movie “Disclosure”, B: Wizdish, C: Virtual Perambulator (Iwata and Fuji 1996), D: omni-directional ball-bearing disc platform (Suryajaya, Lambert et al. 2009), E: Cyberith Virtualizer (Cakmak and Hager 2014), F: Virtuix Omni (Goetgeluk 2013).

Sliding on a surface while the user is not able to see her own feet, can cause her to lose balance. Adding a frame or harness for the user to keep into can help users with their balance and make them more confident. Iwata et al., (Iwata and Fuji 1996) developed Virtual Perambulator, based on this idea. This interfaces uses low friction shoes to help users slide on the flat surface and provide a frame around the user to hold onto (Figure2.7-C). This interface tracks the user’s movements using touch sensors, attached to the shoes. Huang (Huang 2003) demonstrated benefits of using an omni-directional ball-bearing disc platform (OBDP) in a training simulator. This design uses hundreds of custom-made ball bearing sensors attached on a concave surface and support the user with a frame around her waist. Suryajaya et al., (Suryajaya, Lambert et al. 2009) improved this system by using standard ball transfer units, and replace the ball bearing sensors with camera based trackers (Figure2.7-D).

The interaction with sliding-in-place interfaces is close to walking in real world and such concept can provide good balance and control over walking. Moreover, producing an interface based on this concept is relatively low-cost and can be a good choice for a commercial locomotion interface. Novel devices, based on this idea are envisioned for mass production. Cyberith Virtualizer (Cakmak 2015), one such device, enable user to slide on a flat, low friction surface, while being supported by a harness. As shown in Figure2.7-E, users can walk, run, jump and duck using this interface and do not need to wear any specific type of shoes (Cakmak and Hager 2014). Another novel locomotion device, Virtuix Omni (Goetgeluk 2013) patented by Jan Goetgeluk (Goetgeluk 2013, Goetgeluk 2014), uses the same idea. This device includes a convex, low friction, grooved surface and a frame that goes around the user's waist and hold her with a harness (Figure2.7-F). While wearing a pair of special Omni shoes that increase stability and reduce friction with the surface, the user will be able to walk, strafe, duck, run and jump through VEs (Avila and Bailey 2014). Kat Walk (Pang 2016) is another novel locomotion interface prototype which uses a passive, convex, low friction surface and specific shoes to let the user slide in place and employs a harness for balance and safety.

2.6 Treadmills

Walking or running on a treadmill, often does not cause balance problem for the users and if it not more fatiguing than the real-world counterpart. Such interfaces are motorized and actively move the user back, which can overcome the physical space limitation problem for exploring large VEs. Treadmill-like systems has been used in VR based training systems for post-trauma rehabilitation (Fung, Richards et al. 2006, Yang, Tsai et al. 2008). Using a treadmill is natural enough to inspire VR researchers to develop locomotion interfaces based on a treadmill idea. Sarcos Treadport (Christensen, Hollerbach et al. 2000) include a 4x8 ft. treadmill surrounded by three-wall CAVE (Cruz-Neira, Sandin et al. 1993) which enables unlimited locomotion. A second-generation Treadport includes a larger treadmill of 6x10 ft. and faster tilt mechanism (Hollerbach, Xu et al. 2000), shown in Figure2.8-A. User's position is tracked using a six-axis mechanical tie handing from the ceiling, attached to the back of a body harness. An integral control algorithm is responsible to re-center the user as she walks forward, by adjusting the treadmill's velocity proportional to the user's distance from the center, which also allows backward movement. Due to the control system used, to turn to other direction, the user needs to stop turning by moving back to a center position and then move to the other direction. The Treadport will tilt and turn regarding to the user's direction and is able to simulate slope. SpaceWalkerVR (Keles 2016) is a more recent implementation of the same idea. This system uses a relatively small linear treadmill, mounted on a joint which enables turning right or left (Figure2.8-B).

Ground Surface Simulator (GSS) depicted in Figure2.8-D, is a similar system including a treadmill on a spherical joint and a surface simulator, was developed by Noma et al. (Noma, Sugihara et al. 2000). This treadmill-style locomotion device combines two systems: the ATR Locomotion Interface for Active Self Motion (ATLAS) system (Noma 1998) and the ALive Floor (ALF) system (Sugihara and Miyasato 1998). The ATLAS system shown in Figure2.8-C, comprise a linear treadmill able to pitch, roll and yaw using the spherical joint mounted underneath the treadmill. The ALF system is a movable floor, consist of small panels, which can simulate different natural terrain surfaces (e.g. bumps and dips).

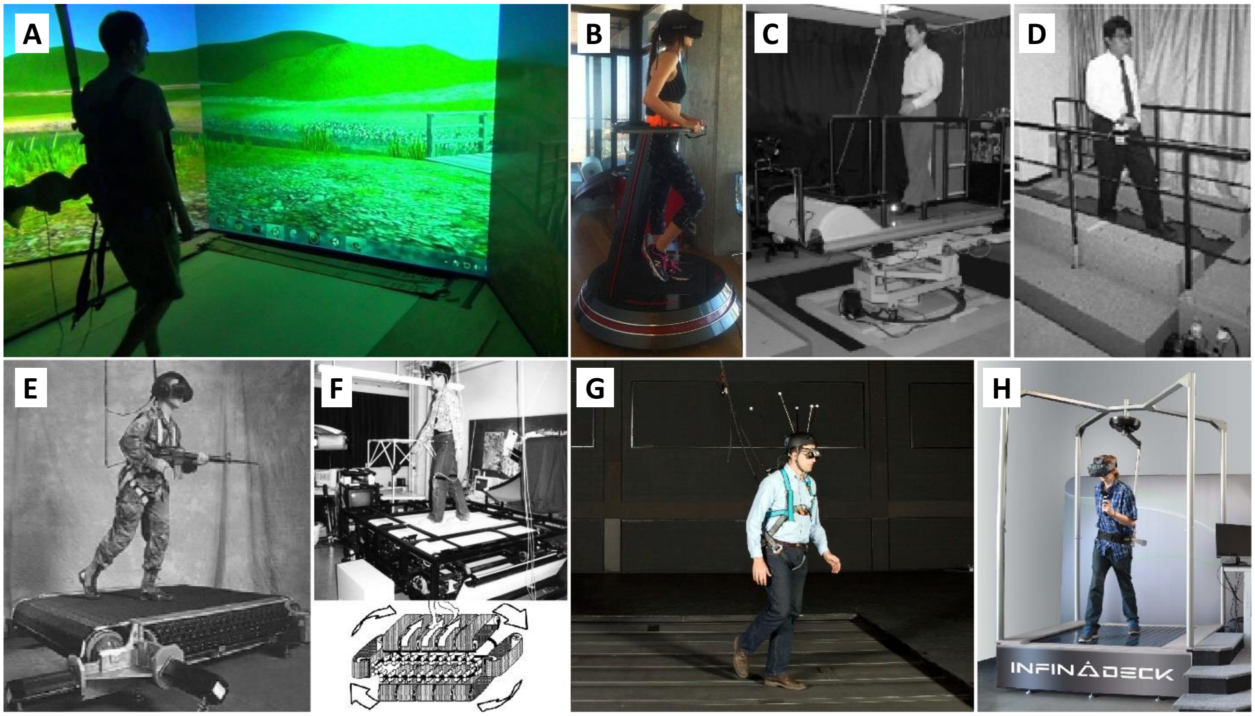


Figure2.8 – Treadmill-based locomotion interfaces, A: Sarcos Treadport, B: SpaceWalkerVR (Keles 2016), C: ATLAS system with a linear treadmill (Noma, Sugihara et al. 2000), D: Ground Surface Simulator (Noma, Sugihara et al. 2000), E: Darken's ODT (Darken, Cockayne et al. 1997), F: Torus Treadmill (Iwata 1999), G: CyberWalk (Schwaiger, Thummel et al. 2007), H: Infinadeck (Burger 2014).

The aforementioned systems employ a treadmill similar to a common sport treadmill. Nevertheless, researchers patented the idea of a treadmill able to turn in any direction (Carmein 1996, Carmein 2000). Darken et al. (Darken, Cockayne et al. 1997) designed and developed Omni-Directional Treadmill (ODT), a two-dimensional treadmill surface, which provides easier means for turning. This interfaces have a 4.2x4.2 ft. active surface with a top velocity of 3 m/sec. ODT include two orthogonal belt arrays. The rollers of the top belt are in parallel with the direction of rotation of this belt. The top belt is rotated by another belt, underneath and orthogonal to it (Figure2.8-E).

Iwata designed and implemented the Torus Treadmill locomotion interface which similarly includes a two-dimensional treadmill (Iwata 1999, Iwata and Yoshida 1999). Walking area is 3.3x3.3 ft. and the maximum velocity is 2.7 mph. This device uses two sets belts to enable rotation in two directions. The first set of belts comprises an array of twelve small treadmills in parallel, rotating in the same direction (Figure2.8-F). 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). The CyberWalk depicted in Figure2.8-G (Schwaiger, Thummel et al. 2007) locomotion interface uses the same idea. An effective control system in the treadmill-based systems actively returns the users back to the center of the treadmill. The control system performs this, based on the user's velocity, acceleration and movement direction. The experimental evaluations of this interfaces (De Luca, Mattone et al. 2009) indicate benefits of using separate control gains for each orthogonal direction. The control system, often is the main cause for walking difficulties in such systems. The CyberWalk has been further improved in (Souman, Giordano et al. 2011) to provide better mechanical features and the control system. Infinadeck shown in Figure2.8-H (Burger 2014) is another locomotion interface based the same idea, aiming to produce a commercial ODT. Infinadeck provides a walking area of almost 5x5 ft. and the maximum velocity of 6 mph (Burger 2014).

Omnifinity *Omnideck* (Schmitz and Johansson 2014) uses several trapezoid roller conveyors which together shape a hexadecagon surface (Figure2.9-A). Rollers are continuous circular cylindrical, all rollers on the same conveyor are in parallel. Rollers are driven using driving belts from below, to rotate toward the center of the hexadecagon surface and move the user back to the center of the hexadecagon, as she move forward and step on them. The marker placed on the top of the user is tracked by video cameras and the speed of the roller conveyors is adjusted based on the user position. Unlike other sliding-in-place locomotion interfaces discussed here, this interface is not passive and has active rollers, however it uses the same concept to keep sliding the user's feet toward the center of the device and move the user back to her initial position.

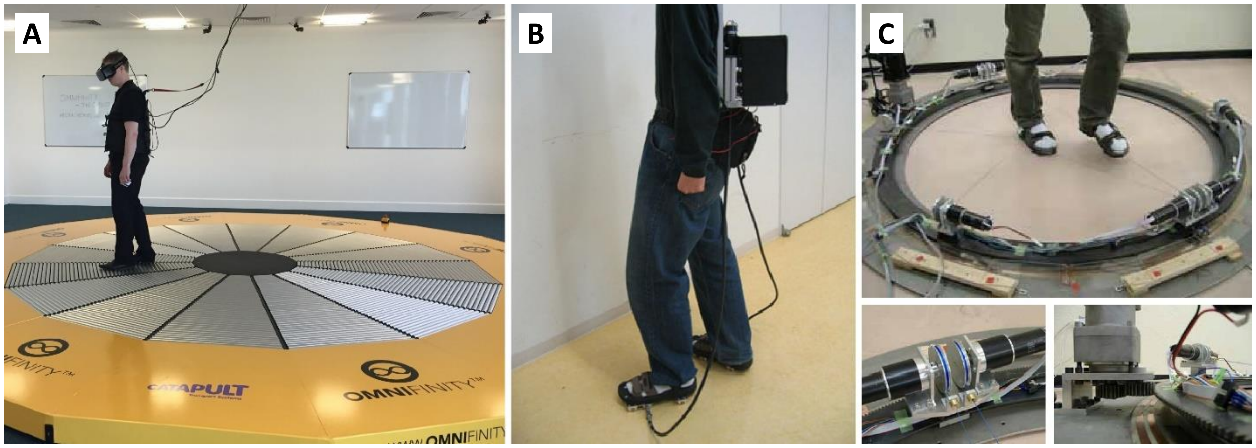


Figure2.9, A: Omnifinity Omnideck (Schmitz and Johansson 2014), B: Powered Shoes (Iwata, Yano et al. 2006), String Walker (Iwata, Yano et al. 2007)

Powered shoes (Iwata, Yano et al. 2006) is a powered active system which fits the user's soles and include three motorized rollers installed underneath the soles (Figure2.9-B). As the user walks, the rollers actively move the user back and enable her to walk with a speed of 6m/s while physically remaining in the same area. The direction of traction force generated by the rollers is the same to the shoes, which allows walking in a straight line and makes it impossible for the user to rotate. String Walker, shown in Figure2.9-C, enables omni-directional walking while the user's position is maintained. It employs eight strings attached to the user's feet to actively pull back the user's feet as she walks. These strings are actuated by motor-pulley mechanism and as the user move her feet in any direction, the string mechanism pulls the user's feet back to initial position. This system is mounted on a turntable and enables various gait such as side-walking.

Both, powered shoes and string walker are not using treadmills. However, we put them in the same category as treadmills, because similar to the treadmills, they actively move the user's feet backward and keep the user in a relatively small physical space.

2.7 Human Joystick

Using a joystick was one of the first _and maybe one of the best_ ideas, for 2D input device. Joysticks use a rate-based control method and are widely employed for both translation and direction control, specifically in video games. However, pushing a knob to navigate does not correspond with the act of walking in real world. A more natural method based on this idea would be, to use the whole body as a joystick. In this locomotion technique the velocity of the travel is adjusted based on the user's distance form a neutral point and the virtual travel's direction corresponds to the direction of the user's. A human joystick technique often employs a rate-based control method.

Bourdot et al. (Bourdot and Touraine 2002) designed a navigation method using 6 degree of freedom (DOF) tracking, and employed a "Neutral Referential" as the basic element of their locomotion technique. When the tracker is far from this Neutral Referential, the view point in the VE will travel proportional to the 6DOF tracker's relative movement. They defined the Neutral Referential as a neutral area in form of a sphere, in opposed to just a point, for psychological reasons (Bourdot and Touraine 2002). McMahan et al. (McMahan, Bowman et al. 2012) employed a similar technique, called *human joystick*, to enable the user travel through VE while inside a CAVE. They used the user's tracked head position to figure out her distance from a "neutral zone" (Figure2.10-A). This neutral zone includes a circle with eight inches radius at the center of the cave. The human joystick technique activates as soon as the user is outside the neutral zone. The velocity of virtual travel is indicated linearly by the 2D distance of the user from the neutral zone with a maximum of two inches/sec when the user is close to CAVE walls.

Guy et al. (Guy, Punpongsanon et al. 2015) designed *LazyNav*, a mid-air travel control technique which uses a pair of tracked body elements to control navigation in the VE. They have designed and studied several body motions for properties such as being accurate, easy to discover and control, socially acceptable and no tiring. The motions of bending forward and backward for the corresponding travel directions and bending right or left for changing the movement direction to right or left is similar to that of a joystick. As shown in Figure2.10-B moreover, they mapped the movements of chest and arm, waist and feet to travel control but they did not observe significant differences between these techniques.

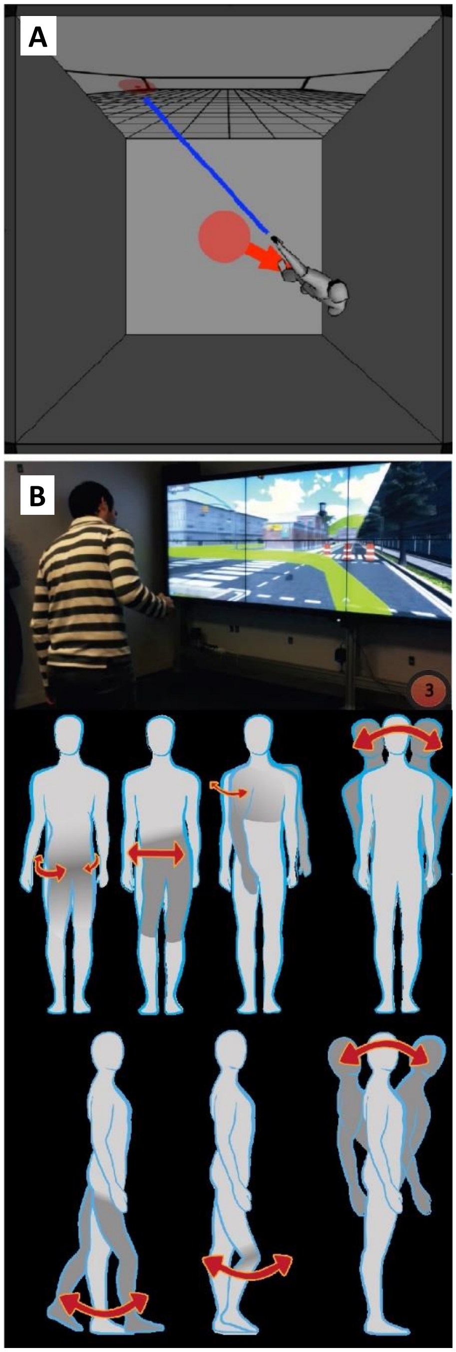


Figure2.10 – A: Human Joystick technique (McMahan, Bowman et al. 2012) in a CAVE, B: different movements designed for LazyNav technique (Guy, Punpongsanon et al. 2015).

VRGO device is a sculpted seat with high friction pads which allow the user to control view movements in the VE (Ryan 2015). As the user incline in any direction, the view in the VE will keep moving in that direction with a rate-based control. By rotating the chair user can rotate view (Figure2.11).

Figure2.11 – VRGO hands free movement device (Ryan 2015).

2.8 Walking-In-Place

A more natural locomotion technique can increase the subjective sense of presence in an immersive VE (Slater, Usoh et al. 1995). Slater et al. developed a technique which allow the user to “walk in place” to travel through VE (Slater, Usoh et al. 1995). They compared this technique to a push-button-fly technique which enable users to move along the ground plane, and observed that users had a higher sense of presence with the technique of *walking-in-place* (WIP). In this technique the user was asked to perform the act of walking while she stayed in the same place. Slater et al. used a neural network to analyze the stream of coordinates received from the HMD and whenever it determined the act of walking, the user was move in her gaze direction. Usoh et al. (Usoh, Arthur et al. 1999) replicated the aforementioned study and compared the results to a third condition of real walking. Usoh observed that the real walking was significantly better than the walking in place and the Slater’s flying technique for the parameters of naturalness, simplicity and straightforwardness. Similar to the Slater’s study, they found out that the subjective parameter of sense of presence is significantly correlated with the users’ degree of association with their virtual avatars. Therefore, tracking all body part of the user has a considerable potential for improving presence.

Templeman et al. (Templeman, Denbrook et al. 1999) developed a WIP technique, called *Gaiter*, to enable user step in-place. using two types of sensors: pressure sensors, placed inside the user’s shoes which sense the pressure from the foot sole, and the six-DOF trackers attached to the user’s knees to observe the knee trajectory (Figure2.12-A). This technique allows the user to move forward in the VE by moving her feet and laps upward and stepping in-place (Figure2.12-B), move sideways in the VE by moving her feet sideways (Figure2.12-C), or move backwards by moving her feet backward and upward while keeping her knees steady (Figure2.12-D).

Feasel et a. (Feasel, Whitton et al. 2008) performed a comparison between the WIP, real walking, VRWalk and joystick techniques. They used pressure sensors in the palm of the user’s shoes, trackers on the user’s knees and a chest-oriented tracker (Figure2.12-E). They developed a novel version of WIP, Low-Latency, Continuous-Motion *Walking-in-Place* (LLCM-WIP), improves both latency and the continuity of synthesized locomotion in the virtual environment (Feasel, Whitton et al. 2008). They have compared these interfaces for starting and stopping latency and analyzed the usability of their system and observed that the LLCM-WIP technique cannot be expected to stipulate better accuracy and responsiveness. Following-up with this work, Wendt et al. (Wendt, Whitton et al. 2010) developed Gait Understanding-

Driven Walking-In-Place (GUD WIP) technique to better simulate the speed of the Real Walking and better respond to the changes in step frequencies such as starting and terminating the gait.

WIP Inside CAVEs:

Yan et al. (Yan, Allison et al. 2004) developed a WIP technique for a six-sided CAVE. This technique employs data from previous motion capture during real walking down a hallway, to fit a model for the WIP technique. This model was used to estimate the speed and the direction of forward walking from each individual's step characteristics during walking in-place (Figure2.12-F). WIP techniques try to overcome the limitation of physical space and try to keep the user in-place but do not limit her rotation. To make the WIP work inside a CAVE-like system (three-sided or four-sided CAVEs),

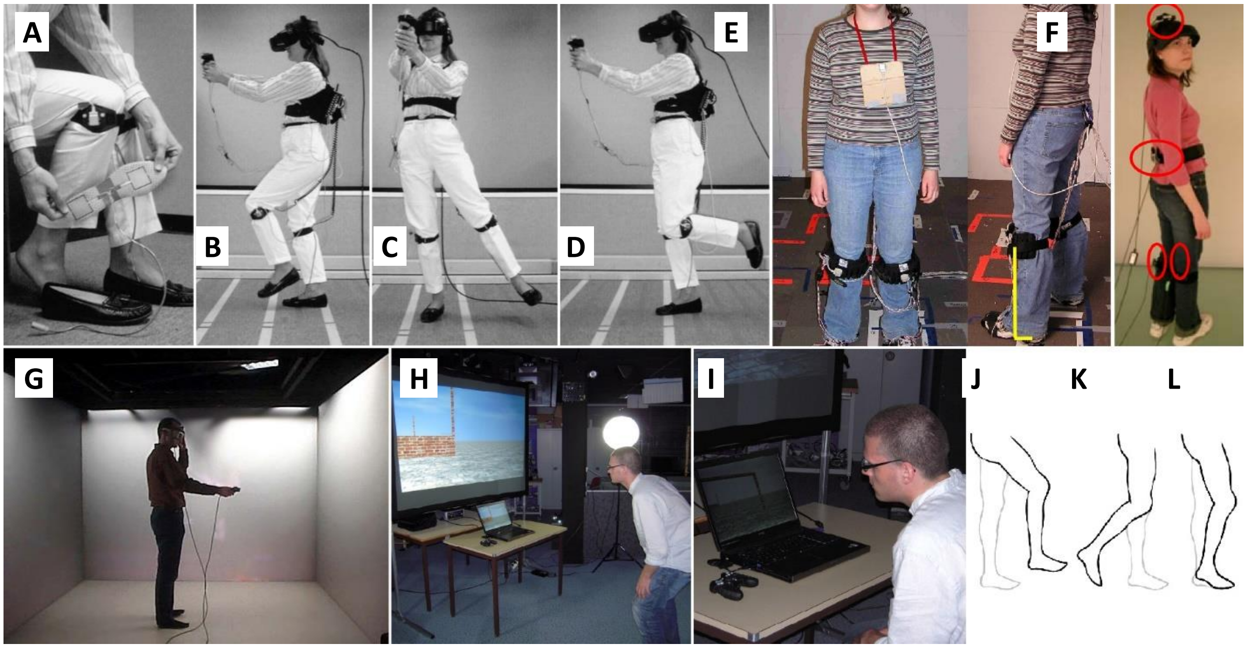


Figure2.12 – Walking-in-place, A: WIP technique with pressure sensors underneath foot sole, and the six-DOF trackers on knees, B: Walking in-place to move forward, C: moving feet sideways to move sideways in the VE and D: moving feet backward to move backward in the VE (Templeman, Denbrook et al. 1999), E: Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP) technique (Usoh, Arthur et al. 1999, Feasel, Whitton et al. 2008), F: WIP technique for a six-sided CAVE uses data from previous motion capture (Yan, Allison et al. 2004), G: Redirected Walking in Place (RWP) for three/four-sided CAVEs (Razzaque, Swapp et al. 2002), H: Stand-Up Shake-Your-Head (Terziman, Marchal et al. 2010), I: Sit-Down Shake-Your-Head, J: Marching gesture for WIP (Ruddle, Payne et al. 1999, McMahan 2011, Nilsson, Serafin et al. 2013), K: whipping gesture, L: tapping gesture.

Razzaque et al. (Razzaque, Swapp et al. 2002) developed a technique to allow users virtually walk around without having to turn and face the back part without a wall (Figure2.12-G). Their Redirected Walking in Place (RWP) technique, determine rate of rotation in the VE based on the user's orientation, her head's angular velocity and the virtual velocity. They employed three type of rotation gain: first, constant rotation gain to keep rotating the point of view in small amounts (rotate the room slowly) until the user is facing the front wall, second, the same type of rotation in the greater amount was applied when the user was walking in place and finally, an additional rotation due to her angular velocity when the user was turning. They have compared this technique with a navigation technique based on a hand-held controller. They did not observe any significant difference in terms of facing the missing wall. However, their results indicated that the sense of presence was negatively correlated with the frequency of facing the missing wall.

Simple Implementations:

Another problem with the WIP technique is, it requires several, non-conventional trackers to track user's feet as well as, the user does not have the possibility to sit down. In a different approach, Terziman et al. (Terziman, Marchal et al. 2010) developed a locomotion technique that stimulates walking in the VE based on the head movements. This technique allows developers to use conventional screens and standard input devices such as basic camera-based trackers and moreover enable the user to sit down. The user is able to move forward, turn and jump or crawl using the different head movements of lateral motion, roll motion and roll motion, respectively. They have compared two configurations of the of the *Shake-Your-Head* technique including *Stand-Up* (Figure2.12-H) and *Sit-Down* (Figure2.12-I) to two navigation techniques using keyboard and joystick. The Sit-Down Shake-Your-Head technique was faster, after a short learning. Moreover, their technique increased the sense of presence and was more fun. An alternative method to reduce development complexity and cost of the WIP technique is to use a pressure-based board, such as the Wii Balance Board. Williams et al. (Williams, Bailey et al. 2011), developed a WIP technique using a Wii Balance Board and compared it a Joystick and a real walking technique. Their results indicate that WIP technique had significantly less turning error comparing to the Joystick and more than the real walking.

Different Gestures:

Some VR researchers believe WIP technique with the stepping gesture can be perceived as more straining comparing to the real walking. Nilsson et al. (Nilsson, Serafin et al. 2013) compared three different gestural input for the WIP technique. In marching gesture depicted in Figure2.12-J, user in turn raise each foot by raising her thighs. The whipping gesture (Figure2.12-K) user is required to alternatively bend each knee while keeping her thighs steady and move her feet backwards. In tapping gesture (Figure2.12-L) user alternatively raise each heel while her toes are in contact with the ground. They observed that the tapping gesture was significantly more natural than the wiping gesture and was less fatiguing and caused less drift than the other two techniques.

2.9 Finger Walking

A miniature version of WIP, Finger Walking in-Place (FWIP), allow users to navigate through VE by sliding her fingers on a multi-touch sensitive surface (Kim, Gračanin et al. 2008). This technique enables users to translate and rotate the view point by moving their fingers in-place. Although, implementing such interface might be convenient and low cost, authors had difficulties with precisely detecting finger motions. They further improved the technique and introduced a unimanual version of this technique which works on iPhone/iPod (Kim, Gračanin et al. 2010) and compared it with a Gamepad technique. They observed improvements on accuracy of replicating the route (Figure2.13-A). Yan et al. (Yan, Lindeman et al. 2016) have developed multiple multi-touch travel techniques for various travel ranges. They employed the same metaphor of the user's fingers become her legs. Their walking technique is designed as low-speed and precise method in which the user has 3-DOF control over the view-point translation. In this technique two fingers mimic walking gesture on a touch interface (Figure2.13-B). The user can achieve higher speed by employing the Segway gesture. To activate this gesture user can put both her fingers down. The speed of movement is determined by the amount of pressure applied by fingers on the surface. The movement direction is controlled by the difference in fingers pressure amount.

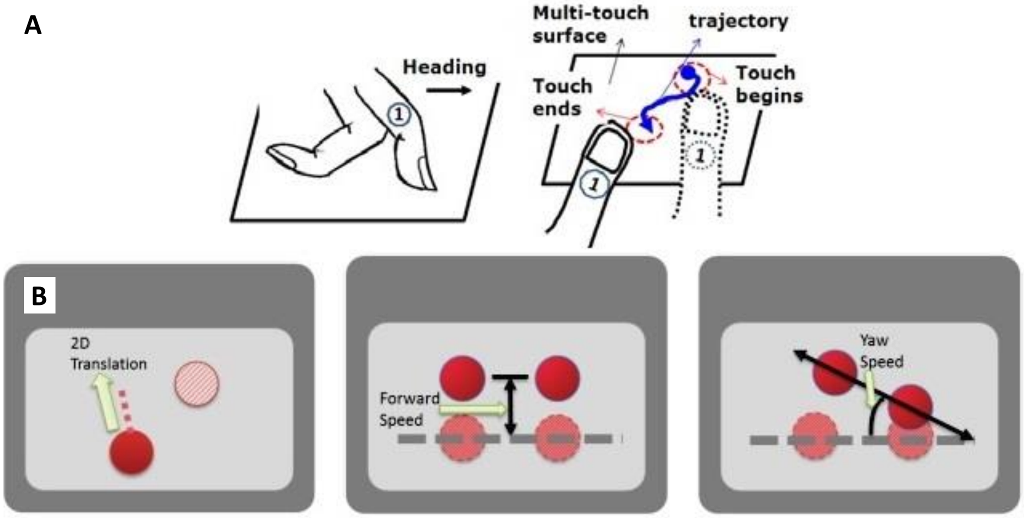


Figure2.13 – Finger Walking-in-place, A: FWIP technique with multi-touch surface (Kim, Gračanin et al. 2010), B: FWIP and Segway techniques (Yan, Lindeman et al. 2016).

2.10 Redirected Walking

Redirected Walking (RDW) first published by Razzaque et al. (Razzaque, Kohn et al. 2001), not only has the benefits of real walking but also can extend the size of the VE (Figure2.14-A). This technique interactively rotate the virtual scene so that the user is compelled to move toward the farthest boundary of the physical tracking space (Razzaque, Kohn et al. 2001). Human perceptual mechanism has limitations and in this technique the goal is that the user does not notice the rotation. The amount of infused orientation which RDW technique applies, depends on the user's real orientation, position, linear velocity and angular velocity. To inject rotation and translation onto user's position and orientation in the VE, RDW algorithms often use three type of gains: *Translation Gain*, *Rotation Gain* and *Curvature Gain*. Translation gain is the proportion of the mapped VE translation to the user's physical translation, rotation gain is the proportion of the amount of rotation in the Veto the user's physical rotation and the curvature gain signifies the radius of the curvature on which user is physically walking to virtually walk straight (Steinicke, Bruder et al. 2010). One important aspect of RDW is not to let the user notice the gains applied to her movements. One might ask what would be the threshold for each gain that most users do not notice. Steinicke et al. (Steinicke, Bruder et al. 2010) conduct a study to find thresholds for the three types of gains. They found that users can be made to rotate 20% less or 49% more than the actual physical rotation, translation can be decreased by 14% and increased by 26% and moreover users can be made to steer on a 22m or larger radius circle while they do not notice the gains applied to their movements (Figure2.14-E).

The main goal with the RDW technique is to make the user rotate away from the boundaries of tracking space. Nonetheless, the final target of the injected rotation, can be different and based on this three type of steering algorithms has been defined: *Steer-to-Center* (steers the user toward lab center, Figure2.14-B), *Steer-onto-Orbit* (steers the user onto a circle around lab center, Figure2.14-C), *Steer-to-Alternating-*

Targets (steers the user toward different targets in the lab, Figure2.14-D) (Razzaque 2005). Hodgson et al. (Hodgson and Bachmann 2013) compared these three approaches to a fourth similar approach, *Steer-to-Multiple+Center*. This approach steer users toward multiple targets including center of the tracking area as a target. They have conducted two experiments based on simulated navigation and live user navigation with both synthetic paths and recorded user data. They used measures of maximum and mean distance from the center, number of reaches to the boundaries of the tracking area and redirection rates mean value for both experiments. Their results indicate that Steer-to-Center performed significantly better than other algorithms, and Steer-to-Orbit performed well in some conditions.

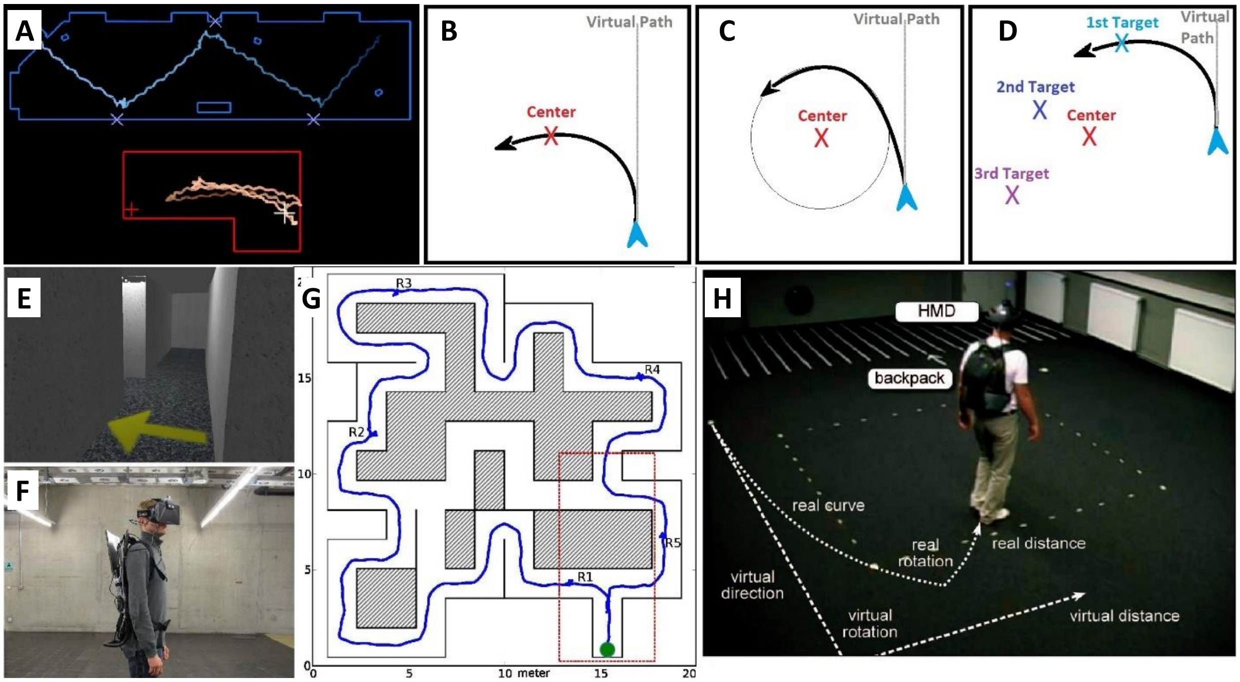


Figure2.14 – Redirected Walking, A: Redirected Walking (RDW) first published by Razzaque et al. (Razzaque, Kohn et al. 2001), B: Steer-to-Center, C: Steer-onto-Orbit, D: Steer-to-*Alternating-Targets, E: Rotation, curvature and translation gains (Steinicke, Bruder et al. 2010), F: VE, G: Hardware setup and H: The path used in the study (Nescher, Huang et al. 2014).*

Optimized RDW

Generalized steering algorithms, make the user move toward collision-free locations. In addition to such algorithms, researchers developed more customized algorithms which demonstrated better results. Zmuda et al. (Zmuda, Wonser et al. 2013) developed an algorithm which uses a multistep, probabilistic estimation of the user's path across the VE as well as the map of the tracking space's shape and barriers to identify a collision-free path to redirect the user. In this algorithm, FORCE, a search base optimization method employs the user's both virtual and physical position and orientation to recognize the optimal steering instruction. Their results indicated that this algorithm identified a higher percentage of collision-free paths, comparing to the generalized algorithms.

Nescher et al. (Nescher, Huang et al. 2014) developed a method to dynamically select and apply redirection techniques and gains and the controlling parameters such as the strength for each gain. They have formulated the problem of redirecting the user in a physically limited space into an optimal control problem to be able to apply an efficient probabilistic planning algorithm. Using this method, it is possible to maximize the space and distance for the user to walk freely. Their algorithm continuously finds the optimal redirection techniques, gains and their control parameters using a map of the VE. Steer-to-Center has been shown (Hodgson and Bachmann 2013) to outperform other generalized steering algorithms. They have conducted an experiment to compare their method to Steer-to-Center as well as the FORCE algorithm (Zmuda, Wonser et al. 2013) which was shown to be more effective than the Steer-to-Center (Zmuda, Wonser et al. 2013). The user could observe the VE (Figure2.14-F) using an HMD and the rendering was done using a laptop carried by the user (Figure2.14-G). Their results indicated that, for the given VE (Figure2.14-H), their algorithm significantly reduced the number of collisions with the boundaries and the amount of redirections applied.

RDW technique has different components which might vary between different redirection-based techniques. Suma et al. (Suma, Bruder et al. 2012) provided a taxonomy of redirection techniques in Immersive VEs. They considered various components for the redirection techniques such as: the alteration in locomotion being continuous or discrete, algorithm performing repositioning or reorientation, alteration being subtle or overt.

Change Blindness

Suma et al. (Suma, Finkelstein et al. 2009) chose a different approach for redirecting the user without requiring translational or rotational gain. Their approach includes dynamically modifying the geometry of the environment to redirect user away from the boundaries of the tracking area. They have provided a proof of concept, in which as the user enters the room (Figure2.15-A), and is walking toward the wall in front of her, they position of the door in the room change (Figure2.15-B), while most users will not notice and feel they have been walking on a straight hallway (Figure2.15-C).

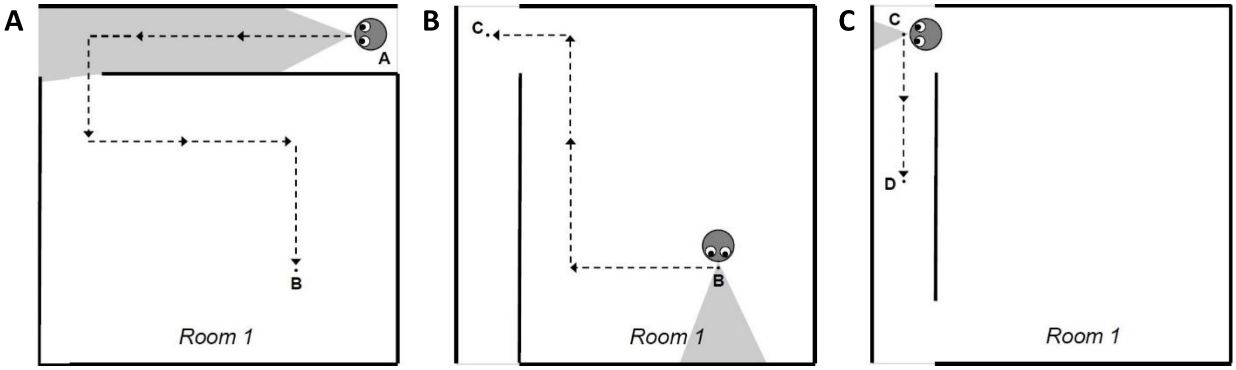


Figure2.15 –Change Blindness, A: User enters the room, B: As the walks toward target the position of door changes, C: User exits the repositioned door(Suma, Finkelstein et al. 2009).

Effects of Redirection

Redirection can affect spatial orientation in both real world and VE. Suma et al. (Suma, Krum et al. 2011) conducted an experiment and compared the effects of change blindness redirection, rotation-based redirection and not redirecting the user. They observed that participants updated their virtual and real world orientation and could accurately point to targets. However, when using the change blindness redirection, the realignment of targets seems more difficult for the users. Based on the literature

(Bowman, Koller et al. 1997, Nabiyouni and Bowman 2015) the strategy user chose might have a greater effect on their orientation understanding, rather than the locomotion technique.

2.11 Low-fidelity Techniques

Gamepad Technique

Gamepad is one of the most common techniques for travel through VE. This device was developed for game and entertainment interfaces and has been adopted by VR researchers (Whitton, Cohn et al. 2005, Sibert, Templeman et al. 2008, Yan, Lindeman et al. 2016) due to its ease of use, familiarity and effectiveness. This interface often uses two joysticks, one for viewpoint translation control and the other for viewpoint rotation control. User pushes the joystick in any direction to steer in that direction using a rate based control. Gamepad employs good HCI design principles and even users who tries it for the first time can learn it quickly and use it effectively. Since the input mapping are not close to walking, this technique can be considered as a non-natural technique.

Flying

Flying technique enable the user to translate and rotate her view point almost freely in the 3D space. It can be similar to a bird or an airplane flying (Usoh, Arthur et al. 1999, Interrante, O'Rourke et al. 2007) (Whitton, Cohn et al. 2005). This technique provides the user with super-natural capabilities which are not normally possible in the real world. The output of this technique has more freedom comparing to a non-natural technique such as gamepad and includes freedom of movement in the all three dimensions. Moreover, this technique has higher freedom on the input side and is not limited to use walking as an input. Therefore, this technique can be categorized as super-natural.

Walking with Teleportation

The idea of teleportation has been discussed for years and some VR researchers and game designers would benefit this metaphor to allow user travel around the VE. Stinicke, Bruder et al. (Steinicke, Bruder et al. 2009) developed a replica of the physical tracking space (Figure2.16-B) and used portals so that user can transition from the simulation of the physical space to the actual VE (Figure2.16-C). This technique was in an architectural walkthrough project (Bruder, Steinicke et al. 2009). Users are able to select rooms in the miniature model (Figure2.16-D) and use the portal to travel to the room (Figure2.16-E).

Some researchers have employed this technique as means of long distance travel rather than local and short distance navigation. Schroeder et al. (Schroeder, Huxor et al. 2001) developed *Activeworlds*, a multi-user VE, available over the internet. They employed teleports throughout the Activeworlds as means of travel. Such teleports, teleport users to a new location based on a Cartesian coordination system. The portals metaphor has been combined with other techniques. Freitag et al. (Freitag, Rausch et al. 2014) used this technique in RDW to reorient users as they reach the boundaries to the physical tracking space and needs to reset their position and orientation. In this study, to direct users to a safe location, the portals are placed automatically and the user walks to the portal to reorient (Figure2.16-F). As users reach the boundaries of the physical space a barrier tape warns them and they can place a portal at their desired location using a hand-held pointing device which employs recasting selection technique. Other reorientation techniques often actively interrupt the user or cause simulator sickness. Comparing to other reorientation methods such as point-and-fly and teleportation, this technique allows users to walk more and can cause less simulator sickness, with the cost of longer completion time.

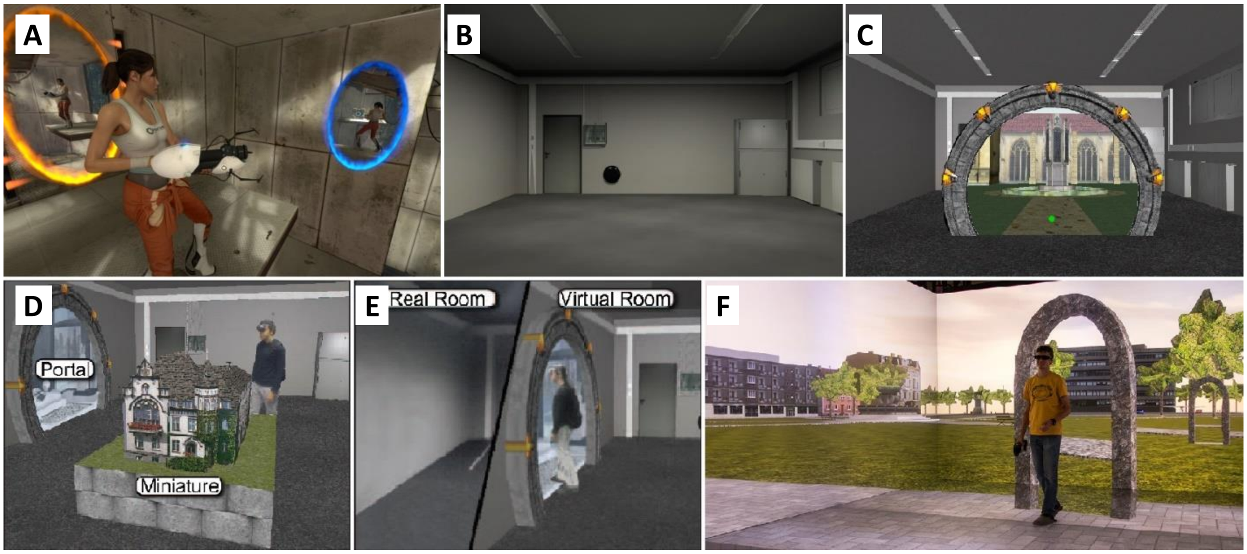


Figure2.16 –Teleportation, A: Gamers can create enter and exit portals using a portal gun (Wolpaw 2011), B: the simulated environment of a library in the same physical place, C: A virtual portal enable user to move through to the actual VE (Steinicke, Bruder et al. 2009), D: User can select a room in the miniature model, E: and travel to the room using the portal (Bruder, Steinicke et al. 2009, Marsh and Kluss 2015), User creates a portal and user walks to the portal to reorient (Freitag,

Game developers also have adopted the similar idea. Portal 2 video game (Wolpaw 2011) provide the user with a portal gun which enables her to create entrance and exit portal gates and use them to travel to other places, which can be unreachable for her using normal navigation method (Figure2.17-A). A Novel locomotion interface, *Blink Elastic VR PlaySpace* (Unger 2015), employs teleportation technique to allow users explore a large VE of *The Gallery* (Unger 2016) video game. This locomotion technique employs teleportation to move a representative of the tracked real world into the VE. They can also rotate the representative of the physical space to better fit area they want to explore. Using this technique, users will select the area they want to explore in the VE and the Blink technique moves them there, and they will be able to explore part of the VE as large as their physical space around them. This interface provides the user with visual effects showing the boundaries of their physical space as depicted in Figure2.17-B and Figure2.17-C. This technique provides users with tangible references to their physical space over time to encourage physical movement and unsure safety. The teleporation technique can be categorized as a super-natural technique.

Figure2.17 –Blink locomotion technique based on teleportation, A: The user can explore part of the VE as large as the physical space at each time, B: The user can move a representative of the physical space to explore other places in the VE, C: A visual effect shows the boundaries of the real world to the user

World-in-Miniature

A *World-in-Miniature* (WIM) (Stoakley, Conway et al. 1995) is a miniscule graphical representation of the VE similar to a small hand-held 3D map (Fisher, McGreevy et al. 1987) or a map cube, which has been used as a navigation and locomotion technique. Stoakley et al. (Stoakley, Conway et al. 1995) have implemented the WIM technique for manipulating, navigating, path planning and visualizing the VE (Figure2.18-A). Using their interface, as the user moves a virtual object in the WIM model, the object will move in the VE simultaneously and correspondingly. User will be able to directly manipulate the virtual object in the Immersive VE as well. To navigate the user can select a virtual avatar of herself in the WIM and move the iconic representation fly through VE.

However, flying through the VE can be confusing and discomforting because meanwhile the user is focused on the WIM model. To solve this problem Pausch and Burnette (Pausch, Burnette et al. 1995) benefit an anthropometric doll icon and an animation method. The user moves the avatar to move herself. As soon as she releases the iconic representation of herself, the interface animates the user into the miniature (Figure2.18-B). To avoid changing the scale of neither WIM nor the user, the old full scale VE imagery fades out and the new WIM appears before the user.

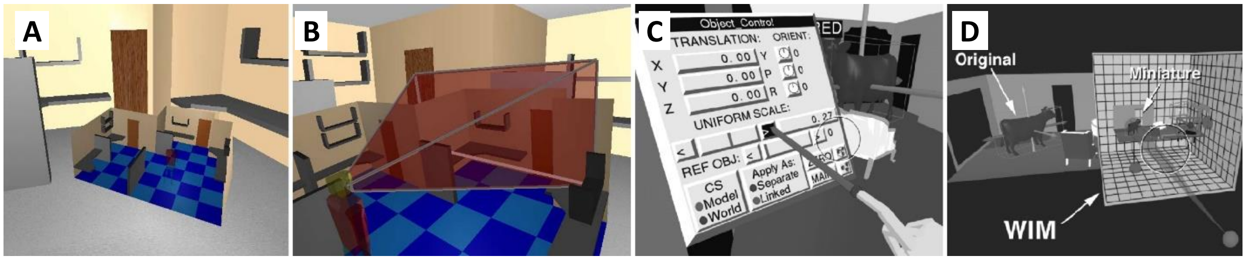


Figure2.18 – World-in-Miniature technique, A: WIM model against the background of the actual VE, B: The frustum shows the user's view in the VE (Pausch, Burnette et al. 1995), C: Object control Panel, D: WIM superimposed over the VE (Mine 1996).

Mine (Mine 1996), used two 6DOF trackers to enable user duplicate and manipulate virtual objects and navigate the VE using the Stoakley's WIM (Stoakley, Conway et al. 1995). He attached one 6DOF tracker to a physical clipboard and attached the other tracker to a bat, which kept one in each hand (Figure2.18-

C). The virtual hand-held miniature was attached to the clipboard tracker (Figure2.18-D). Mine implemented the WIM in the Immersive Simulation Animation and Construction (ISAAC) program as a means of travel and object manipulation (Mine 1997). To provide users with more control over object manipulation, he used grid and constrained motion functions in conjunction with the WIM technique. WIM is nothing similar to walking both on the input and output, therefore it is a super-natural technique.

3 Related Work: Results of Prior Studies

3.1 The Effects of Fidelity

To evaluate fidelity, some virtual reality (VR) researchers have compared interfaces with different levels of fidelity for different aspects of realism, such as display and interaction fidelity. For locomotion interaction, specific aspects of fidelity have been considered by researchers to compare interfaces. For instance, Ruddle et al. (Ruddle, Payne et al. 1999) compared a head-mounted display (HMD) to a desktop system for the task of navigating a large-scale VE. They found that users could navigate the VE significantly faster using the high-fidelity HMD. Bowman et al. (Bowman and McMahan 2007) used a CAVE (Cruz-Neira, Sandin et al. 1993) system for generating high-fidelity and low-fidelity conditions. They investigated several components of immersion affecting performance, being accuracy and time. They observed that higher levels of display fidelity can improve interaction task performance.

In addition to display fidelity, specific interaction aspects have been considered by researchers. Chance et al. (Chance, Gaunet et al. 1998) compared three locomotion interaction techniques, and found that the more natural techniques produced greater spatial orientation in users than the less natural ones. Techniques providing more integrated degrees of freedom (DOFs) for the task of 3D object manipulation (Hinckley, Tullio et al. 1997) and rotation (Pausch, Proffitt et al. 1997) were more effective. McMahan et al. (McMahan 2011, McMahan, Bowman et al. 2012) showed that pointing directly to a target is more effective than using a mouse to aim.

In (Pausch, Proffitt et al. 1997) Pausch, et al., has compared a VR interface with a stationary monitor and a hand-based input device. They showed that users completed a search task faster with a VR interface than, with a stationary monitor and a hand-based input device. They asked users to look for camouflaged objects while the user was standing in the center of a virtual room. They observed that VR users did not do significantly better than other users. However, for the task of searching the room to see whether the object exists. VR users were faster than the other two groups. Desktop users took 41\% more time to look around and examine the area. They conclude that techniques providing more integrated degrees of freedom (DOFs) for the task of 3D object manipulation and rotation (Pausch, Proffitt et al. 1997) were more effective. Pausch, et al., (Pausch, Proffitt et al. 1997) showed that higher fidelity interaction can increase user performance, by comparing natural head tracking to hand-based view point control, for a search task.

Other results show increasing interaction fidelity can decrease user performance, which seem to be in contrast with the aforementioned studies. McMahan, et al., (McMahan, Bowman et al. 2012) presented a comparison between two locomotion interfaces: semi-natural (human joystick) technique and non-natural (mice and keyboard) techniques in a first-person 3D game. They have conducted an experiment to evaluate interaction fidelity and display fidelity independently using a six-sided CAVE. They have compared interaction and display fidelity at extremely high and low levels, for a VR first-person shooter (FPS) game to gain a better understanding of the effects of fidelity on the user in a complex, performance-intensive context. Their results indicate that both display and interaction fidelity significantly affect different parameters such as performance, strategy, subjective judgments of presence, usability, and engagement. They observed that the two conditions of low fidelity (representative of traditional FPS games) and high fidelity (similar to the real world), outperformed conditions with medium level of fidelity. As another example, “natural” interaction techniques using a steering wheel for driving a vehicle in a racing game were significantly less effective than low-fidelity techniques using buttons (McMahan, Alon et al. 2010). These experiments compared higher and lower fidelity techniques, but it is unclear whether these results are generalizable.

3.2 Analyzing Interaction Fidelity

McMahan, et al. (McMahan, Bowman et al. 2012) posited that the overall level of interaction fidelity depends on a combination of system characteristics. They pointed out that each element of an interface may fall at a different location on interaction fidelity spectrum. This idea has been further discussed in (McMahan 2011), which introduced the Framework for Interaction Fidelity Analysis (FIFA). The FIFA framework compares interaction techniques to their real world counterparts across several dimensions. FIFA allows us to compare interaction techniques and where they fall on the fidelity spectrum. We employ FIFA to better understand differences among the three locomotion interfaces in our study using this established framework.

FIFA describes interaction fidelity with three primary factors: biomechanical symmetry, control symmetry and system appropriateness. In this framework, each technique is compared to the real-world counterpart for the interaction task, to understand how this technique compares to natural interaction.

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. Sub-components of biomechanical symmetry include kinematic, kinetic, and anthropometric symmetry. *Kinematics* is concerned with body motions or trajectories; *kinetics* refers to the forces applied to cause body movements; and *anthropometry* considers which body parts are used.

Control symmetry describes how the control provided through the interaction technique compares to control in the real-world task. It also has three sub-components: dimensional, transfer function, and termination symmetry. *Dimensional symmetry* considers the similarity between the control dimensions in a real-world task and those in an interaction technique. *Transfer function* symmetry refers to how interaction techniques interpret and transform input data into an output effect. *Termination symmetry* is concerned with how the interaction is stopped (although not included in the original FIFA publication, we also consider initiation–how the interaction is begun).

System appropriateness characterizes the suitability of the system for performing a particular aspect of the interaction, and includes four factors: input accuracy, input precision, latency, and form factor. *Input accuracy* is how close to the ground truth measurements of input are. *Input precision* refers to how repeated measurements produce the same results in static conditions. *Latency* is the amount of delay between user input and feedback generated by the system. Finally, *form factor* is concerned with the shape and size of the input device.

In a more recent version, FIFA (McMahan, Lai et al. 2016) considers three categories of biomechanical symmetry, input veracity, and control symmetry. Biomechanical symmetry is similar to the old version. Input veracity concern with the degree of exactness with which the input system capture user’s movements and includes accuracy, precision and latency. In the new version of FIFA, control symmetry only depends on the transfer function symmetry.

The new version of FIFA, emphasizes the importance of the interaction phases, including: the initiation phase, the continuation phase and the termination phase. The initiation phase requires all three biomechanical, input, and control aspects to start using a technique. Moreover, the continuation phase includes all aspects required for continuing the interaction. Eventually, the termination phase encompasses what is required to terminate the interaction.

3.3 Locomotion Interaction Effectiveness

While there have been many studies comparing purely virtual travel techniques, relatively few studies have directly compared the performance of two or more higher-fidelity locomotion interfaces. Griffiths et al. (Griffiths, Sharples et al. 2006) devised a set of VE tasks and tests to study the performance of navigation and object manipulation. However, it is not clear if higher fidelity leads to better performance. Before answering this question, we need to know how to evaluate the effect of fidelity for various interfaces.

Interaction techniques with relatively high, low and medium levels of fidelity have been compared for performance. Gamberini et al. (Gamberini, Spagnolli et al. 2013) compared three locomotion techniques (walking-in-place with head tracking, walking-in-place and Joystick) for a complicated walking task. They observed better performance with the highest-fidelity technique (walking-in-place with head tracking). Peck, et al., (Peck, Fuchs et al. 2012) compared a large-scale real-walking locomotion interface called Redirected Free Exploration with Distractors (RFED) to walking-in-place and joystick techniques. They have evaluated the effects of locomotion interface on cognitive performance for tasks of navigation and wayfinding. The RFED technique was significantly better, and participants using this technique made fewer wrong turns, pointed to targets more accurately and more quickly, and traveled shorter distances. They did not observe any significant difference between the walking-in-place and joystick techniques, although the mean values for joystick were better than walking-in-place.

Similar results were observed by Feasel, et al., (Feasel, Whitton et al. 2008), for comparing high-fidelity techniques real walking and VRWalk to Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP) and joystick techniques. Locomotion interface based on walking-in-place (WIP) technique in virtual environments often have two problems: system latency and changing the user's viewpoint. Usability problems of system latency, specifically affect starting and stopping locomotion. Additionally, in locomotion techniques based on WIP, changing the user’s viewpoint might not be continuous and seamless. Feasel, et al., introduce a novel WIP interface (Feasel, Whitton et al. 2008) that improves both latency and the continuity of synthesized locomotion in the virtual environment. They created a direct mapping from foot-motion to locomotion basing the virtual avatar motion on the speed of the user’s heel motion while walking in place. This method is responsive, intuitive, and easy to implement. They have analyzed the starting and stopping latency for their technique, and discussed their experimental results on the suppression of false steps and also general usability of their system. Their evaluation includes an analysis of the time required to train to competence with LLCM-WIP, as compared to other locomotion techniques, as well as user comments about possible improvements. Two measures were specifically analyzed in this paper. The first measure was body-seconds of exposure, including the amount each user was in the open and not safely sheltered within a safe-zone during gunfire. The second measure was the length of the head's trajectory during gunfire. This measure would be near zero, if the user didn't need to take any corrective steps to get into place and could reached the safe-zone in time. They observed that the results of using WIP and joystick were close, but these results were considerably worse than all real walking conditions. They have found that stationary locomotion interfaces cost-effective and convenient, which makes the tradeoff worthwhile. They concluded that a WIP system which has the medium level of fidelity, cannot be expected to out-perform a gamepad like interface for performance measures such as accuracy and responsiveness.

Whitton, et al., (Whitton, Cohn et al. 2005) compared three high-fidelity walking techniques, a low-fidelity flying technique using a joystick and a medium-fidelity technique of walking-in-place. They have characterized task behavior and task performance in a both computer generated environment and a corresponding real environment. Participants were asked to navigate a maze and walk as close to targets on the walls as possible. They have designed and implemented five experimental conditions using a combination of one of three visual conditions (head-mounted display, unrestricted natural vision, or field-of-view-restricted natural vision), and one of three locomotion interfaces (really walking, walking-in-place, and joystick flying). We identified metrics and collected data that captured task performance and the underlying kinematics of the task. For the performance metric of final distance to target, there was a main effect of interface type indicating, the walking-in-place technique was outperformed by the joystick technique. For other performance measures such as peak velocity and peak deceleration the walking-in-place was better than the joystick technique.

A study on cognitive implications of semi-natural locomotion interfaces was performed by Marsh, et al., (Marsh, Putnam et al. 2012). They compared a gamepad interface (least natural), the position-to-velocity (P2V) interface (slightly more natural) and real walking (completely natural baseline). In the P2V interface the user's virtual velocity was indicated by the distance from the center of the physical environment. They have conducted a user study, in which participants were asked to perform a basic task of locomotion while remembering a sequence of spatial or verbal items. Users employed one of the three locomotion interfaces. They observed the stopping time and memory task were significantly better for gamepad and real walking compared to the P2V interface, while they did not observe any significant difference between gamepad and real walking. For the measure of memory items missed, the cognitive load of real walking was significantly less than both P2V and the gamepad interface. Their results indicated that semi-natural locomotion interfaces require spatial working memory resources. They concluded that a locomotion interface competes with the ongoing spatial tasks, but not for the verbal or general attention resources.

Articles such as (Pausch, Proffitt et al. 1997) observed an increase in user performance with increasing level of fidelity. This work was conducted in 1997, and the apparatus used in their system was old comparing to state-of-the-art technology we have today, which might challenge the validity of the results using novel devices such as head mounted displays (HMD) with higher resolution and field of view. In addition, their performance comparison is based on the search task, and might not be valid for other tasks. Other articles seem to have results in contrast with (Pausch, Proffitt et al. 1997). Results from (Feasel, Whitton et al. 2008) and (McMahan, Bowman et al. 2012) indicated that interface with medium level of fidelity can have lower performance comparing to well-designed interfaces non-natural interfaces with low level of interaction fidelity. Faesel, et al., (Feasel, Whitton et al. 2008) focuses on describing the novel locomotion method and maybe a study using more controlled conditions and more task performance measure could better differentiate between the locomotion interfaces. McMahan, et al., (McMahan, Bowman et al. 2012) defines four conditions with high and low levels of interaction and display fidelity. This study uses various well-defined measures of effectiveness and can better indicate difference between the levels of fidelity. (Peck, Fuchs et al. 2012) uses three different levels of locomotion interaction fidelity for various locomotion tasks. They found the same results for comparing medium level of interaction fidelity with highly natural interfaces. Although, they did not find any significant difference between low and medium levels on interaction fidelity, their results showed better mean values for low fidelity interface. This means, maybe with more statistical power they might observe significant differences.

Other articles found rather mixed results. Whitton, et al., (Whitton, Cohn et al. 2005) included five locomotion techniques in their comparison and performed a controlled experiment to evaluate various performance measures. On the other hand, Marsh, et al., (Marsh, Putnam et al. 2012) used locomotion as the secondary task and asked users to perform verbal or spatial memory tasks while using the locomotion interfaces. Both of these articles found rather mixed results for comparing different levels of interaction fidelity for different tasks. This indicate the need for more in depth studies to better understand the effects of fidelity.

Like interaction fidelity, effectiveness is not a single construct. Researchers have been comparing different travel techniques based on different metrics. In an early battery of tasks and measures (Lampton, Knerr et al. 1995) developed to characterize the effectiveness of interaction techniques, task completion time and accuracy (number of collisions) were used as performance measures for locomotion tasks. Metrics such as amount of pressure on the foot or spatial awareness were used for locomotion devices based on walking (Iwata 1999). Subjective measures such as presence, simulator sickness or ease of use have also been used to compare navigation techniques (Usoh, Arthur et al. 1999, Hollerbach 2002). Other researchers used a combination of objective and subjective measures such as spatial ability and simulator sickness(Chance, Gaunet et al. 1998) in addition to object recall and object recognition (Suma, Finkelstein et al. 2010). Bowman et al. (Bowman, Koller et al. 1997) introduced a taxonomy of travel techniques along with a framework for evaluating the quality of different techniques for tasks including absolute motion, relative motion and spatial awareness. This framework was expanded into a testbed (Bowman, Koller et al. 1997) that allows evaluation of not only the effects of various travel techniques, but also the impact of different factors including environment, task and user characteristics.

3.4 Locomotion Interaction Improvement

3.4.1 Employing Hyper-Natural Techniques

Hyper-natural techniques allow users to perform interactions that would be impossible in real world, although unlike super-natural techniques, hyper-natural techniques use natural metaphors or interactions to extend users' abilities. For example, the Go-Go technique (Poupyrev, Billinghurst et al. 1996) allows the user to reach far into the virtual environment (VE) by extending his physical hand. This technique enables users to select and manipulate virtual objects at a distance based on the real-world interaction of reaching and grabbing objects. Similarly, in Wii Sports tennis, users can perform forehands and backhands based on the real-world action of swinging a tennis racket, but without a direct mapping of the physical movements to the virtual movements. This technique enhances precision by mapping a wide variety of swing movements to “perfect” swings in the game.

Although magic travel techniques are numerous and diverse (e.g., camera in hand or flying techniques (Ware and Osborne 1990, Hand 1997)), only a few of them can be considered hyper-natural. Scaling up the user’s movement with a constant factor allows faster movements through a larger environment (Interrante, Ries et al. 2007). However, this may reduce precision and the user’s distance estimation ability. Interrante et al. (Interrante, Ries et al. 2007) scaled up the movements of the user using a non-uniform scaling. To improve precision, this technique scales the movement only when the speed is higher than a certain threshold, like a mouse acceleration.

3.4.2 Training and Cues

Training can help users acclimate to the interface and improve performance (Anderson 1982, Bowman, Kruijff et al. 2004, Richardson and Waller 2005). Gerathewohl studied the training transfer for the application of flight simulator and found out the amount of training transfer is proportional to the degree of fidelity of the system (Gerathewohl 1969). Marsh et al. examined the effectiveness of training on performance and cognitive resource demands in the Virtusphere (Marsh, Hantel et al. 2013). They found that using the Virtusphere imposes cognitive demands on users that make this interface less effective than real-world walking. They also showed that training can have a positive effect on movement abilities and performance. Richardson et al. (Richardson and Waller 2005) studied the effect of using error corrective feedback on distance estimation in VEs. They observed that receiving feedback improves ability to estimate distances for which feedback was provided. Moreover, they argued that feedback training effects are specific to both the type of judgment and the type of response. Darter et al. (Darter and Wilken 2011) employed a real-time visual feedback in a rehabilitation VR system. Their results showed that providing suitable visual cues will improve movement abilities in rehabilitation application.

While walking in a VE, the user may receive vestibular and proprioceptive cues that are different than the cues that would occur when walking in the real world. Visual cues dominate vestibular (Razzaque 2005) or proprioceptive (Kennedy, Lane et al. 1993) cues in our perceptual system. Considering this fact, providing appropriate visual feedback can facilitate learning of semi-natural interfaces.

4 Designing Effective Travel Techniques with Bare-hand Interaction

This project is an early research experiment we did on 3D travel techniques as the first study for this dissertation. Even though this project is not about walking in VR, it informed our thinking about interaction fidelity and 3D movement.

In this experiment we compare travel techniques with various interaction fidelity levels for absolute search, naïve search and path following tasks. The camera-in-hand metaphor employs a 1:1 transfer function of the hand movements to the translating and rotation the viewpoint in the VE. On the other hand, the airplane metaphor uses a rate-based control for view point rotation and a speed control movement for the view point translation. Moreover, using the camera-in-hand metaphor, the user applies forces in the direction she wants to move virtually, while the forces in the airplane metaphor are completely different.

In terms of transfer function and kinetic symmetry, the camera-in-hand metaphor has higher level of fidelity comparing to the airplane metaphor. Comparing these techniques in an experiment, can provide us with more evidence for the RQ1.

4.1 Introduction

Emerging novel 3D interaction technologies allow precise tracking of bare hands and fingers, but due to the differences between these devices and traditional trackers, it is not clear how to design effective interaction techniques using these technologies. Using the Leap Motion Controller, we designed travel techniques with bare-hand interaction. We prototyped both unimanual and bimanual techniques using various metaphors (e.g., airplane and camera-in-hand), control mappings (position- vs. rate-control), camera movements (scene vs. camera dependent) and methods for speed control. Based on our experiences with these prototypes, we discuss the challenges and design issues for bare-hand interaction techniques. We present the results of a user study comparing the usability of five representative techniques for three travel tasks: absolute travel, naïve search and path following (Figure 4.1). We found that the limited workspace of the Leap caused movements with the camera-in-hand metaphor to be faster and less accurate, making it more effective for search but less effective for path following tasks. In addition, the Leap's ability to precisely track small finger movements benefited the usability of continuous speed control techniques.

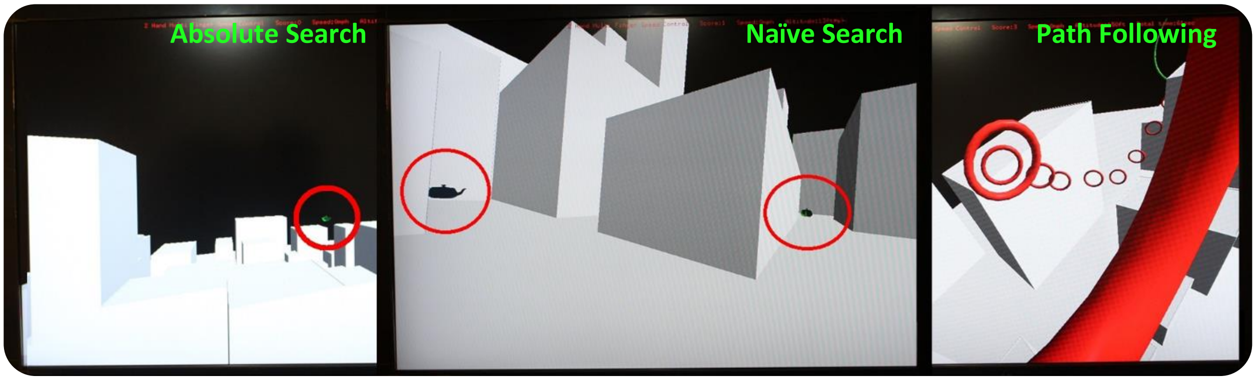


Figure 4.1: Tasks of absolute search, naïve search and path following.

4.2 Technique Design

The Leap Motion Controller (www.leapmotion.com) is a novel 3D interaction technology, able to detect and track hand and finger position and orientation with a high level of precision. The Leap device can distinguish inputs from about 3 cm up to 50 cm from the device, and its field of view spans about 150 degrees above the device. Although the Leap device is highly capable, it has some limitations. The Leap may not recognize fingers individually if they are right next to each other or crossed over. Also, the Leap might lose tracking of the fingers and palm if the hand is rotated (rolled or pitched) by more than about 80 degrees. The amount of fatigue caused by using the Leap may also be significant.

Figure 4.2: Bare-Hand Travel using the Airplane Metaphor.

Our strategy in designing travel techniques for the Leap was to use the user's hand for two different metaphors: airplane metaphor (A) and camera-in-hand metaphor (C), based on (Ware and Osborne 1990) and (Hand 1997). Since the Leap device can recognize how many fingers are visible, we tried discrete speed control methods (M), which map the number of visible fingers to movement speed. To use the Leap's ability to detect hand and finger position and orientation, we designed continuous speed control methods: thumb speed control (T) and gas pedal metaphor (G).

We designed both unimanual (U) and bimanual (B) techniques to have a better understanding of the usability of these types of techniques with the Leap. In bimanual techniques, we dedicated the more precise task of steering to the dominant hand and the coarser task of speed control to the non-dominant hand (Guiard 1987, Balakrishnan and Kurtenbach 1999).

The Leap is unable to detect 360-degree rotation. If the hand is rotated more than about 80 degrees around the roll or pitch axes, the Leap may lose tracking. While position control mappings can provide a more natural control method, rate control can increase coordination and provide a smoother and steadier movement due to the Leap's limitation (Guiard 1987, Balakrishnan and Kurtenbach 1999). To study these limitations, we implemented rate-controlled and position-controlled pitch and yaw.

After exploring the design space and trying many combinations of these components, we selected five candidate prototype designs to evaluate. We used both the camera-in-hand and airplane metaphors in the user study. The camera-in-hand metaphor (CU) used a direct mapping of the Leap's workspace to the virtual world (Figure 4.3). For the airplane metaphor techniques, the forward direction of movement was defined by the current orientation of the camera. Different techniques using the airplane metaphor are shown in Table 1. Rate-controlled mappings were selected for the airplane metaphor techniques.

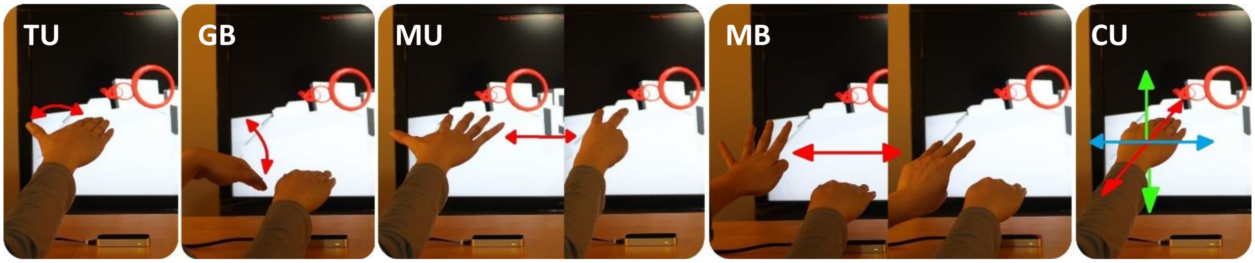


Figure 4.3- TU: Thumb Control Unimanual Technique, GB: Gas Pedal Bimanual Technique, MU: Multi-finger Unimanual Technique, MB: Multi-finger Bimanual Technique, CU: Camera-in-hand Unimanual Technique.

A position-controlled mapping was selected for the camera-in-hand metaphor to provide a natural feeling of mapping hand position and orientation to camera position and scene.

Table 4.1: Selected designs for airplane metaphor

	Continuous Speed Control	Discrete Speed Control
Unimanual	Thumb Speed Control (TU)	Unimanual Multi Finger Speed Control (MU)
Bimanual	Gas Pedal Speed Control (GB)	Bimanual Multi Finger Speed Control (MB)

4.3 Evaluation

The goal of our study was to understand how different travel techniques were affected by the characteristics of the Leap device, so that we could give guidance to designers of such techniques. We had two main research questions:

1. How do the characteristics of the Leap affect the usability of different sorts of techniques?
2. Which bare-hand technique designs are most effective for various travel tasks?

To examine these questions, we designed an experiment to evaluate the five travel techniques for different standard travel tasks. Twelve unpaid volunteer participants were recruited for this study. The ordering of the five selected techniques (CU, TU, GB, MU, and MB) was counterbalanced. We designed three travel tasks based on (Bowman, Kruijff et al. 2004).

The first task, absolute travel, required the user to travel from a starting position to a known target position. The second task, naïve search, required the user to search for targets in a specific time-frame. The third task was path following, in which the user was required to follow a specific path by passing through a number of rings. All of the tasks were set in a simple virtual city environment as seen in Figure 4.2.

We ran a one-way analysis of variance (ANOVA) on the results of the five techniques for each task. For the absolute travel task, we measured time to reach the target. We found that the effect of technique on time was not significant ($p = 0.3724$).

In naïve search, participants were asked to find 12 objects in a 120-second timeframe. We measured the time it took to find three (T_3), six (T_6), nine (T_9) and twelve (T_{12}) objects. We observed a significant effect of technique on efficiency for naïve search. The camera-in-hand metaphor (CU) was significantly faster than all four airplane metaphor techniques for all measured times (except TU technique for T_3). For the final time T_{12}, CU was faster than TU ($p = 0.0049$), MB ($p = 0.0008$), MU ($p < 0.0001$) and GB ($p = 0.0014$). The comparison between the camera-in-hand and airplane metaphors is depicted in Figure 4.4.

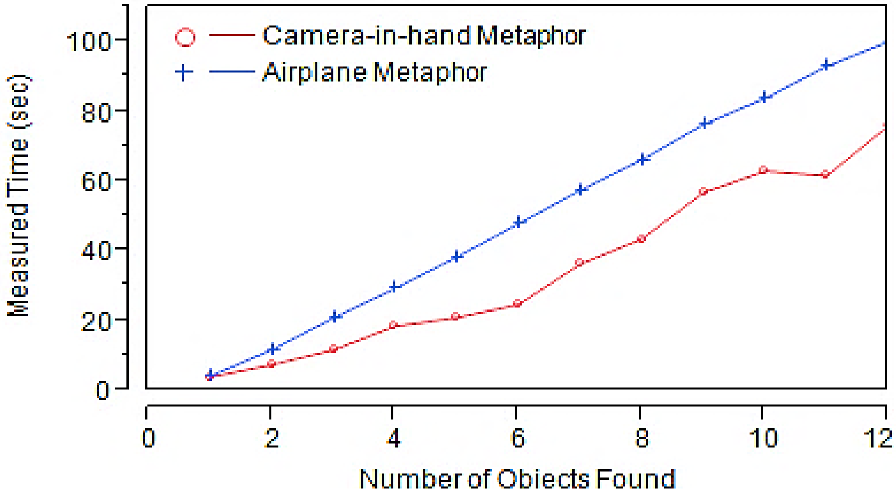


Figure 4.4: Camera-in-hand and Airplane metaphor Comparison for Naïve Search.

For the third task, the user was expected to pass through 20 rings in a 60-second timeframe. Our score function added the time for this task to a penalty of five seconds for missing a ring. We found a significant effect of technique ($p < 0.0001$) on path following. The four airplane metaphor techniques were significantly better than the camera-in-hand metaphor (Figure 4.5).

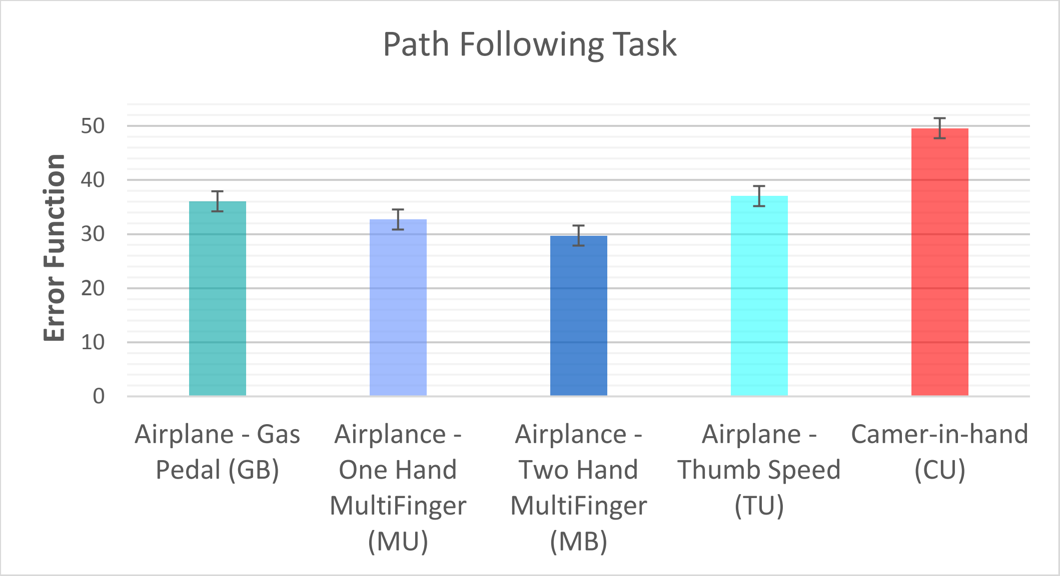


Figure 4.5- Error value of the various techniques for the path following task. The lower amounts are better. The error bars indicate standard error.

4.4 Discussion

For naïve search, camera-in-hand was significantly faster in finding objects. The Leap has a relatively small workspace. Mapping a small workspace to a comparatively large 3D environment can result in fast travel in the environment while decreasing movement precision. In naïve search, it was more important to explore the environment quickly to find the targets than to precisely follow a given trajectory, so the camera-in-hand technique performed well despite its lack of precision.

Additionally, results indicated that the GB technique was significantly slower than the other continuous speed technique TU, for finding the first six targets in naïve search. GB and TU are both continuous speed airplane metaphor techniques but GB is bimanual and TU is unimanual. The GB technique was not significantly slower for the second half of the naïve search to find targets seven to twelve. Bimanual techniques require the user to focus on both hands. The increasing efficiency of the GB technique over time may indicate that for continuous speed control, more training is needed for bimanual techniques as compared to unimanual.

In path following, on the other hand, the airplane metaphor was significantly more efficient than the camera-in-hand metaphor. This is because the task requires precise trajectory control, and because the airplane metaphor does not require hand translation for traveling in the environment. Thus, it can be used in devices with relatively small workspaces for accurate bare-hand interaction.

Based on our experience with designing the techniques and user's opinions, we observed that continuous speed control can provide a better user experience. Additionally, the Leap's accurate palm and finger detection ability benefits navigation for the delicate task of path following.

4.5 Summary

In this experiment generally we compared two 3D travel techniques, airplane metaphor and camera-in-hand metaphor for the tasks of absolute search, naïve search and path following. The camera-in-hand metaphor directly maps hand position and orientation to the position and orientation of the camera, while airplane metaphor provides a rate-based control for controlling pitch, roll and yaw. Each technique uses a different transfer function to map hand motions to the viewpoint transfer and the camera-in-hand metaphor's transfer function is more natural. Although both these techniques are considered as super-natural, the camera-in-hand metaphor has higher level of interaction fidelity, due to the hand position and orientation mapping, comparing to the airplane metaphor.

The camera-in-hand metaphor was significantly faster for the naïve search due to mapping of the small Leap's workspace to a relatively large VE. On the other hand, the airplane metaphor was significantly more effective for the task of path following. Although, camera-in-hand had lower level of interaction fidelity, users performed better and has better experience using this technique. This study helped us to find initial answers for the RQ1 about the relationship between interaction fidelity and effectiveness.

To address RQ1, we need to compare interfaces with medium level of fidelity with low- and high-fidelity locomotion interfaces. We have covered this in section 5.1, 5.2 and 5.3 (Nabiyouni, Laha et al. 2014, Nabiyouni and Bowman 2015, Nabiyouni, Saktheeswaran et al. 2015). In section 5.2, we discuss the effects of various components of interaction fidelity as well as the effects of the hyper-natural techniques and run an experiment with several techniques to cover the RQ2 and RQ3 (Nabiyouni and Bowman 2015). Section 5.3 discusses an experiment to improve effectiveness of the medium-fidelity locomotion interaction and addresses RQ4.

5 For RQ1: Comparing the Performance of Natural, Semi-Natural, and Non-Natural Locomotion Techniques

One of the goals of much virtual reality (VR) research is to increase realism. In particular, many techniques for locomotion in VR attempt to approximate real-world walking. However, it is not yet fully understood how the design of more realistic locomotion techniques affects user task performance.

To gain a better understanding of these contradictory results reported in the literature about the fidelity-performance relationship, discussed in Section 1.6, we tested three locomotion interfaces with different levels of fidelity. We performed an experiment to compare a more natural locomotion technique (based on the Virtusphere device (Latypov 2006)) with a traditional, non-natural technique (based on a game controller) and a fully natural technique (real walking (Usoh, Arthur et al. 1999)). We found that the Virtusphere technique was significantly slower and less accurate than both of the other techniques.

Based on this result and others in the literature, we speculate that locomotion techniques with moderate interaction fidelity will often have performance inferior to both high-fidelity techniques and well-designed low-fidelity techniques. We argue that our experimental results are an effect of interaction fidelity, and perform a detailed analysis of the fidelity of the three locomotion techniques to support this argument. The results of our study contribute an improved understanding of the performance of locomotion techniques at varying levels of interaction fidelity. These results partially answer the RQ1 we aforementioned in chapter 1: How does the effectiveness of locomotion techniques change at varying levels of fidelity? Does increasing interaction fidelity "guarantee" increase in effectiveness?

Figure5.1 – Virtusphere used in this study

5.1 Design

5.1.1 Locomotion Interfaces

The gamepad technique was designed similar to a standard gaming interface in which translation (forward/backward and left/right) used a thumbstick controlled by the dominant hand while rotation (yaw and pitch) used the other thumbstick controlled by the non-dominant hand. The user was not head tracked for this technique, and viewing direction and moving direction were coupled.

In the Virtusphere technique, the user's walking inside the Virtusphere was directly mapped (direction and scale) to the viewpoint movement in the VE (Figure5.1). The viewing direction and walking direction were decoupled.

For the real walking technique, users were physically walking in a tracked space, while wearing a tracked HMD. The user's position and orientation were mapped directly to the VE without scaling.

5.1.2 Tasks

A standardized training task involved walking along a straight line to reach the target. Participants were instructed to walk precisely on the line to reach the target. The training task was performed in a different 3D environment than the other tasks, and was intended to allow participants to become comfortable with all three locomotion interfaces.

In the experimental task, participants walked on an indicated straight line to reach a target placed on the ground (shown in Figure5.2). This task was carried out in a 3D art gallery environment. Participants were asked to walk precisely on the line to twelve individual targets as quickly as they could. Audio and visual feedback told participants when each target had been reached. After reaching every target, the target and the indicating line disappeared, and the next target was revealed. All users were asked to perform two tasks of this nature (24 total targets), differing only in the order in which the target lines appeared, for each interface.

We also included a multi-segment task in the experiment, in which the lines leading to the target included sharp or perpendicular turns However, since the results did not differ between the two tasks, we report only on the straight-line task for the remainder of the paper.

5.1.3 Measures

We used path deviation as a measure of accuracy. We defined path deviation as the perpendicular distance between the user's position in the VE and the indicated line. We recorded the perpendicular distance every 50ms, and calculated the area between the indicated line and the walking path. Additionally, we measured completion time, which was the sum of all times taken to walk to the 12 targets in one task. Calibration time was excluded from the completion time. A post-questionnaire gathered subjective ratings from the participants about the three locomotion interfaces.

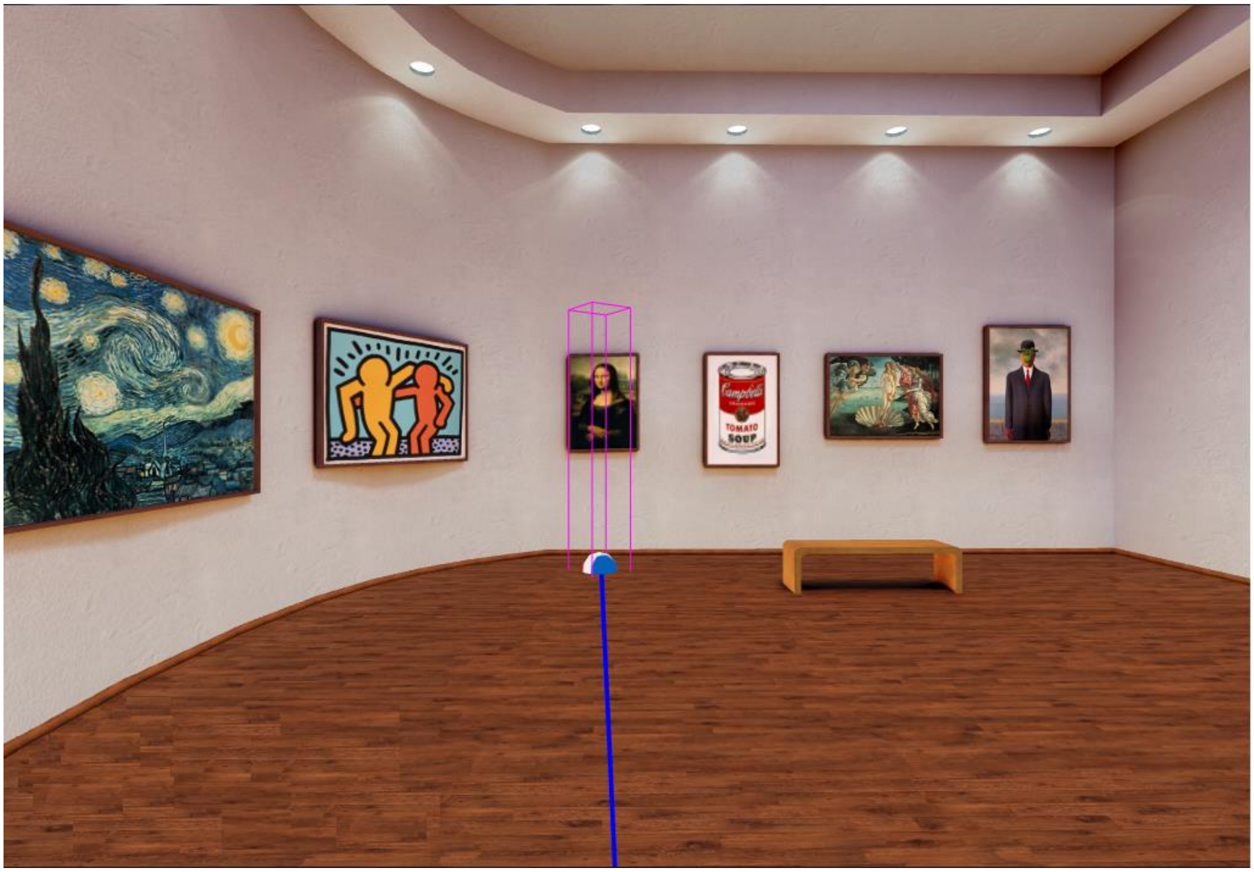


Figure5.2 – User's view of the straight-line walking task. The red, white, and blue ball on the floor represents the target.

5.1.4 Participants

12 participants (10 males and 2 females) from the university undergraduate and graduate population were recruited on a voluntary basis for our study. The participants ranged in age from 18 to 35 years. We excluded subjects under the age of 18 and people with weight over 190 lbs (the weight limit of the Virtusphere). None of the participants had prior experience with the Virtusphere before the experiment.

5.1.5 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, and study procedures. Following that, participants were introduced to the locomotion interfaces. Participants had a short training session before using each locomotion interface, in which they were introduced to 3D environment and were asked to perform a simple straight-line locomotion task.

For each locomotion interface, after completing the training session, participants were asked to perform three tasks through a 3D virtual model of an art gallery. The first two tasks were straight-line tasks and the last was a multi-segment line task. The same tasks were performed in all three locomotion interfaces to maintain consistency. We divided the 12 participants into three groups, and each group used a different ordering of the locomotion interfaces, based on a Latin square.

After completing the tasks with each locomotion interface, participants filled out an interface questionnaire, using a seven-point Likert scale to measure their opinions regarding fatigue, ease of walking, ease of learning, naturalness, fun, and precision. Each interface questionnaire was followed by a simulator sickness questionnaire.

5.2 Results

In this section, statistically significant results in our study are reported. Dependent variables of deviation and time metrics in our study were numeric continuous type, while all other subjective dependent variables in the questionnaires were numeric ordinal type. Our primary analyses were one-way analyses of variance (ANOVAs) for the time metric and the deviation metric.

5.2.1 Deviation

We used the deviation measure to evaluate task performance accuracy. We observed a significant effect of locomotion interface on the straight-line task performance accuracy, as shown in Figure 5.3A (F2,69=35.10; p<0.0001).

Pairwise comparisons using the Student’s t-test showed that participants performed significantly less precisely using the Virtusphere, compared to real walking and gamepad techniques (p<0.0001 in both cases). No significant differences between the real walking and gamepad techniques were observed. In addition to the total deviation measure, we measured average and maximum deviation from the indicated line and total travel distance for each task. The statistical analysis results were the same as for the total deviation measure.

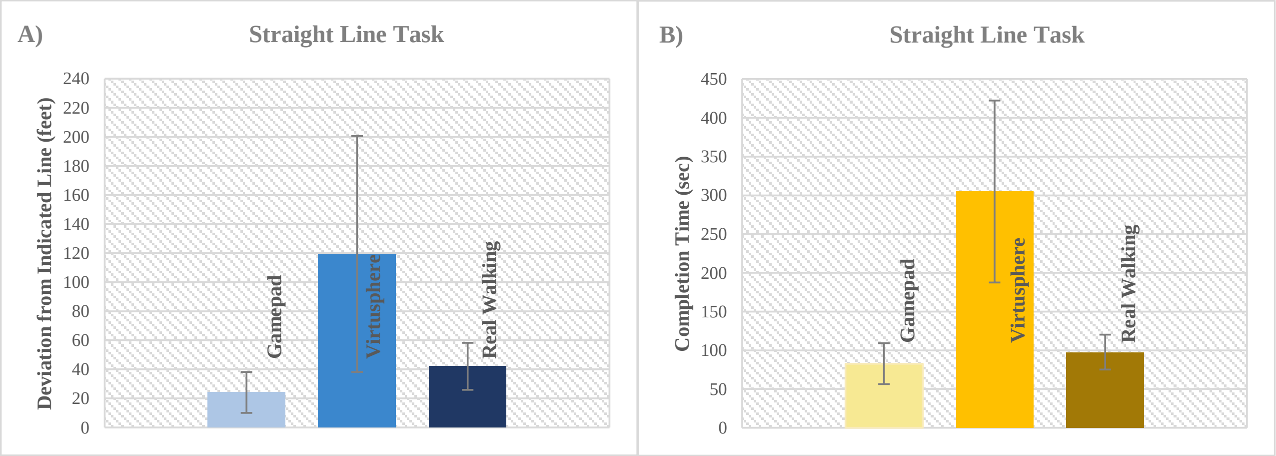


Figure5.3– Performance measures for the three locomotion techniques. A) Deviation for the straight-line task, units are in feet. B) Completion time for the straight-line task, units are in seconds. Error bars represent standard deviation.

5.2.2 Completion Time

We also found a significant effect of locomotion interface on the speed of straight-line task performance, as shown in Figure 5.3B (F2,69=77.41; p<0.0001). Pairwise comparisons using a Student’s t-test indicate that participants performed significantly faster using the real walking and gamepad techniques as compared to the Virtusphere (p<0.0001 in all cases). No significant differences between real walking and gamepad interfaces were observed.

5.2.3 Questionnaire Results

We ran a Chi-Square analysis to compare the subjective ratings given in the post questionnaire. Participants felt that both the gamepad (χ26=15.59; p=0.02) and real walking techniques (χ26=17.45; p=0.01) were significantly easier to learn than the Virtusphere. Similarly, users found Virtusphere significantly more fatiguing than real walking (χ25=15.99; p<0.01) and gamepad (χ25=21.22; p=0.01) techniques. Mean values are shown in Figure 5.4. We also asked users about their subjective opinion of each technique being fun, and despite Virtusphere having a higher mean rating than the gamepad technique, we did not observe any significant differences for this question.

We also asked users about their perception of interface naturalness. Users felt the Virtusphere was significantly more natural than the gamepad technique (χ26=13.36; p=0.04) and less natural than the real walking technique (χ26=15.99; p=0.01) for walking in a straight line. The mean values for users' ratings are provided in Figure 5.4. The results for perceived naturalness mirror our interaction fidelity analysis (section 5).

Users perceived precision as significantly better with the gamepad technique compared to the Virtusphere technique for ease of walking (χ26=12.68; p<0.05), initiation (χ26=19.35; p<0.01), and termination (χ25=19.95; p<0.01). Mean values are provided in Figure 5.4. However, perceived precision and ease of walking were not significantly different when comparing real walking and the Virtusphere for "steady state" straight-line walking (i.e., once walking has begun, users do not perceive the Virtusphere to be significantly less precise or harder to use). Our analysis in section 5 also addresses this result.

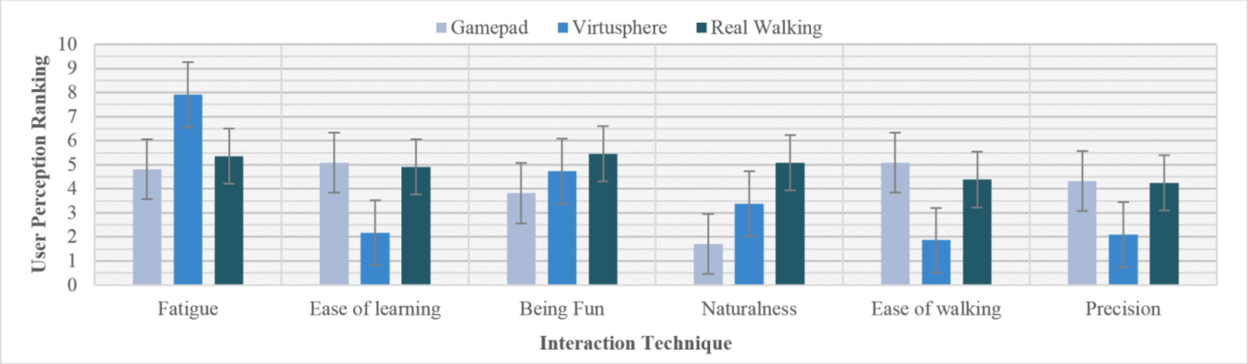


Figure5.4 – Mean values for users' subjective ratings. Error bars represent standard deviation. Greater ratings are better.

5.2.4 Movement Patterns

Besides speed and accuracy, a higher fidelity locomotion interface should result in more realistic walking patterns(Griffiths, Sharples et al. 2006). We recorded each participant's position in VE while performing the tasks and used this data to illustrate movement patterns, as depicted in Figure 5.5. For each interface, a representative pattern is indicated using a red dotted line.

As participants reached a target in VE, they turned around looking for the next target. Using the real walking technique, participants usually started walking as they were looking for the next target. Therefore, as can be seen in Figure 5.5, the movement pattern is more deviated at the beginning of walking. The user could rectify his movement gradually while walking toward the target.

The movement patterns with the gamepad technique are similar to the real walking technique, although there are some distinctive. Gamepad movement pattern is not as smooth. It is easy to move in a straight line with the gamepad technique, but if the straight line is not going exactly in the right direction, then the user will correct his direction, which creates a jagged movement pattern. Despite this, the user can still keep close to his desired path.

The movement patterns with the Virtusphere are nothing like the movement patterns in real-world walking. The user often was not able to initiate the walk in the preferred direction. In addition, some participants could not hit the target at first and instead walked around it.

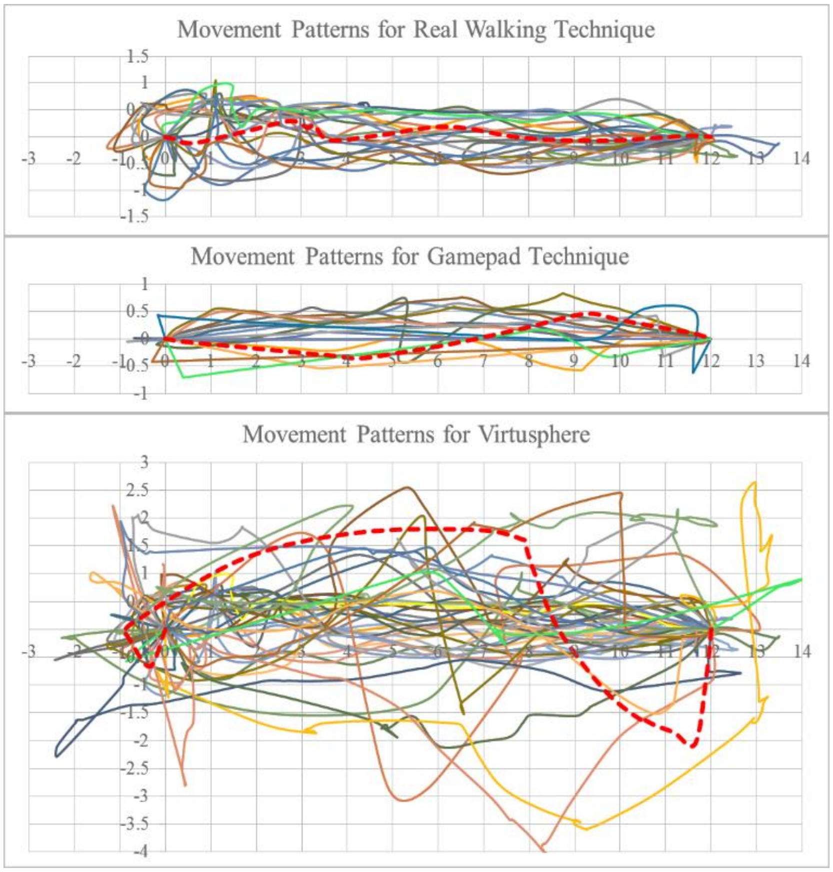


Figure5.5 – Walking patterns for several walking tasks using real walking, Virtusphere and gamepad interfaces. A representative pattern is indicated with red dotted line. Units are in feet.

5.2.5 Results Summary

As we hypothesized, the Virtusphere was outperformed significantly by both the gamepad and real walking interfaces, indicating that it is slower, less precise, harder to use, more fatiguing, and more difficult to control. But why is this the case? Is the Virtusphere simply too novel and unfamiliar to users, or are there more fundamental issues with this locomotion technique and others like it? To address this question, we performed a detailed analysis of the differences among the three techniques in our study.

5.2.6 Analysis of Locomotion Techniques

McMahan introduced the Framework for Interaction Fidelity Analysis (FIFA) (McMahan 2011). The FIFA framework compares interaction techniques to their real-world counterparts across several dimensions. FIFA allows us to compare interaction techniques and where they fall on the fidelity spectrum. We employ FIFA to better understand differences among the three locomotion interfaces in our study using this established framework.

FIFA describes interaction fidelity with three primary factors: biomechanical symmetry, control symmetry and system appropriateness. In this framework, each technique is compared to the real-world counterpart for the interaction task, to understand how this technique compares to natural interaction.

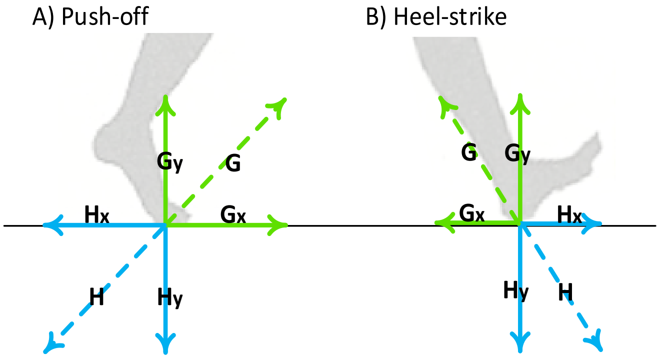


Figure5.6 - Forces applied by the human foot (H) during gait are shown in blue. Reaction force elements from the ground (G) are shown in green. A) In the push-off phase the foot applies backward force. B) In the heel-strike phase the foot applies forward force to the ground.

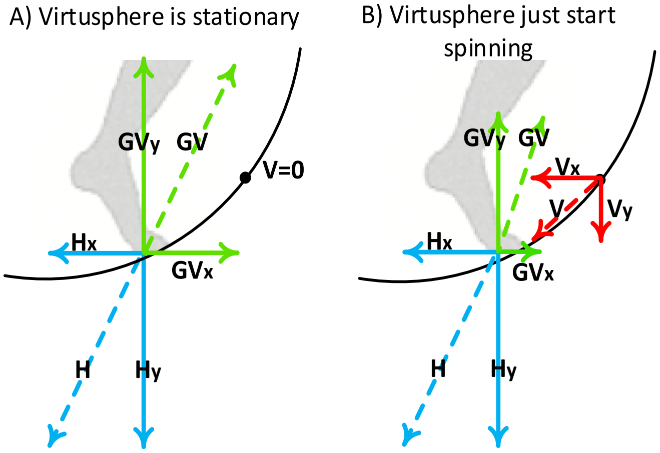


Figure5.7 - A) User takes a few steps before the Virtusphere starts spinning. B) As the Virtusphere starts spinning, backward and downward forces are applied to the user's foot (Vx,Vy) which decreases ground reaction force (GV).

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. Sub-components of biomechanical symmetry include kinematic, kinetic, and anthropometric symmetry. Kinematics is concerned with body motions or trajectories; kinetics refers to the forces applied to cause body movements; and anthropometry considers which body parts are used.

Control symmetry describes how the control provided through the interaction technique compares to control in the real-world task. It also has three sub-components: dimensional, transfer function, and termination symmetry. Dimensional symmetry considers the similarity between the control dimensions in a real-world task and those in an interaction technique. Transfer function symmetry refers to how interaction techniques interpret and transform input data into an output effect. Termination symmetry is concerned with how the interaction is stopped (although not included in the original FIFA publication, we also consider initiation–how the interaction is begun).

System appropriateness characterizes the suitability of the system for performing a particular aspect of the interaction, and includes four factors: input accuracy, input precision, latency, and form factor. Input accuracy is how close to the ground truth measurements of input are. Input precision refers to how repeated measurements produce the same results in static conditions. Latency is the amount of delay between user input and feedback generated by the system. Finally, form factor is concerned with the shape and size of the input device.

A FIFA analysis of the three locomotion techniques in our study is depicted in Table 5.1. The following sections explain this analysis, beginning with a description of the baseline to which the techniques will be compared: natural walking.

5.2.7 Natural Human Walking

The most common force applied to the human body during gait is the ground reaction force. This force is a three-dimensional vector comprising a vertical component and two shear components. The two shear components act on the ground surface in anterior-posterior and medial-lateral directions (Winter 2009), as shown in Figure5.6. The fourth variable is the location of the center of ground reaction force vector. Since the foot is supported over a varying surface area with different amounts of pressure applied to each area, it is an expensive calculation problem to evaluate to the net effect of all pressures as they change over time (Grieve and Gear 1966, Meriam, Kraige et al. 1987, Cruz-Neira, Sandin et al. 1993, Winter 2009).

The human gait cycle has two main phases: the stance phase (60% of total time), in which the foot is in contact with the ground, and the swing phase (40% of total time), in which the foot moves forward in the air. During the stance phase, the foot exchanges forces with the ground. The stance phase is subdivided into heel-strike, foot-flat and toe push-off (Schafer 1987, Steinicke, Visell et al. 2013). In heel-strike, the human foot (H) contacts the ground and exerts two elements of force in forward (Hx) and downward (Hy) directions into the ground. The ground reacts with the same amount of force in the opposite direction (Gx, Gy) to the foot (Figure5.6.B). Heel-strike continues with foot-flat in which the whole foot sole meets the ground and applies forces in the backward direction. Foot-flat changes into push-off, in which the foot exerts the largest backward force in the gait to translate the body forward (Figure5.6.A). The ground reacts with the same amount of force in the opposite direction.

5.2.8 Analysis of Real Walking Technique

Using a real walking interaction technique (Usoh, Arthur et al. 1999), users can translate and rotate in a tracked physical space while viewing the VE through a tracked HMD. In this technique, all translation and rotation scales are the same as the real world, and no gains are applied to the user’s movements.

As shown in Table5.1, the real walking technique is extremely high fidelity. During the initiation, continuation, and termination of walking, all aspects of biomechanical symmetry and control symmetry are exactly as they are in natural walking. The only notable distinction between our real walking technique and natural walking is that the user is unable to observe her own body, legs, and feet while wearing the HMD, which might cause lower confidence in walking, leading to slower walking speed.

5.2.9 Analysis of Virtusphere Technique

The Virtusphere enables the user to perform unlimited locomotion in the VE, like other locomotion devices such as Omni-directional treadmills (Darken, Cockayne et al. 1997).

5.2.9.1 Initiation

In natural walking we initiate the gait with the push-off phase. Because of the Virtusphere’s inertia and static friction, as the user takes the first step or two, the Virtusphere may remain stationary (Figure5.7.A) and react with the same force in the opposite direction to user (GV). As the user moves forward, because of the curved inner surface, the user’s downward force increases and overcomes the Virtusphere’s static friction and inertia. As soon as the Virtusphere starts spinning (Figure5.7.B), the static friction turns into dynamic friction, which is less than static friction. This decrease in friction force reduces the amount of resistance against the force applied by the user’s feet. An element of this force acts to overcome the dynamic friction, while the rest increases the Virtusphere's momentum, creating two elements of force in backward and downward directions on the user's feet (Vx and Vy in Figure5.7.B). This will decrease the Virtusphere's ground reaction force in forward direction (GVx) and downward direction (GVy). Consequently, the user will suddenly begin to move backward in the Virtusphere.

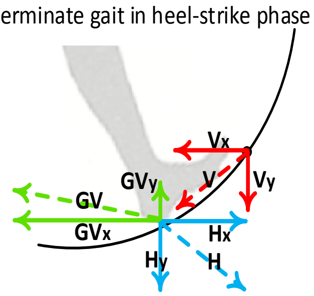


Figure5.8 – The user applies a large forward force (Hx) in the heel-strike phase to terminate gait in the Virtusphere

Users who are not acclimated to the Virtusphere have two typical reactions to the sudden backward movement. In the first scenario, the user will race to maintain her position while increasing walking speed, which will increase the Virtusphere's velocity and momentum. Then the user tries to slow down, but the Virtusphere's backward forces will translate her further backward. This can create a cycle, which ends up with the user losing her balance. In the second scenario, instead of racing, the user will try to slow the Virtusphere down at the very beginning. Inexperienced users might terminate Virtusphere's spinning and try to start over again. This can cause a gait initiation-termination cycle. To avoid these two ineffective approaches, after the Virtusphere starts spinning, the user needs to gently slow the Virtusphere down and keep it spinning at a convenient speed.

This large difference in vertical and shear ground forces in the walking initiation phase causes a low kinetic symmetry between the Virtusphere and natural walking. Not only is the amount of vertical force that the user applies in walking initiation different, but also instead of a simple push-off, the user needs to control large changes in ground forces and move differently. This results in different kinematics in the Virtusphere as shown in Table5.1. As shown in Figure5.5, user could not have a precise control over their movements as they initiate walking in the Virtusphere, which will result in more deviation from the indicated path (Figure5.4) and make the Virtusphere more fatiguing and less precise (Figure5.5).

5.2.9.2 Walking

As shown in Figure5.6.B, while the user is walking in the Virtusphere its momentum will exert backward and downward forces on the feet. During the heel-strike phase, this force increases the reaction force in the forward direction. Maintaining a constant speed while walking in the forward direction will create a balance between human forces and reaction forces. This balance makes linear walking in the Virtusphere relatively natural. Because of the curved surface of the Virtusphere, if the user takes large steps, she might notice the difference in height. Taking smaller steps not only will keep both feet at the same height but also will decrease the downward force element (Hy), which helps keep the Virtusphere's momentum in control. Nevertheless, walking on a curved surface is a different form factor than natural walking. On the other hand, since exactly the same body parts are used for walking in VE, the Virtusphere has a high anthropometric symmetry. The precise input sensors can detect minor movements and have minimal latency as shown in Table5.1. As a result, participants reported the Virtusphere to be more fun and natural comparing to the gamepad technique, which is indicated in our results (Figure5.5).

Table5.1 - Analyzing interaction fidelity for locomotion interaction techniques

	Gamepad Technique	**Virtusphere Technique**	**Real Walking Technique**
BIOMECHANICAL SYMMETRY			
Kinematic Symmetry	Tilt the joystick handle thumb to translate and rotate	Move thighs, legs, and feet to step on curved surface	Move thighs, legs, and feet to translate entire
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces; force toward walking direction	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet	Thighs, legs, and feet
CONTROL SYMMETRY			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-velocity	1:1 position-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps; Apply force to reverse direction	Stop taking steps
SYSTEM APPROPRIATENESS			
Input Accuracy	Standard Joystick	Virtusphere movement sensor	Tracking system camera
Input Precision	Standard Joystick	Virtusphere movement sensor	Tracking system camera
Latency	Standard Joystick	Virtusphere movement sensor	Tracking system camera
Form Factor	Handheld, sensory cues	Closed area, curved surface, different sensory cues	Slightly different sensory cues
	Low Fidelity		**High Fidelity**

5.2.9.3 *Termination*

In natural walking, we terminate the gait in the heel-strike phase. As the user tries to stop the Virtusphere, she needs to overcome the Virtusphere's momentum by exerting a larger forward force in the heel-strike phase. Inexperienced users might end up with two walking termination scenarios. In the first scenario, the user applies a larger forward force in the heel-strike phase, while reducing the backward force in the push-off phase, similar to natural walking. In this case, the Virtusphere's momentum translates the user backward and upward on its inner curve. Subsequently, the user increases the push-off force to go forward to maintain her position and control her balance. This can cause the user to move backward and forward several times, and eventually lose balance.

In the second scenario, the user applies a heel-strike forward force considerably larger than that of natural walking, to overcome the Virtusphere's momentum (Figure5.8). We used a first-generation Virtusphere (Figure 1) in this study, which weighs about 600 lbs. (Latypov 2006). Therefore, depending on its velocity, the Virtusphere can have a relatively large momentum. Due to its momentum, the reaction force from the Virtusphere to the user's foot is relatively large and the user's muscles might not be able to overcome this reaction force (GVx, Figure 8). This can also cause the user to lose balance. Experienced users will gradually increase forward force in the heel-strike phase while gradually reducing backward force in the push-off phase to terminate gait and maintain balance. Even in this case, termination is considerably different than natural walking. Thus, kinetic symmetry and termination symmetry are low-fidelity in the Virtusphere. These actions consume a considerable amount of energy if they are done over a long period of time, helping to explain the significantly higher reported fatigue (Figure 4) with the Virtusphere in our study. Consequently, the user required more time to complete the tasks, which is indicated in our results (Figure 3).

5.2.10 Analysis of Gamepad Technique

In the gamepad technique, walking is initiated by pushing the translation joystick forward, which causes forward movement in the VE almost immediately. The user can keep walking in VE by keep pushing the translation joystick forward, while he can strafe by pushing the translation joystick to right and left. The user is able to control translation with high accuracy and precision. Termination of walking simply requires releasing the joystick.

The gamepad technique has high accuracy and precision, low latency, and high dimensional symmetry. In terms of interaction fidelity, biomechanical and control symmetry are very low. Different body parts are used, and movements and forces are entirely different. Transfer function symmetry is low, since tilting a joystick is mapped to velocity in the VE. Termination and form factor are also low-fidelity (Table5.1).

This type of interface has been widely used and is familiar for users, many of whom are experts at navigating using this sort of device. The lack of interaction fidelity is not an issue for techniques of this sort, since this technique is not designed to approximate real walking in any way.

5.2.11 Analysis Summary

Looking at the color coding in Table5.1, we can see that the real walking technique has high interaction fidelity as it satisfies all three symmetry conditions for high-fidelity. Conversely, the gamepad technique has very low biomechanical symmetry, transfer function and termination symmetry and a very different form factor. Hence, the gamepad technique is near the low extreme of the interaction fidelity spectrum. The Virtusphere has a combination of both high-fidelity and low-fidelity properties. Considering this, we classify the Virtusphere as a medium-fidelity technique. This analysis also provides a framework we can use to explain the results of our study.

5.3 Discussion

5.3.1 This experiment

In our experiment, the Virtusphere had significantly worse performance than the gamepad and real walking techniques, indicating that it is difficult to learn and use. The FIFA analysis described above helps us to understand the source of these usability problems. The Virtusphere presents itself as a “natural walking interface,” implying to users that they can use their real-world walking skills and experiences to use the device. However, it turns out that initiating and terminating walking (not to mention changing direction) are significantly different, in terms of motions and forces, in the Virtusphere than in real walking. These differences cause users to struggle to control the Virtusphere, to physically fall down at times, and to be unable to walk proficiently along the desired path in the VE. The Virtusphere not only produced inferior performance, but it made the walking behavior significantly different than real-world walking.

In contrast, the real walking technique has none of these issues. Users are able to transfer all of their real-world walking experience and skills directly to the interface, resulting in excellent performance. But if the Virtusphere has inferior performance because of its deficiencies in fidelity, why does the low-fidelity gamepad technique not perform even worse? We suggest that users of the gamepad technique do not expect the technique to be like real-world walking, and thus the low-fidelity aspects of the interface are not a hindrance to good performance. Instead, because the gamepad technique is well designed, with an easily understandable mapping between joystick movements and translational/rotational velocity, performance can be on par with real walking, at least for the metrics of speed and accuracy on the task of straight-line walking.

Another advantage for the gamepad technique is familiarity. Many users have seen and used this type of interface often in games and other contexts. Certainly, familiarity does have an influence on performance. But was it a primary factor in the results of our experiment?

Three of our participants claimed that they played video games less than one hour per week, and that they used devices very different from gamepads (e.g. smartphones). Thus, these participants were novices in using techniques similar to the gamepad navigation technique. Their mean completion time was 105.3 seconds using the gamepad, compared to 262.0 seconds using the Virtusphere. The deviation with the gamepad technique for this group of participants was 19.1 feet, while it was 82.0 feet when using the Virtusphere. Therefore, even participants who claimed a low level of expertise with gamepad-like techniques could navigate much faster and more accurately with the gamepad than with the Virtusphere. This suggests that the gamepad technique we used was very easy to learn and use, enabling users to obtain excellent task performance even without prior training or high level of expertise with such a device.

In our experiment, therefore, we see that:

1. The high interaction fidelity of the real walking technique led to a high level of performance.
2. The medium fidelity of the Virtusphere technique (i.e., its deficiencies in fidelity compared to real-world walking), combined with user expectations that it would support natural walking, led to significantly worse performance.
3. The low interaction fidelity of the gamepad technique was not detrimental to performance, due to its easy-to-learn and easy-to-use design. However, the effectiveness of the low-fidelity techniques can depend on the task and measure and such interfaces might not be highly effective for certain tasks and measures.

Of course, we were only able to evaluate three specific locomotion techniques in this study. We must ask ourselves whether these results are generalizable.

5.3.2 Generalizing the results

McMahan et al. hypothesized that high- and low-fidelity interaction techniques often perform better than medium-fidelity ones (McMahan 2011, McMahan, Bowman et al. 2012). In other words, he argued that the relationship between interaction fidelity and performance might look like a U-shaped curve, with higher performance at the two extremes and lower performance in the middle. Our results support this hypothesis. We observed that increasing fidelity from a low-fidelity standard technique (gamepad) to a medium-fidelity technique (Virtusphere) decreased performance and that increasing from medium-fidelity to highly natural (real walking) contributed positively to performance. However, we acknowledge that well-designed low-fidelity interface might have be highly effective for certain tasks and measures and might not be highly effective for some other tasks and measures.

This hypothesis is sensible because medium-fidelity techniques appear similar to high-fidelity interactions. Therefore, users try to employ them in a similar way to highly natural techniques. Nevertheless, due to their differences from real-world actions, medium-fidelity techniques require users to change the way they naturally interact. The brain must adapt to the non-natural parts of the medium-fidelity technique.

Despite all of the efforts to develop more-natural locomotion interfaces (such as omni-directional treadmills, walking in place, and robotic stepping systems), these and most other practical locomotion interfaces lie in the middle of fidelity spectrum. So it is important to understand the potential performance of this category of locomotion interfaces.

One might argue that the results in our study could be due primarily to the particular medium-fidelity interface we chose (the Virtusphere). While we acknowledge that the Virtusphere has some clear deficiencies (in particular, its weight and curved shape), we argue that these findings are valid for most medium-fidelity locomotion techniques to some degree. It is possible that this conclusion may also be true for other interaction tasks besides locomotion, but further study is required.

Our results are consistent with other studies showing the inferior performance of semi-natural interfaces in the literature. A comparison between two locomotion interfaces—human joystick (medium-fidelity) technique and mouse/keyboard (low-fidelity)—indicated that the low-fidelity technique outperformed its more natural counterpart(McMahan, Bowman et al. 2012). Another empirical study compared a medium-fidelity steering wheel interface to a low-fidelity game controller interface for the Mario Kart Wii racing game (McMahan, Alon et al. 2010). Results from this study indicated that the non-natural interaction technique significantly outperformed its more natural counterpart (McMahan, Alon et al. 2010). A comparison between a gamepad interface (least natural), the P2V interface (slightly more natural) and real-world locomotion (completely natural baseline) showed that the least natural and most natural interaction techniques were significantly better than the semi-natural one for stopping time and memory tasks (Marsh, Putnam et al. 2012). Similarly, a high-fidelity walking technique and a low-fidelity joystick technique were better than a medium-fidelity walking-in-place technique for the performance metric of final distance to target, as reported by (Whitton, Cohn et al. 2005) (results for other measures in this study, however, were not consistent with McMahan's hypothesis).

On the other hand, some studies have revealed high levels of performance for certain semi-natural techniques, such as redirected walking or seven league boots (Interrante, Ries et al. 2007). Based on a FIFA analysis similar to the one in section 5, we can see that these techniques are actually quite high fidelity in terms of the muscle groups and forces they use; thus they have high biomechanical symmetry. The transfer function for both of these techniques is slightly different than natural walking. With redirected walking, the user might not even notice the difference with real walking, depending on the level of gains used 39. The gain used in seven league boots can be perceptible for the user, nonetheless it is in favor of navigation speed and performance. Therefore, such techniques are close to the high extreme in the interaction fidelity spectrum, and their good performance does not contradict McMahan's hypothesis.

The effects of familiarity are not independent of the effects of interaction fidelity. By definition, a technique with high interaction fidelity is highly familiar, since a high-fidelity technique is very similar (familiar) to the actions used in the real world. Also by definition, a technique with low interaction fidelity is completely unfamiliar until users have trained with it or used it for a while. Medium-fidelity techniques are by definition somewhat familiar.

Nevertheless, this is the main problem with the Virtusphere: Since it presents itself as a natural walking technique, users assume that regular walking motions and skills will apply to it. When they try to use regular walking in the Virtusphere, they have great trouble. Therefore, familiarity is actually a downside of the Virtusphere, and its closeness to natural walking is more of a distraction for the user than an advantage.

The primary reason why low-fidelity techniques may perform well is not familiarity; it's that they can be well designed, using established principles of human-computer interaction. Because these techniques are not based on real-world actions, designers are free to invent techniques that will perform well. Certainly, low fidelity does not guarantee good performance, but well-designed low fidelity techniques can have excellent performance for specific tasks and measures. The hypothesis we present here, has three main parts:

1. High interaction fidelity interfaces often have high level of effectiveness.
2. Moderate-fidelity interfaces, do not typically achieve high levels of effectiveness.
3. low-interaction fidelity techniques' effectiveness depends on the task and measure and the way we define the effectiveness.

Users' performance with medium-fidelity techniques need not always remain low. It is possible to improve performance by training users (Marsh, Hantel et al. 2013). However, if an interface requires extensive training to be usable, it is not likely to be appropriate for many potential applications. Moreover, the need for significant training with a technique runs counter to the idea of "natural" interaction. How much and how quickly the performance of medium-fidelity techniques can be improved is a topic for future work.

In summary, based on the literature, our results, and our deep analysis of interaction techniques, we argue that McMahan's hypothesis is correct, at least for basic task performance measures with locomotion techniques. That is, high-fidelity locomotion techniques and well-designed low-fidelity locomotion techniques will often outperform their medium-fidelity counterparts.

5.4 Summary

Despite the common belief that more realism in VR systems is always better, we have demonstrated that the relationship between interaction fidelity and effectiveness is more complicated. By analyzing and evaluating three locomotion interfaces at different points on the interaction fidelity spectrum, we have contributed a deeper understanding of the effects of interaction fidelity on effectiveness.

Based on the literature and our results and analysis, we suggest that high-fidelity locomotion techniques and well-designed low-fidelity techniques can outperform medium-fidelity locomotion interfaces. Our results support McMahan's hypothesis (McMahan 2011, McMahan, Bowman et al. 2012) about the interaction fidelity-performance relationship. We claim that this result will be valid for most medium-fidelity locomotion interfaces, and potentially techniques for other tasks as well.

This study tried to partially address the first research question about how does the effectiveness of locomotion techniques change at varying levels of fidelity and does increasing interaction fidelity "guarantee" increase in effectiveness. Based on our discussion here, we can say that increasing level of interaction fidelity does not guarantee increase in effectiveness. Our results indicate that low- and high-fidelity techniques have high effectiveness and outperform medium-fidelity ones. Therefore, we can say that we found evidence to support the uncanny valley graph in the chapter 1.6.

6 For RQ2 and RQ3: An Evaluation of the Effects of Hyper-Natural Components of Interaction Fidelity on Locomotion Performance in Virtual Reality

Virtual reality (VR) locomotion techniques that approximate real-world walking often have lower performance than fully natural real walking due to moderate interaction fidelity. Other techniques with moderate fidelity, however, are intentionally designed to enhance users' abilities beyond what is possible in the real world. We compared such hyper-natural techniques to their natural counterparts on a wide range of locomotion tasks for a variety of measures. The evaluation also considered two independent components of interaction fidelity: bio-mechanics and transfer function. The results show that hyper-natural transfer functions can improve locomotion speed and some aspects of user satisfaction, although this can come at the expense of accuracy for complicated path-following tasks. On the other hand, hyper-natural techniques designed to provide biomechanical assistance had lower performance and user acceptance than those based on natural walking movements. These results contribute to a deeper understanding of the effects of interaction fidelity and designer intent for VR interaction techniques and address our second and third research question.

6.1 Evaluating the Effects of Interaction Fidelity

In this section we describe the framework within which we evaluate the effects of interaction fidelity for VR locomotion tasks, the specific techniques evaluated in our study, and the testbed we designed for this and future evaluations.

6.1.1 Evaluation Framework

In the experiment described below, we manipulate the level of biomechanical symmetry and transfer function symmetry, and study hyper-natural technique components as compared to their natural counterparts. We chose to study biomechanics holistically, because its sub-components are tightly bound together for locomotion. Previous studies showed evidence of negative effects for low levels of biomechanical symmetry in semi-natural techniques (McMahan 2011, Nabiyouni, Saktheeswaran et al. 2015). We wondered whether it was possible to achieve hyper-natural biomechanics and whether the effects would be different. We evaluated transfer function symmetry because of its importance in technique design (e.g., redirected walking (Razzaque, Kohn et al. 2001) or seven league boots (Interrante, Ries et al. 2007) techniques manipulates the transfer function to achieve the designer's intent). System appropriateness mostly depends on the system specifications, so we used the best available system specifications and kept those levels constant in all of the experiment conditions.

Table 6.1: *Interaction techniques used in our experiment*

	Natural biomechanics	**Hyper-natural biomechanics**
Natural transfer function	Real Walking	Jump Boots
Hyper-natural transfer function	Seven League Boots	Seven League Jump Boots

6.1.2 Interaction Techniques

Our research questions for this study focus on the effects of hyper-natural techniques as compared to natural ones, and the specific effects of two components of interaction fidelity: biomechanical symmetry and transfer function symmetry. We identified natural and hyper-natural techniques for both of these components, leading to four conditions (Table 6.1).

Real walking in VR

We used the real walking technique as the technique that is closest to natural human walking. In this technique the user's head was tracked to show him the VE using a head mounted display (HMD). This technique used a one-to-one mapping of physical to virtual movements to be as natural as possible.

Hyper-Natural Transfer Function

Our hyper-natural transfer function technique was based on Seven League Boots (Interrante, Ries et al.). This technique scales users' movements and enables them to move faster and travel farther without increasing the amount of physical movement. This could be achieved using a uniform scaling factor; however, this would result not only in exaggerated head bobbing, but also a reduction in accuracy due to the speed-accuracy tradeoff. The method we designed was similar to the implementation in (Interrante, Ries et al.). The scaling was applied only in the direction of movement and parallel to the ground. We do not scale the movements orthogonal to the ground plane to avoid making users feel they are shorter or taller or their viewpoint bouncing up and down excessively.

Scaling is activated only when the user's velocity is larger than a certain threshold V_{th}. When moving slower than V_{th} there is a one-to-one mapping between physical and virtual movement to ensure control and accuracy over delicate movements. At each frame, we calculate the vector $\vec{D}$ that the user has moved in the last time window T_w. The amount $V_{user} = |\vec{D}|/T_w$ is the user's speed in the last time window. The scaling factor F_{7L} is a function of how much faster the user is moving over the activation threshold V_{th}. F_{7L} is multiplied by the user's movement in the last frame, $\overrightarrow{\delta d}$, to reduce acceleration latency and ensure an immediate termination as the user stops. We chose a sub-second T_w to allow users to activate the acceleration shortly after they start walking. Based on our experience, this can improve control over travel and mostly eliminate the need for predicting users' direction of travel by their gaze direction.

A suitable acceleration method should allow a seamless transition from real walking to Seven League Boots, and, once activated, should provide the user with enough acceleration to effectively and significantly increase movement speed. We prototyped and implemented different linear and polynomial functions for the scaling factor F_{7L}. A linear function does not provide a seamless activation. We used the polynomial function $F_{7L}=ax^2+bx+c$ with $x=V_{user} -V_{th}$, $a=1.2$, $b=0.7$ and $c=1$. The constant values were selected to provide a seamless change of transfer function and appropriate acceleration for higher speeds.

Hyper-Natural Biomechanics

Figure 6.1: Setup for the experiment with Kangoo Jumps Boots (KJB).

To study the effect of biomechanical symmetry in hyper-natural techniques we required a method to biomechanically assist users for walking. Robotic exoskeletons such as the Honda walking assist device (Razzaque, Kohn et al.), can physically help people walk by reducing the floor reaction force, leg muscle activity and total body energy consumption. Such devices were designed mainly to help elderly or physically challenged people walk and might not serve our purpose of helping healthy users walk faster and easier. On the other hand, spring-based athletic shoes have shown positive effects on cardiovascular and athletic activities (Miller, Zumbo et al. 2003). Among those we reviewed, Kangoo Jumps™ boots (Figure 6.1) appears to provide better balance because of the large contact surface with the ground and high friction surface.

It is claimed that these boots provide an effective method for improving aerobic capacity comparing to normal running shoes (Miller, Zumbo et al. 2003). Moreover, the reduction in the level of peak pressure and regional maximum force on the sole of the foot (Shropshire 2005) can provide users with an easier means of jogging and running. Since these boots have shown advantages in the real world we used them to develop our hyper-natural biomechanical technique. The user walks in the boots while wearing the HMD. We had the user wear knee and elbow pads since balance may be an issue.

6.1.3 Locomotion Testbed

The large number and wide variety of novel VR applications makes it impractical to evaluate locomotion techniques directly for each application. A general testbed can provide a practical solution for mapping techniques to a set of performance requirements.

Various path-following, spatial awareness, search or cognitive load tasks have been introduced in previous testbeds (Lampton, Knerr et al. 1995, Bowman, Koller et al. 1997, Bowman, Koller et al. 1998) or sets of tasks (Suma, Finkelstein et al. 2010) (Slater, Usoh et al. 1995, Chance, Gaunet et al. 1998, Griffiths, Sharples et al. 2006). We added newly designed locomotion tasks of speed control and maximum movement speed. Our testbed can be reused to provide consistent and comparable measurements between different techniques. The set of metrics we currently include in our testbed for locomotion interfaces includes:

- Accuracy (deviation from desired path)
- Speed control (control ability over movement speed and distance from a moving object)
- Movement speed (task completion time)
- Spatial awareness (users' knowledge of their surroundings and their orientation in the environment)
- User comfort (cyber sickness (Kennedy, Lane et al. 1993))
- User experience (to capture presence, enjoyment, flow and users' experience with the techniques (IJsselsteijn, De Kort et al. 2013))
- Fatigue (tiredness in general and specifically in feet and legs, based on users' ratings and heart rate)
- Ease of learning (novice users' ability to utilize the technique)
- Ease of use (user's opinion about the complexity of the technique (Bowman, Koller et al. 1998))

We use general locomotion tasks in this testbed to reveal different performance metrics. We measure accuracy of travel using path-following tasks which require users to move as accurately as they can on the indicated lines. Since we track the users' heads, to move on the line they need to keep the indicated line underneath them. We do not set a time limit for this task, which could persuade users to move fast and lose accuracy. Likewise, we do not want users to move very slowly since it could make the comparison unfair. Therefore, we instruct them to use their "normal" walking speed to make it more ecologically valid. Different techniques might provide specific maneuvering abilities (e.g., a gamepad can be accurate for moving on straight lines but not curved paths). Thus, we designed six different maneuvering tests including: straight line, paths with 45°, 90° and 135° turns and paths with 1m and 2m diameter curves (Figure 6.2), all with the same total length of 16m. The total area between the indicated path and the user's track signifies the deviation.

To capture speed control abilities with different speeds we include three courses with slow (relative to normal human walking speed), fast (human jogging speed) and random speed (varies randomly between the slow and the fast). Users follow a moving virtual robot in a hallway and attempt to maintain a certain distance (2m). As shown in Figure 6.2, an indicator on the upper left provides them with distance hints. Green indicates the ideal distance, while yellow, orange, and red indicate distances too far behind and light to dark blue tones indicate that the user is too close. We use discrete colors instead of a continuous color range to avoid confusion about the color of the ideal distance. We also decided against using a bar as a distance indicator so that users would focus on the robot and not just on controlling the indicator. We used the score function, $F_1+C_1+2(F_2+C_2)+4(F_3+C_3)+0.1H$ based on the amount of time user spent in each zone (F_1/C_1: warning far/close, F_2/C_2: far/close, F_3/C_3: too far/close) and the number of times the user hit the walls (H) which indicate lack of control over walking.

In the maximum movement speed task, we ask users to move as fast as they can in a simple hallway that goes around the tracked area for two laps, for a total length of approximately 45 meters. This task evaluates users' ability to move quickly, although it still requires them to maintain some control over their path. Users are instructed not to collide with the walls. Collisions add a penalty to the score, although the software keeps the view inside the corridor. We note that this task might not be applicable for evaluating techniques with constant speed or a fixed maximum speed, but for techniques based on real walking it allows evaluation of the user's ability to walk quickly.

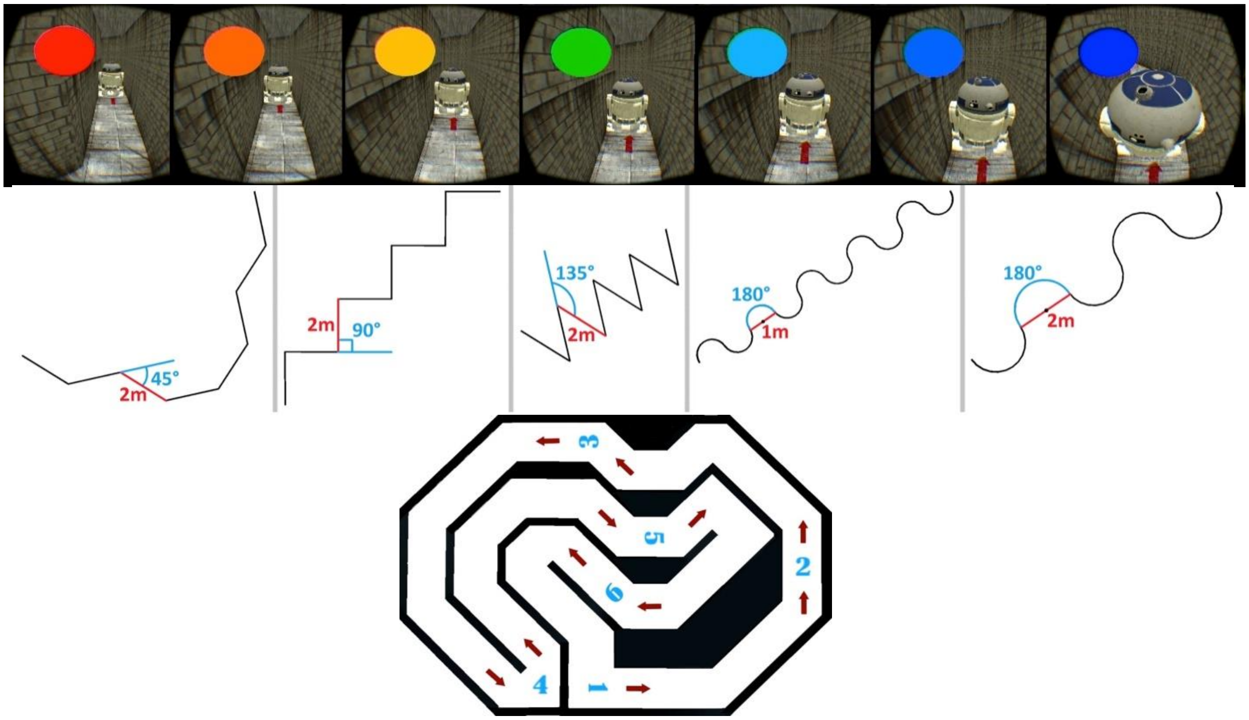


Figure 6.2: Above: Speed control task and the distance indicator. Middle: Courses of path-following task to evaluate maneuverability. All courses are 16m long. Below: Spatial awareness task environment.

To evaluate spatial orientation, we designed a task similar to Bowman et al. (Bowman, Koller et al. 1997) and Chance et al. (Chance, Gaunet et al. 1998). We designed a complicated hallway with six numbers on the ground. At each numbered location, users must stop and turn their head to face towards the previous numbered location, which is no longer visible (Figure 6.2). We capture the head orientation at each location and calculate the error relative to the actual direction toward the previous number. We use the accumulated errors for all six points as a measure of the user's spatial orientation.

As part of this testbed, to quantify presence, enjoyment, flow and the general user experience as well as ease of use and ease of learning, we include the Game Experience Questionnaire (IJsselsteijn, De Kort et al. 2013) and an interface questionnaire we designed. To evaluate fatigue, we include questions about tiredness in general and in specific body parts, and also measure users' heart rate. The standard Simulator Sickness Questionnaire (Kennedy, Lane et al. 1993) quantifies user comfort. In a background questionnaire, we ask about the user's age, gender, visual acuity, ability to fuse stereo images, experience with computers, games, 3D games and VR, physical fitness, technical background and proficiency.

6.2 Experiment

Using this framework, we designed and ran a controlled experiment comparing natural and hyper-natural components of biomechanical and transfer function symmetry in VR locomotion techniques.

6.2.1 Goals and Hypotheses

Hyper-natural techniques, like semi-natural techniques, change the way users naturally interact. Broadly, our goal is to understand how hyper-natural techniques influence the performance. This leads us to our first research question:

1. *What is the effect of hyper-naturalism on performance of locomotion techniques?*

Although hyper-natural techniques are known to have positive effects on some performance metrics for certain tasks (Poupyrev, Billinghurst et al. 1996, Interrante, Ries et al. 2007), this may not be true in all situations. Moreover, different components of fidelity can have different effects on performance. This inspires our second research question:

2. *How does the level of fidelity of a locomotion technique's biomechanics and transfer function affect performance?*

Since the intent of hyper-natural techniques is to enhance the user’s abilities, they may improve effectiveness for some performance metrics. However, since they change the way users naturally interact, they may be worse than natural (high interaction fidelity) techniques in other ways. For example, we expect the scaling in Seven League Boots to have a detrimental effect on accuracy in difficult path-following tasks.

Based on prior results with semi-natural techniques (Nabiyouni, Saktheeswaran et al. 2015), we expect hyper-natural biomechanics to have some detrimental effects on performance. We also hypothesize that users will be able to adapt more easily to hyper-natural transfer functions, since this has been shown for various manipulation techniques (McMahan 2011) and even occurs in real-world locomotion (e.g., moving sidewalks). Thus, we expect that hyper-natural transfer functions will have more benefits than disadvantages.

6.2.2 Apparatus

The study took place in the Cube 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 a rendering laptop. We tried to minimize the latency as much as possible. In all four conditions the VE was displayed to the user with an Oculus Rift Development Kit 2 (DK2) HMD with a FOV of 100°, resolution of 1920x1080 for both eyes and stereoscopic rendering. We used a rigid body of four reflective markers attached to the HMD to track the user. Users carried the laptop used for rendering in a backpack. We used a wireless keyboard to control the study. We used Unity3D to interface with the hardware, render the VE, log the data and manage the flow of the experiment.

6.2.3 Participants

We recruited 24 participants, 17 males and 7 females, on a voluntary basis for this study. Participants were undergraduate and graduate students, ranged in age from 18 to 31, and one had prior experience with the Kangoo Jumps.

6.2.4 Experimental Design

The primary independent variables in the experiment were transfer function symmetry (varied within subjects) and biomechanical symmetry (varied between subjects). As described above, the Seven League Boots (7L) technique was used as a hyper-natural transfer function (lower level of transfer function symmetry), while the natural technique (high level of transfer function symmetry) was a one-to-one transfer function we called real walking (RW). Hyper-natural biomechanics (lower level of biomechanical symmetry) was achieved via the Jump Boots (JB) technique, while the natural biomechanics conditions (high level of biomechanical symmetry) used the user's own shoes. This resulted in four conditions (Table 1). We called the condition with both hyper-natural biomechanics and transfer function the Seven Jump Boots (7JB) technique.

We divided the 24 participants into two groups of 12 based on whether or not they were using the Jump Boots. We counterbalanced the ordering of the 7L and RW techniques so that half the participants used 7L first and the other half used RW first. A secondary independent variable was course type for the path-following and speed control tasks.

6.2.5 Procedure

The study was approved by the university's Institutional Review Board. As participants arrived, they were asked to read the informed consent form and sign it if they agreed. Next, they completed a background questionnaire asking for their age, gender, eyesight and any prior experience with different types of video games, stereoscopic displays or the jump boots. They were provided with an outline about the facilities to be used, our experiment background and the locomotion techniques, followed by a training course in which they got used to the technique they were going to use.

For each locomotion technique, participants were asked to perform four sets of tasks. The first task was the set of path following tasks. In the maximum speed task participants walked through the hallway before they start the task, to make get familiar with the path. In the speed control task, deviation was not calculated until after the participant had walked about ten feet, so that she had time to adjust her speed with the moving robot. The last task was the spatial orientation task. After completing all tasks, participants were asked to fill out an interface questionnaire followed by the GEQ (IJsselsteijn, De Kort et al. 2013) and SSQ (Kennedy, Lane et al. 1993). The interface questionnaire used a seven-point scale to measure users' opinions regarding naturalness, similarity to walking in the real world, being fun, ease of learning and fatigue.

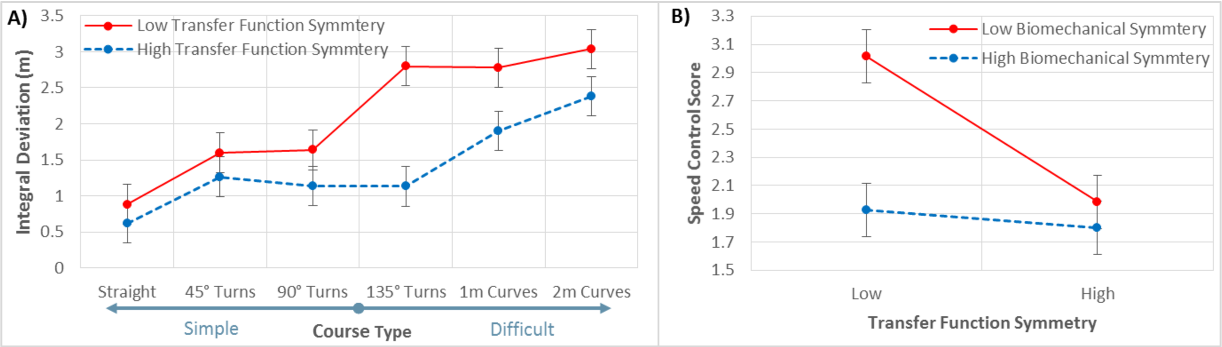


Figure 6.3: A: Interaction between course type and level of transfer function symmetry for the task of path following. B: interaction between level of transfer function and biomechanical symmetry for the speed control task. Lower score is better.

6.3 Results

We present the statistically significant results of the study in this section. All dependent variables were numeric continuous variables, except for the questionnaire data which were numeric ordinal values. To understand the two-and three-factor interactions and main effects of our three independent variables (transfer function symmetry level, biomechanical symmetry level, course type), we used a three-way analysis of variance (ANOVA) on the values of the performance metrics for each task, and an Ordinal Logistic Regression analysis based on a Chi-square statistic on the questionnaire data. Student's t-tests with appropriate corrections were used for post-hoc pairwise comparisons between combinations of the performance metrics.

6.3.1 Accuracy

We found a significant interaction effect of transfer function symmetry level and course type ($F_{5,282}=7.06$; $p<0.0001$) on deviation from indicated line. For easy tasks (straight line, 45° turns, 90° turns), transfer function symmetry did not affect accuracy, but for more difficult tasks (135° turns, 1m and 2m diameter curves), high transfer function symmetry (i.e., natural) conditions were significantly better (Figure 6.3-A). We also found a significant effect of biomechanical symmetry level on deviation ($F_{1,286}=19.58$; $p<0.0001$). Users had significantly less deviation with a high level of biomechanical symmetry (mean = 1.59 meters) than with hyper-natural biomechanics (mean = 1.94 meters).

6.3.2 Speed Control

We found a significant interaction between the levels of biomechanical symmetry and transfer function symmetry ($F_{3,140}=5.77$; $p=0.0177$) on speed control ability. The locomotion technique with low levels of both biomechanical and transfer function symmetry (7JB) was significantly worse than the other three conditions (Figure 6.11-B). As mentioned in section 3, scores were a combination of completion time and number of collisions to walls, and lower scores were better. We also found a significant effect of course type ($F_{2,141}=22.35$; $p<0.0001$). Speed control score for the random speed course was significantly worse than the scores for the slow and fast speed courses.

6.3.3 Maximum Movement Speed

We observed a significant effect of transfer function symmetry level on maximum movement speed ($F_{1,43}$=7.70; p=0.0081). Users with low transfer function symmetry (Seven League technique) could move significantly faster. We did not observe a significant effect of biomechanical symmetry on maximum speed.

6.3.4 Spatial understanding

We did not observe any significant effect of transfer function symmetry ($F_{1,47}$=0.72; p<0.40) or biomechanical symmetry ($F_{1,47}$=0.42; p<0.52) or any significant interaction ($F_{1,47}$=0.18; p<0.67) between them on spatial orientation. The mean values for errors for the different techniques were: RW=16.08°, JB=17.76°, 7L=19.26° and 7JB=19.81°.

6.3.5 Questionnaire Results

Using low levels of both biomechanical symmetry and transfer function symmetry (the 7JB technique), users felt significantly more annoyed compared to JB (χ^2=2.18; p=0.0342), 7L (χ^2=2.06; p=0.0453) or RW (χ^2=2.53; p=0.0152). Similarly, the techniques with low levels of both components (7JB) was significantly more tiresome (χ^2=2.10; p=0.0413) than just 7L. Chi-square analysis indicated that users felt 7L (χ^2=4.428; p=0.0354) was significantly more similar to real-world walking compared to JB or 7JB. Subjective ratings for simulator sickness showed significantly more sweating (χ^2=2.71; p=0.0096) using the low level of biomechanical symmetry compared to other techniques. We did not observe any significant differences in other comfort measures. Users felt that the RW and JB techniques were more comfortable, natural, precise, and easy to learn compared to the 7L and 7JB techniques respectively. On the other hand, users had more fun with the 7L technique compared to RW.

6.4 Discussion

As we expected, we found mixed results for our hyper-natural locomotion techniques. The 7L technique had performance similar to or better than RW in several situations, while the other two hyper-natural techniques, JB and 7JB, were sometimes harmful or undesirable for users (Table 6.2). This demonstrates that the effects of various hyper-natural interaction fidelity components are not uniform. Supporting our second hypothesis, a hyper-natural transfer function demonstrated mostly positive effects. The 7L technique improved maximum movement speed and was more fun for users. However, techniques with the hyper-natural transfer function (7L and 7JB) were significantly less accurate than techniques with a natural transfer function for more complicated path-following courses. Overall, then, we infer that well-designed hyper-natural transfer functions can be understood and adapted to by the user, resulting in improved speed performance (as in (Interrante, Ries et al. 2007)), but that they may still be more difficult to control when complicated, precise movements are required.

	7L	JB	7JB
Accuracy	Decreased	Decreased	Decreased
Speed control	n.s.	n.s.	Decreased
Movement speed	Improved	n.s.	Improved
Spatial awareness	n.s.	n.s.	n.s.
User comfort	n.s.	Sweating	Sweating
User experience	More Fun	n.s.	Annoying
Fatigue	n.s.	n.s.	Tiresome
Ease of learning	n.s.	n.s.	n.s.
Ease of use	n.s.	n.s.	n.s.

Table 6.2: *A summary of our findings. Green shows improvement over RW technique, red shows a disadvantage, and orange shows partial disadvantage.*

Our findings were not the same for biomechanical symmetry. As we have hypothesized, hyper-natural biomechanics did not improve locomotion performance in VR, despite published benefits for real-world locomotion (Miller, Zumbo et al.). The conditions using Jumps Boots not only decreased accuracy but also disturbed user comfort. Moreover, we observed that users' movements with the boots did not appear similar to real-world walking. Although one might expect the JB technique to increase the maximum movement speed, we did not find a significant advantage in our study. We observed that JB and 7JB users in our study did not walk confidently, and that they tended to walk more slowly than they would in the real world. Changing biomechanical forces and movements with the boots, while at the same time removing real-world visual cues (including the user's view of his own body) seems to be too difficult for users to cope with all at once. However, we note that our participants were not trained extensively with the boots, and effective training has shown some positive effects on improving VR locomotion performance (Nabiyouni, Scerbo et al. 2015).

Combining hyper-natural components of fidelity was mostly harmful to performance. The 7JB technique decreased speed control ability and caused users to feel more annoyed and tired. Modifying multiple components of fidelity, even in ways that are intended to enhance performance, can affect users' ability to understand their interaction and adapt to the differences.

We did not observe any effects of the hyper-natural techniques on users' spatial orientation. Our subjects had different strategies in the spatial understanding task. Based on our observation and the literature (Bowman, Koller et al.), the strategy users took for performing this task might have had a greater effect on their results than the techniques themselves.

6.5 Summary

This work contributes a deeper understanding of the effects of interaction fidelity, specifically for the hyper-natural design approach, and separates the effects of two critical interaction fidelity components.

Revisiting our research questions in section 5.1, we found that not all the effects of hyper-natural locomotion techniques are positive. Such techniques can improve some performance metrics while they might be harmful to some others. Additionally, we learned that methods that improve real-world interactions might not be beneficial in VEs. Our results also showed that well-designed hyper-natural transfer functions can improve movement speed and user experience, while they might decrease accuracy. Designers should consider the possibility of losing accuracy and use hyper-natural transfer functions for suitable applications. In applications where tracking space is large, but not large enough (e.g., simulating outdoor augmented reality systems), techniques like 7L may be good alternatives when natural walking is the desired mode.

On the other hand, the biomechanical component of interaction fidelity appears to be more sensitive to changes and might not be a good candidate for hyper-natural technique design. Designers should use caution when manipulating this component in their designs. Finally, we saw that modifying multiple fidelity components decreases the naturalness of the technique and can affect the users' ability to adapt to and learn the interaction. This work has contributed not only empirical results related to hyper-natural locomotion techniques, but also a theoretical framework for understanding interaction fidelity and designer intent in VR interaction techniques, and a testbed for evaluating locomotion technique performance holistically.

Using this experiment, we could address RQ2 and RQ3. RQ2 was about how do various components of interaction fidelity impact the effectiveness of interaction techniques? We figured out that changing biomechanics of walking will be mostly detrimental to the effectiveness while chancing transfer function might lower the effectiveness for specific aspects of locomotion. RQ3 was asking, what is the effect of hyper-naturalism on the effectiveness of locomotion techniques? Hyper-natural transfer function techniques can improve some components of effectiveness (such as movement speed and exploration range) and disturb some other components (such as accuracy). On the other hand, hyper-natural biomechanics will be mostly detrimental to the effectiveness of the interface.

7 For RQ4: Design and Evaluation of a Visual Acclimation Aid for a Semi-Natural Locomotion Device

One of the limitations of most virtual reality (VR) systems is that users cannot physically walk through large virtual environments. Many solutions have been proposed to this problem, including locomotion devices such as the Virtusphere. Such devices allow the user to employ moderately natural walking motions without physically moving through space, but may actually be difficult to use at first due to a lack of interaction fidelity. We designed and evaluated a visual aid that shows a virtual representation of the sphere to the user during an acclimation phase, reasoning that this would help users understand the forces they were feeling, plan their movements, and better control their movements. In a user study, we evaluated participants' walking performance both during and after an acclimation phase. Half of the participants used the visual aid during acclimation, while the other half had no visual aid. After acclimation, all participants performed more complex walking assessment tasks without any visual aid. The results demonstrate that use of the visual aid during acclimation was effective for improving task performance and decreasing perceived difficulty in the assessment tasks. This can contribute toward increasing the effectiveness of locomotion interfaces using effective training. This study helps us to address the fourth research question: How can we improve the level of effectiveness in moderate fidelity locomotion interfaces?

7.1 Visual Cue Design

The Virtusphere affords similar body movements compared to walking in the real world. However, it is quite different from the real world in terms of the direction and magnitude of forces used in walking. Although experienced users might be able to reach an appropriate level of performance, many new users struggle to walk in the Virtusphere. The Virtusphere's inertia and momentum, caused by its significant weight, makes initiating walking, maintaining balance, and terminating walking a challenge. Walking on the curved inner surface of the device also feels different than real-world walking.

To address these problems, we propose to train users *not* to think of themselves as walking through an environment, but rather to think of themselves as rolling a ball through the environment. Thinking this way should allow users to understand better the forces they are feeling, change the way they move, and adapt their actions to be more appropriate for the Virtusphere.

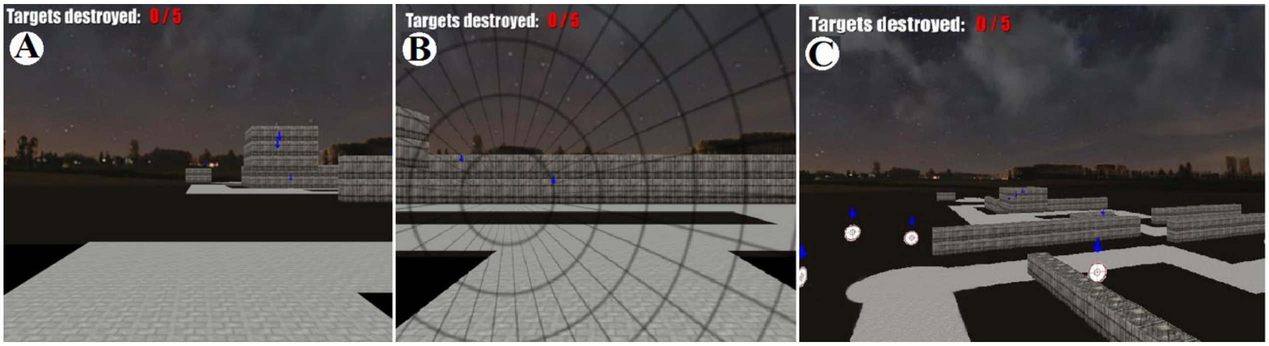


Figure 7.1: Study environment, A) without visual cue, B) with visual cue, C) overview of one of the assessment courses

Inspired by the video game Super Monkey Ball, we designed a virtual spherical visual aid that rotates around the camera in sync with the movement of the Virtusphere. Considering the dominance of visual cues in the human perceptual system (Razzaque, Kohn et al.), we hypothesize that showing the virtual sphere will keep users aware of the form factor of the device and make them adjust their walking accordingly and learn the differences between the Virtusphere and real walking more quickly.

We needed to create a texture that would convey the manner of rotation to the user observing it from the inside. We prototyped different transparent visual patterns. We found brightly colored patterns to be distracting, while fine-grained grid patterns occluded the user's vision. A transparent pattern with a mid-size grid (Figure 7.1B) was not very distracting and induced the feeling of walking inside the Virtusphere. The size of the visual sphere was similar to the actual Virtusphere.

7.2 Experiment

We designed an experiment to investigate the value of acclimation to the Virtusphere using the visual cue we designed.

7.2.1 Virtual Environment and Tasks

In a large number of real-world applications, locomotion is not the primary task but rather enables the user to perform another primary task. We evaluated our visual cue using a task in which walking is useful but is not the focus of the action. We designed a target practice course, with the targets placed in locations that required the user to move into strategic positions in order to shoot them. Our VEs (figure 7.1C) featured raised platforms without walls so that users could fall off the platforms if they did not walk accurately.

For each course, we asked the user to shoot the targets while navigating a pathway, without falling off the platform. A (virtual) fall caused the user to be re-spawned at the last location on the pathway to continue the task. We logged the number of virtual falls as a measure of how accurately users could control the navigation. We also measured the total time spent to finish the course, which required the user to shoot all targets.

7.2.2 Experimental design

Our experiment had two independent variables: course type and visual aid. Course type (with levels acclimation and assessment) was varied within subjects, while the presence of the visual aid was varied between subjects.

During the acclimation phase of the study, users completed four courses of relatively low difficulty. These courses averaged 150 feet in length with a few turns and one or two targets. To manipulate the visual aid independent variable, during the acclimation phase we showed the visual aid to half of our participants, while the rest did not use the visual aid.

In the assessment phase, participants completed two complicated courses. These courses averaged 600 feet in length with several turns and eight targets. None of the participants had the visual cue during the assessment phase.

The dependent variables were completion time, number of falls from the virtual platform, number of times the user physically lost balance, and the perceived difficulty for each course.

To assess simulator sickness, we used the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane et al.). In this questionnaire, 16 symptoms of simulator sickness are evaluated on a four-point nominal scale (i.e., none, slight, moderate, severe). We also asked participants about level of fatigue, ease of use and naturalness of walking in the Virtusphere.

7.2.3 Apparatus

We visualized the VE using a Sensics zSight HMD with a 60° field of view, stereoscopic rendering and resolution of 1280x1024. The user wore a backpack containing wireless video equipment and batteries. The user also wore knee and elbow pads, for safety considerations. The participant's head orientation was tracked using the inertial sensors in a Sony Move controller attached to the HMD. Another Sony Move controller was used as a wand to shoot targets. We used the "Move.me" application on a Sony PlayStation 3 to perform orientation tracking for both controllers. The Virtusphere's rotation was tracked with its own custom optical tracker allowing the user's viewpoint to translate in the VE. We used WorldViz's Vizard 4.0 software to interface with the hardware, render the VE, manage the flow of the experiment, and log the users' data.

7.2.4 Participants

We recruited 24 participants (13 females and 11 males) from the university undergraduate and graduate population on a voluntary basis for this study. The participants ranged from 19 to 29 years old. Subjects under the age of 18 and those weighing over 190 lbs. (the weight limit of the Virtusphere) were excluded. None of our participants had prior experience with the Virtusphere.

7.2.5 Procedure

We received approval from our university's Institutional Review Board (IRB). Upon arrival, participants were asked to read and sign the approved consent form. Then, they completed a background questionnaire, asking for their gender, age, occupation and experience of playing video games. After an introduction to our experiment and study procedures, participants were introduced to the Virtusphere and had a chance to use it for about seven minutes without the HMD. Participants were introduced to the VE by wearing the HMD and were asked to start the four acclimation courses. After each course they were asked about the perceived difficulty of the course on a scale of one to ten, with ten being extremely difficult to perform. The twelve participants in the visual cue group received the visual cue during the acclimation courses, while the other group did not.

After the acclimation phase, participants started the assessment phase, in which both groups performed the same tasks without the visual cue. Both Move controllers were calibrated at the beginning of each training or assessment course to eliminate the drift caused by the inertial sensors. Participants were allowed to rest at the end of each course. After finishing the assessment courses, participants filled out an exit questionnaire.

7.3 Results

7.3.1 Virtual Falls

We performed a two-way ANOVA on the visual cue and course type. We found a significant effect of visual cue on number of virtual falls ($F_{3,140}$=9.27; p=0.0017). The group trained with visual cue had significantly fewer virtual falls (mean per course=1.96) than the group trained without visual cue (mean per course=3.04). Comparisons of the number of virtual falls on each course using the Student's t-test (Figure 7.2) showed that participants trained with the visual cue performed significantly better on the first assessment course ($T_{1,22}$=-2.30; p=0.03). Participants trained with the visual cue also had fewer virtual falls on the second assessment course, but this difference was not significant.

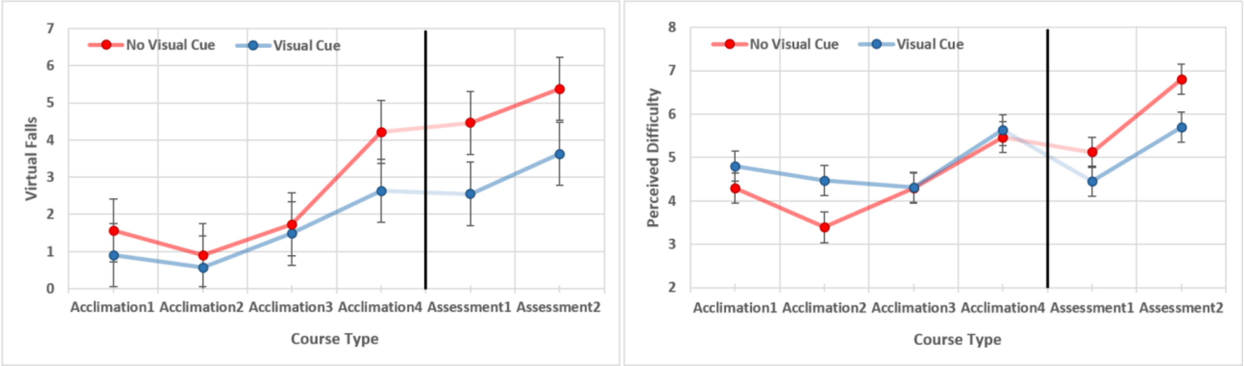


Figure 7.2 - Measure of virtual falls and perceived difficulty for the acclimation and assessment phases.

7.3.2 Completion Time

We did not observe any significant interaction between course type and visual cue. Our results indicated a significant effect of course type on normalized completion time (time divided by distance). Users in both groups walked faster in the assessment phase than the acclimation phase ($F_{3,140}$=12.33; p<0.0001). Pairwise comparisons using the Student's t-test did not show any significant differences between the two visual cue groups.

7.3.3 Perceived Difficulty

User's perceived difficulty gives insight about the subjective ease of use and the effect of visual cue on user experience. We found a significant interaction of visual cue and course type on perceived difficulty levels ($F_{3,140}$=12.86; p=0.0042). Per-course comparisons using the Student's t-test, shown in Figure 7.2, indicated that on the second acclimation course users with visual cue had significantly higher levels of perceived difficulty ($T_{1,22}$=2.54; p=0.0185) while on the second assessment course, users without visual cue had higher levels of perceived difficulty ($T_{1,22}$=-2.13; p=0.0444). We did not observe any significant differences for other courses.

7.3.4 Physical Falls

The number of times users fall down indicates their ability to maintain balance while using the Virtusphere. The mean number of physical falls for each person in the group trained without the visual cue was 0.42 falls per course, while people who were trained with the visual cue had an average of 0.31 physical falls per course. Although the mean values are different, our analysis did not reveal any significant differences for this measure.

7.3.5 Questionnaire Results

We ran a Chi-Square analysis to compare the subjective ratings given in the post questionnaires. Participants with visual cue felt significantly more difficulty focusing ($\chi^2_6=7.2$; $p=0.03$). We did not observe any significant differences for other measures. Overall, 58.3% of participants reported moderate to severe levels of sweating and 25% reported moderate to severe fatigue.

7.4 Discussion

Most of the effects of visual cue were positive. The number of virtual falls improved significantly when the visual cue was used for acclimation (Figure 7.2), and this difference was seen primarily on the assessment courses, after the visual cue had been taken away. Perceived difficulty was also significantly lower during assessment (Figure 7.2) after acclimation with the visual cue. Providing the visual cue did not have any negative effects on completion time and number of physical falls.

The virtual sphere we designed keeps the users aware of the fact that they are rolling a ball through the environment rather than walking on a flat surface. We believe that this helped the users better understand the required forces and adjust the way they moved to be more appropriate for the Virtusphere. This better understanding helps users to have a better overall experience. Although the conditions for the assessment courses were the same for both groups, the visual cue group had a better experience due to better understanding and control over the Virtusphere.

We have normalized the results for perceived difficulty and completion time (Figure 7.3). We wanted to see if the system entropy decreases as the users get acclimated more with the system and make progress through the courses. We have divided the values for perceived difficulty and completion time, by the difficulty level for each acclimation and assessment course. The difficulty level for each course was calculated based on the number of targets in the course, number of turns and the length of the path. We observed that as the users get more acclimated, both normalized perceived difficulty and normalized completion time decreases and the user could perform with higher level of effectiveness.

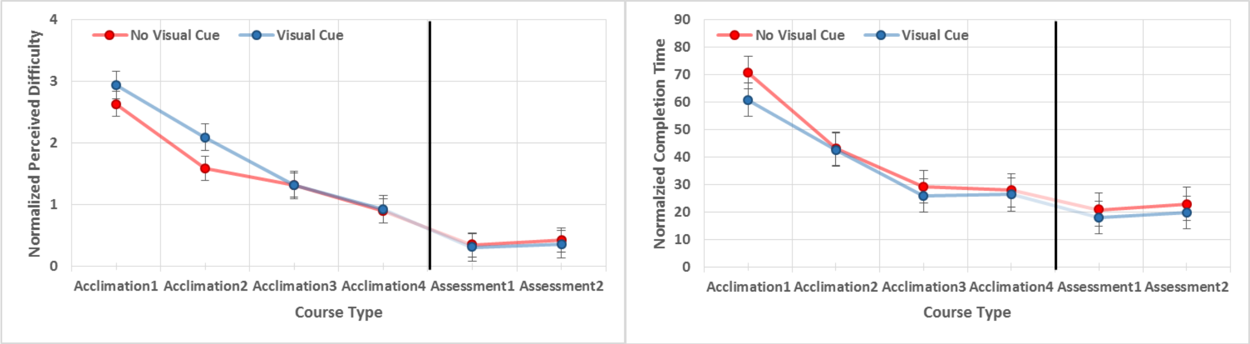


Figure 7.3 – Normalized perceived difficult and normalized completion time.

We did not observe any significant difference for completion time and physical falls, which suggests that the visual cue did not affect walking speed and balance control. The increase in accuracy was not a result of walking more slowly. We cannot say for certain whether the visual cue caused any differences in balance control although the visual cue group did have fewer physical falls in the assessment phase.

Semi-natural locomotion interfaces like the Virtusphere often have low performance and poor usability when users try to walk naturally. Our results show that appropriate visual assistance can help the user learn how this interface is different and how she should adapt her actions to it. To improve realism and not distract the user, the visual cue can be removed after the acclimation phase. Our results show that even without the visual cue, what users learned during acclimation can unconsciously help them to better understand their interaction and have better control.

Most of the participants who received the visual cue did not like it. We received several comments about the visual cue distracting users and occluding their view: "Virtual sphere did not help, I liked it when it was removed;" "It was not useful and occluded my view." Some users liked the visual cue at the beginning of their acclimation, but preferred it to be removed after several acclimation courses: "At first the virtual sphere was useful, but after I got used to walking in the ball, it was better when you removed it." The frustration of some users with the visual cue at the beginning is noticeable in the results. As shown in Figure 7.2, users with the visual cue perceived the second training course to be significantly more difficult than the group without the cue. Nonetheless, in the assessment phase, users in the visual cue group perceived significantly less difficulty and performed more accurately. It seems that, like vegetables for children, this visual aid actually helped participants to perform better despite their dislike of it. Thus, we jokingly refer to the virtual sphere as a "vegetable cue."

7.5 Summary

Users often require acclimation to be able to easily and effectively employ semi-natural locomotion interfaces. We designed a visual cue that helps to acclimate users to the differences in forces and walking movements between the Virtusphere and real walking. We found that acclimating with this visual assistance helps users better understand their interaction with the locomotion interface and be able to more easily cope with the novel technique they are using. Our results indicate that acclimating users with this visual cue can improve their accuracy and reduce the perceived difficulty of complex walking tasks after the cue is removed, while it does not harm the walking speed and balance. Even if users do not prefer having a visual aid, providing an effective cue can improve their performance.

The RQ4 was about, how to improve the level of effectiveness in moderate fidelity locomotion interfaces. This experiments shows us the use of training in locomotion interaction for semi-natural interfaces and the results indicate that effective training can improve user's experience and performance. This will make the acclimation phase more effective and enable users to perform more accurately and have a better experience.

8 A Meta-Analysis of Interaction Fidelity's Effects on User Experience

8.1 Introduction

We discussed our fidelity-user experience hypothesis (Figure 8.1) for locomotion interaction fidelity in Chapter 1, Section 1.6. We argued that increasing locomotion interaction fidelity does not necessarily guarantee an increase in user experience. Techniques and devices with a medium level of fidelity often provide inferior user experience compared to high-fidelity counterparts. The effectiveness of well-designed low-fidelity interaction techniques depends on the task and measurements, and such interfaces can outperform moderate-fidelity interfaces based in certain situations.

The hypothesis we presented is conceptual in nature and not an exact quantification of the relationship. The curves presented in Figure 8.1 only illustrate the idea rather than denoting absolute numeric values. This hypothesis has three main parts:

1. High-fidelity interfaces almost always result in a high level of effectiveness.
2. Moderate levels of interaction fidelity often do not achieve high levels of effectiveness.
3. The effectiveness of low levels of interaction fidelity depends on the way effectiveness is defined, as well as the task and measurements.

We illustrate these three postulated insights with the curves in Figure 8.1. However, these graphs do not make any prediction about any absolute value of performance and the height of the curves and the distance between the curves is not meant to be quantitatively meaningful.

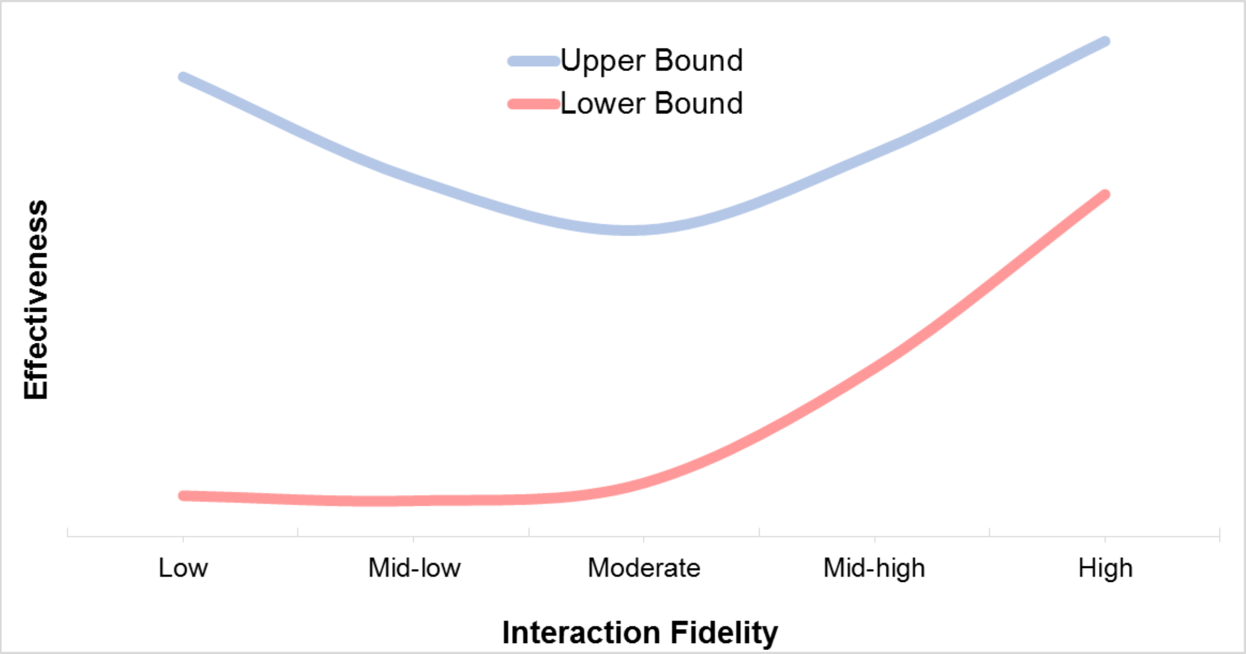


Figure 8.1 – Illustrative diagrams of the hypothesized Interaction Fidelity-Effectiveness Relation.

This meta-analysis is not intended to find values for the height of the curves and the distance between the curves. Instead, it is intended to determine whether or not there is more evidence for the aforementioned three parts of the hypothesis. In figure 8.1, we present the concepts of this hypothesis graphically, since it is the easiest way to understand the literature results, together. Nonetheless, we acknowledge that these graphs do not represent any quantitative and numeric values.

Our own user studies, described in chapters 5, 6 and 7, support this hypothesis. But do other experiments in the literature support it as well? We need to know more about what measures support this hypothesis, what counter examples and outliers may exist, and the reason behind them. Therefore, we assessed research literature that compared two or more locomotion interfaces with varying levels of fidelity. To classify the fidelity level of each technique, we first did a FIFA analysis. The FIFA analysis gave us insights about how to compare the different techniques to their natural counterparts and to each other. Then we classified each technique into one of five categories: low, mid-low, moderate, mid-high, and high level of fidelity. The highest level of locomotion interaction fidelity described in the research literature is real walking, in which the user's head is tracked and she observes the VE through a VR display. We consider the real walking technique the highest level of fidelity. The gamepad technique employs joysticks to allow the user to rotate and translate in the VE. It involves different forces, movements, transfer functions, and even uses different body parts. Altogether it is very different from real walking. We consider this technique to be on the low end of the fidelity spectrum, along with other similar techniques, such as joystick and mouse and keyboard. Techniques such as walking-in-place (Usoh, Arthur et al. 1999), omni-directional treadmill (Darken, Cockayne et al. 1997) and Virtusphere (Latypov 2006), simulate walking motions while they employ different forces or different transfer functions for walking. Such techniques mimic an important component of interaction fidelity closely, while they disregard another important component. We consider these techniques moderate-fidelity techniques, in the middle of the fidelity spectrum. In addition, techniques such as finger walking (Kim, Gračanin et al. 2015), which differ in a couple of important components of fidelity (forces and body parts in the finger walking example), are lower than moderate fidelity. However, they are more natural than the low fidelity techniques and thus we assign them the mid-low level of fidelity. Finally, techniques such as Seven League Boots (Interrante, Ries et al. 2007), moderately change one important component of fidelity (transfer function for this example). They are more natural than the moderate-fidelity techniques but are not as natural as the high-fidelity one. We classify such techniques as mid-high level of fidelity.

The tasks and measures used in the various experiments from the literature are often very different from each other. We normalized the quantitative results regarding locomotion techniques using a scale of zero to one, making it possible to compare all results in a single framework. For each specific task and specific measurement, we extracted the best and worst possible cases, and employed these values for normalization. As an example, if the measurement was a subjective user experience value using a Likert scale from 1 to 7, then we have absolute best and worst cases, so we set the worst possible value to one and best possible value to seven. Normalized to [0,1] an original value of 4 would result in 0.5 on our new scale. For performance data such as completion time, the lowest absolute value would be zero and highest absolute value would be infinity. However, these values cannot possibly be encountered. Therefore, for completion times and similar metrics, we used the highest and lowest actual values, if we had access to this information from the articles. For the articles that did not provide such details of the collected data, we chose as the worst case the highest mean value plus the variance and as the best possible case the lowest mean value minus variance. We used the form of variance presented in each paper (e.g., standard error). We extracted the mean and variance values in form of numbers if available. Otherwise, we used presented graphs to estimate and extract the mean values and used error bars in the graphs to estimate the variance.

We also have another type of variable for performance measures in which one bound of the variable has a feasible absolute value. For example, measures such as the number of virtual falls, the number of times a user collided with a virtual wall, or the number of mistakes made in a task, have an absolute best case of zero. For such variables, we set the best case to zero and set the worst case to the highest mean value plus the variance. In all cases, data was normalized such that higher values meant superior effectiveness.

We acknowledge that the differences in values do not necessarily impose statistical significance. We perused 20 relevant articles from the literature. All of these articles are listed and analyzed in Appendix II. We discuss some examples and counter examples here. In these examples, the level of fidelity for compared techniques is discussed. However, a more thorough analysis is performed using the FIFA framework and is presented for each article in Appendix II.

8.2 Examples

8.2.1 Marsh, Putnam et al. 2012

In this study, three locomotion interfaces, namely Gamepad, P2V (Human joystick, shown in Figure 8.2) and Real Walking were compared (Marsh, Putnam et al. 2012). Real walking closely mimics real world walking actions, therefore we consider this technique as a high-fidelity technique. The joystick technique is considered low fidelity due to dissimilarity of the input actions to walking in the real world. The act of walking to reach a movement zone in the human joystick technique is similar to walking. However, this technique maps the position of the user to the velocity of movement in the VE. Moreover, to stop walking, the user needs to walk back to the dead zone. Therefore, we consider this technique to be a medium-fidelity technique. The interaction fidelity of the three techniques is further discussed in Appendix II.

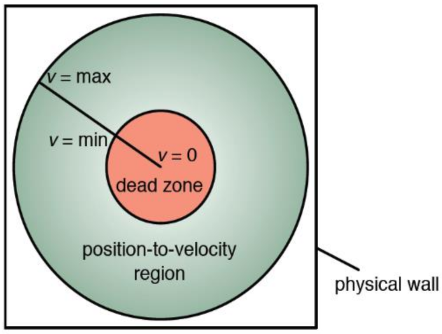


Figure 8.2 – Human Joystick technique (Marsh, Putnam et al. 2012).

In this study, the task included performing basic locomotion task with one of the three interfaces while remembering a sequence of spatial or verbal items. The measures included number of memory items missed for the memory task, and stop time, the amount time taken by the user to stop navigation.

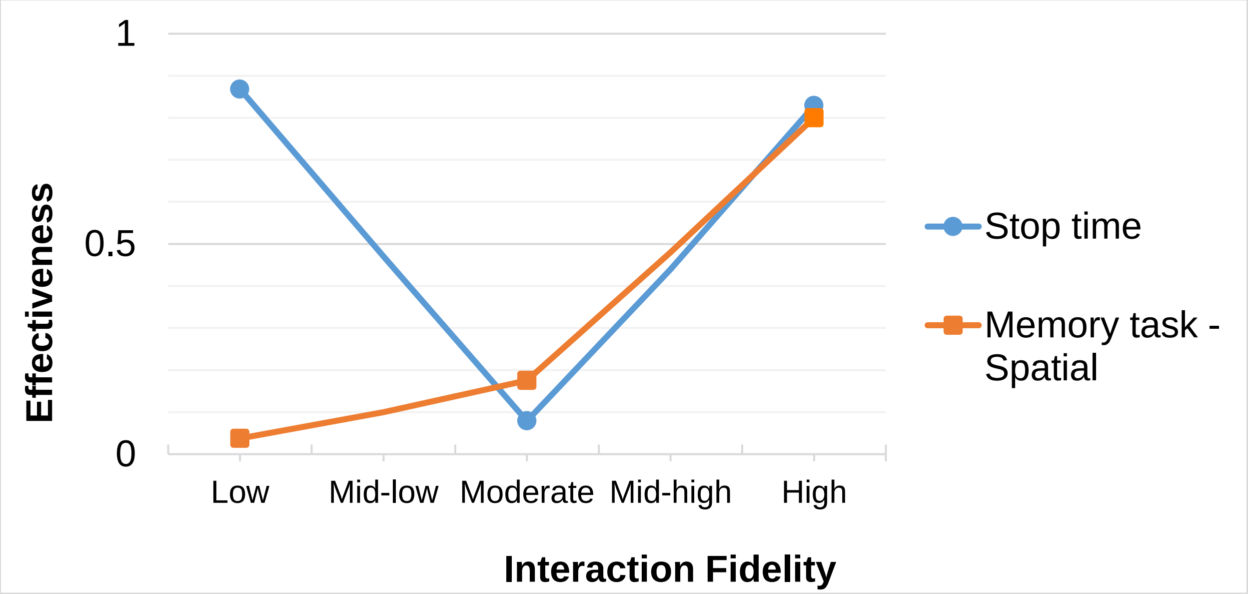


Figure 8.3 – Measures of stop time and memory for (Marsh, Putnam et al. 2012).

As shown in Figure 8.3, for the stop time measure the moderate level of fidelity has the least effectiveness. This is in line with the high bound of our hypothesis shown in Figure 8.1. For the memory task, both the moderate- and low-fidelity interfaces have low level of effectiveness. This is in line with the low bound shown in Figure 8.1.

With increased level of interaction fidelity, the memory task performance increases. This may indicate that low-fidelity locomotion interfaces place cognitive demands on the user and that they compete for the same cognitive resources as the spatial memory tasks. However, the low-fidelity interface was very effective in terms of stop time. A well-designed low-fidelity interface using the gamepad allowed the user to stop locomotion immediately, by stopping to operate the joystick, while the moderate-fidelity human joystick technique requires the user walk back to the neutral (dead) zone.

8.2.2 McMahan, Alon et al. 2010

In this article, the three interfaces Gamepad, Wii Remote, and Wii Wheel (Figure 8.4) were compared. The task consisted of navigating a vehicle in the Mario Kart driving game (McMahan, Alon et al. 2010). The time measure indicated completion time for this game. Moreover, users selected the interfaces which they found easiest to use and they most liked.

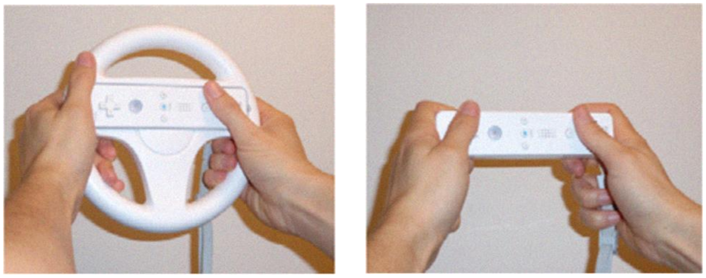


Figure 8.4 – The Wii Wheel and Wii Remote used in the article (McMahan, Alon et al. 2010)

We consider the Wii Wheel to be a moderate-fidelity interface since it lacks the haptic feedback of a real-world steering wheel and the user steers the wheel in midair. Therefore, the forces and movements are different from the natural counterpart. Since the Wii Remote additionally lacks the form factor of a steering wheel, we consider it a mid-low level of fidelity.

As shown in Figure 8.5, users had better completion time with the low-fidelity gamepad comparing to the mid-low- and moderate-fidelity Wii interfaces. Subjective ratings showed similar results. Altogether, these results provide more evidence to our hypothesis.

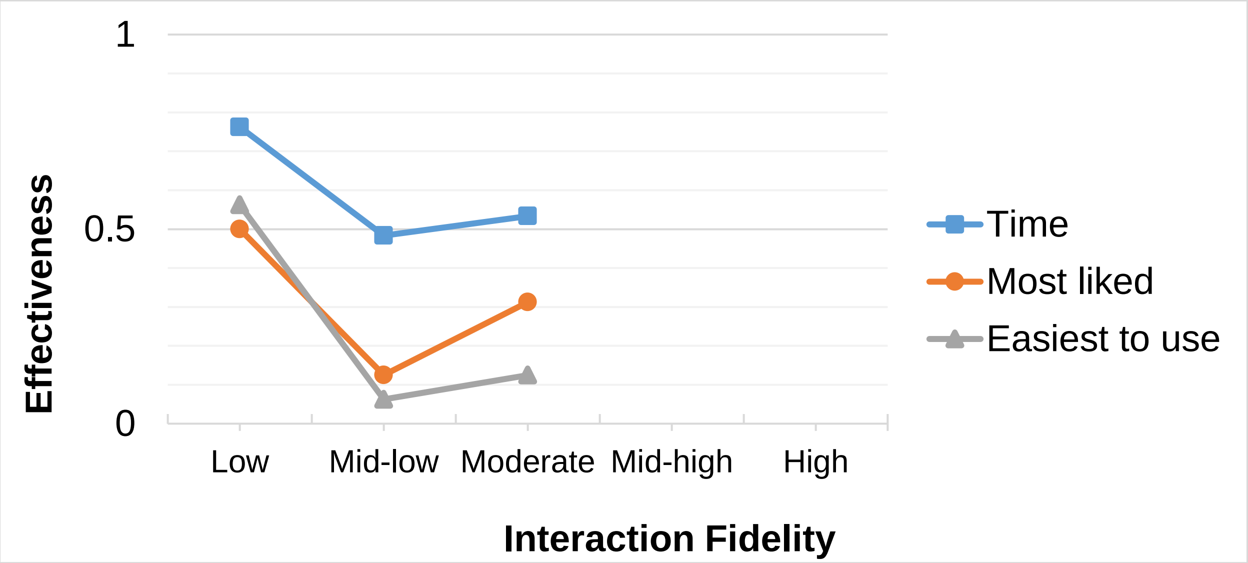


Figure 8.5 – Measures of completion time, most liked and easiest to use (McMahan, Alon et al. 2010)

8.2.3 Usoh, Arthur et al. 1999

This article implemented and compared flying, walking-in-place (WIP) and real walking (Usoh, Arthur et al. 1999). In the WIP technique, the user marches in place to move forward in the VE. In WIP, the act of removing one’s feet from the ground is similar to real-world walking. However, forces and movements for the push-off and hill strike phases of walking are different. Therefore, we consider this technique moderate-fidelity. Flying, on the other hand, is quite dissimilar to walking, therefore we consider it a low-fidelity technique. Further analysis of these techniques was performed using the FIFA framework and is presented in Appendix II.

In this study, the task involves moving an object and putting it on a chair on the other side of the virtual room. As the user enters the virtual room, she is on a ledge which is 6m higher than the room’s floor. This ledge goes around the room and a chair is placed on the ledge on the other side of the room. A direct path from the entrance to reach the chair would mean walking in thin air. Moreover, it is possible to reach the chair by moving along the edge of the room, “safely”. The measurements include subjective ratings of 1-7 asking the user’s subjective opinion on how simple, how straightforward and how natural their experience with the locomotion technique was.

As shown in Figure 8.6, the questions how simple and how straightforward each interface was to use, mostly falls in line with the higher bound of our hypothesis while the question on naturalness comes close to the lower bound. It seems that it was both simple and straightforward to perform the task with all these interfaces. However, users did not feel natural using the moderate- and low-fidelity interfaces.

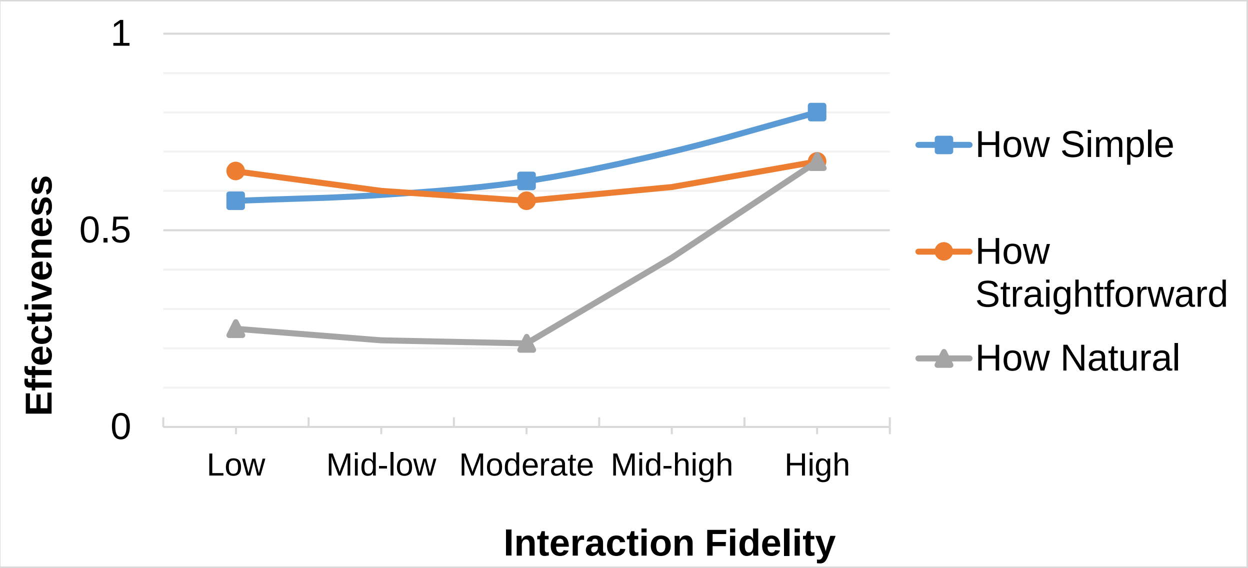


Figure 8.6 – Results for the pit study by (Usoh, Arthur et al. 1999)

8.2.4 Chance, Gaunet et al. 1998

In this study, three techniques were compared: visual turning using a joystick, physical turning with body direction, and real walking (Chance, Gaunet et al. 1998). The first two technique use a constant speed. In the body-direction technique, users controlled their turning with the direction of their body. Joystick turning is on the lower end of the fidelity spectrum. Using body direction for turning is more natural, therefore we consider this technique a mid-low level of fidelity. All subjects participated in three sessions each for a locomotion technique. In each session, the user explored three one-target mazes and three three-target mazes. The dependent measure in this study was the absolute error of the user's spatial estimate to each target as she reaches the terminal location. Subjects were asked to verbally report the minute hand position of each target. In this method, the forward direction would be 0 minutes and the object directly to the right would be 15 minutes (similar to a clock). The mean absolute error from the first session is called accuracy 1 and the mean absolute error from the third session is called accuracy 2 in the Figure 8.7. Motion sickness data was also gathered from the participants.

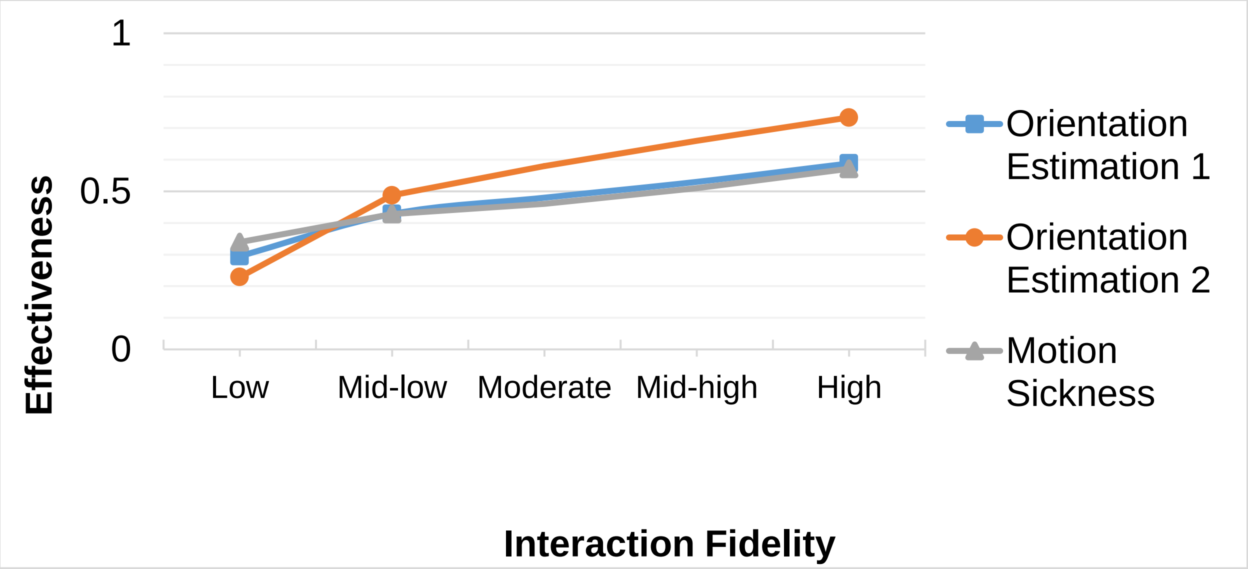


Figure 8.7 – Mean absolute error from first session (accuracy 1) and third session (accuracy 2) in addition to motion sickness results (Chance, Gaunet et al. 1998).

The orientation estimation data fits into our fidelity-effectiveness hypothesis. Users were less accurate with the low-fidelity technique comparing to the mid-low one. A contributing reason might lie in the way the joystick was mounted on a rifle for the low-fidelity interface which can decrease the ease of use for employing the joystick. However, we observed similar results for the orientation estimation from other articles (Iwata 1999, Sibert, Templeman et al. 2008, Kim, Gračanin et al. 2010, Williams, Bailey et al. 2011, Kim, Gračanin et al. 2015). Most of these articles use a standard gamepad technique for the low level of fidelity. Therefore, we can see that orientation estimation seems to have a direct relationship with the interaction fidelity and increases as the interaction fidelity increase.

Users experienced less motion sickness with real walking comparing to mid-low and low levels of fidelity, which may be due to vestibular cues received from real walking. Moreover, the users had less motion sickness with the mid-low level of fidelity comparing to low fidelity interface. The reason is likely that using body direction to turn provides partial vestibular information to the user, which can alleviate simulator sickness effects.

8.2.5 McCullough, Xu et al. 2015

This experiment employs and compares Joystick, Myo arm–swinging, and walking techniques for locomotion in VE (McCullough, Xu et al. 2015). In Myo arm-swinging, the user can swing her arm, similar to the same action while walking in the real world, to traverse through the VE. This technique mimics the arm swinging action while it does not mimic feet movements. Therefore, we consider this a technique with mid-low level of fidelity.

Figure 8.8 – Myo arm-swinging technique (McCullough, Xu et al. 2015)

In this study, the users were asked to perform a spatial orientation task. To measure spatial orientation, researchers asked the users to turn and face remembered objects from different positions in the VE. They recorded the turning errors and the corresponding latencies associated with participants' actions. Moreover, they asked users about their subjective opinions for these questions:

- Did your movements feel accurately translated into the environment?
- Did you experience any motion sickness or vertigo while using this equipment?
- Overall, how would you rate your experience with this machine?
- If this device was within your price range, would you buy it?
- If you owned this device, how frequently would you use it?

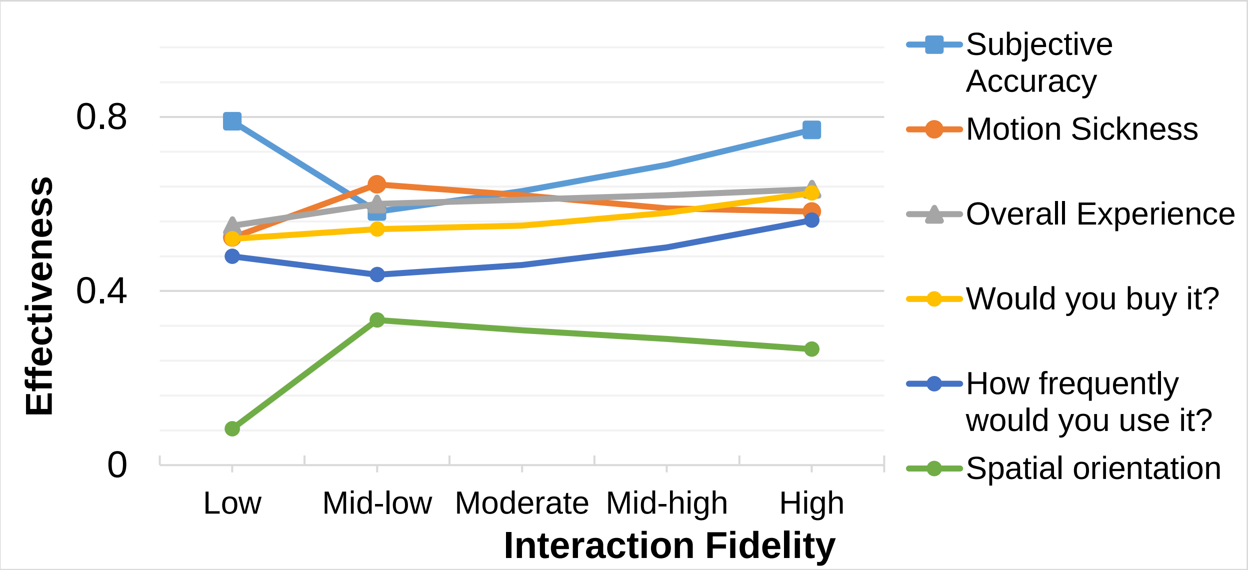


Figure 8.9 – Measures from (McCullough, Xu et al. 2015)

As shown in Figure 8.9, the subjective accuracy results indicate inferior effectiveness for the mid-low interface. However, other subjective measures as well as motion sickness data, indicate equal or higher effectiveness for mid-low level of fidelity comparing to the low- and high-fidelity techniques. This does not match our hypothesis. The turning error data indicates low levels of effectiveness for both high- and low-fidelity techniques. The effectiveness of the real-walking technique depends on several factors such as latency, field of view, and resolution of the display system, form factor, how cumbersome it is to wear the HMD, and whether the user's feet are visualized. Such factors along with the difficulty of the task might be the reason for the low effectiveness of the high-fidelity technique in this article.

8.2.6 Interrante, O'Rourke et al. 2007

This article describes the implementation of Seven League Boots (Figure 8.10) and compares this technique to joystick, constant gain (10x) and real walking techniques (Interrante, O'Rourke et al. 2007). The Seven League Boots technique has been described in Chapter 6. It employs the same forces and movements as real walking. However, it uses a different transfer function to move users even faster in the VE while they are physically moving fast. Due to its closeness to natural walking we consider this technique to be of mid-high level of fidelity. Constant gain (10x) linearly maps each step to 10 steps in the VE, therefore this technique is less natural than the seven league boots and we consider it a moderate-fidelity interface.

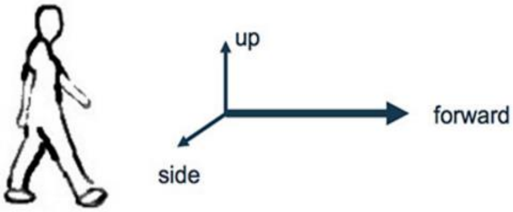


Figure 8.10 – Seven league boots technique (Interrante, O'Rourke et al. 2007).

In this experiment the tasks involved exploring a virtual hallway. This allowed users to employ various techniques in a realistic fashion. Measures in this study included responses to:

- Overall impression
- Ease of use
- Feels natural
- Accurate distance impression
- Cyber-sickness

For the overall impression, the high-fidelity technique was less effective than the mid-high level of fidelity. A reason might be that the user enjoyed the hyper-natural ability of the Seven League Boots technique and could travel more easily long distances. Therefore, this measure does not support our hypothesis (Figure 8.11). On the other hand, for responses on ease of use, 'feels natural', and accurate distance impression, the results support the high boundary of our hypothesis.

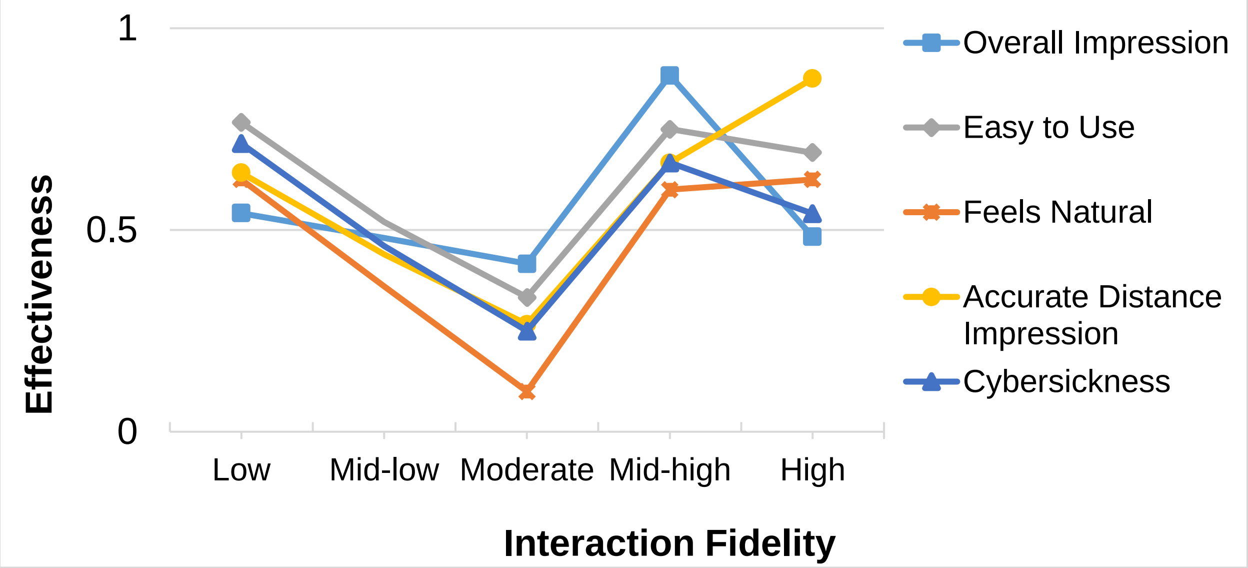


Figure 8.11 – results from subjective measures (Interrante, O'Rourke et al. 2007).

8.3 Overall Meta-Analysis

The graph depicted in Figure 8.12 shows the overlay of all the results from the 20 articles used in our meta-analysis. We overlaid the illustrative higher and lower bound curves on the plots. These higher and lower bounds illustrate the concepts of our hypothesis. As described in Section 1.6, our hypothesis consists of three main concepts:

1. High interaction fidelity almost always leads to high level of effectiveness.
2. Moderate levels of interaction fidelity, do not typically achieve high levels of effectiveness.
3. The effectiveness of the low-interaction fidelity techniques depends on the task and measurements, and the way we define the effectiveness.

We further characterize the measures and tasks based on whether the points in general correspond to the three concepts in the hypothesis.

Our hypothesis suggests a positive slope for the data lines, from moderate to high level of interaction fidelity. In general, this can be observed in Figure 8.12. However, there are a few lines that have negative slope in this region. In the next two sections, we analyze these results and characterize the type of tasks that defy this hypothesis and the tasks that fit.

As mentioned in the introduction section of this chapter, the differences do not necessarily indicate statistical significance in all cases. Nonetheless, we are looking for general patterns from different tasks to better understand how they do or do not support this hypothesis.

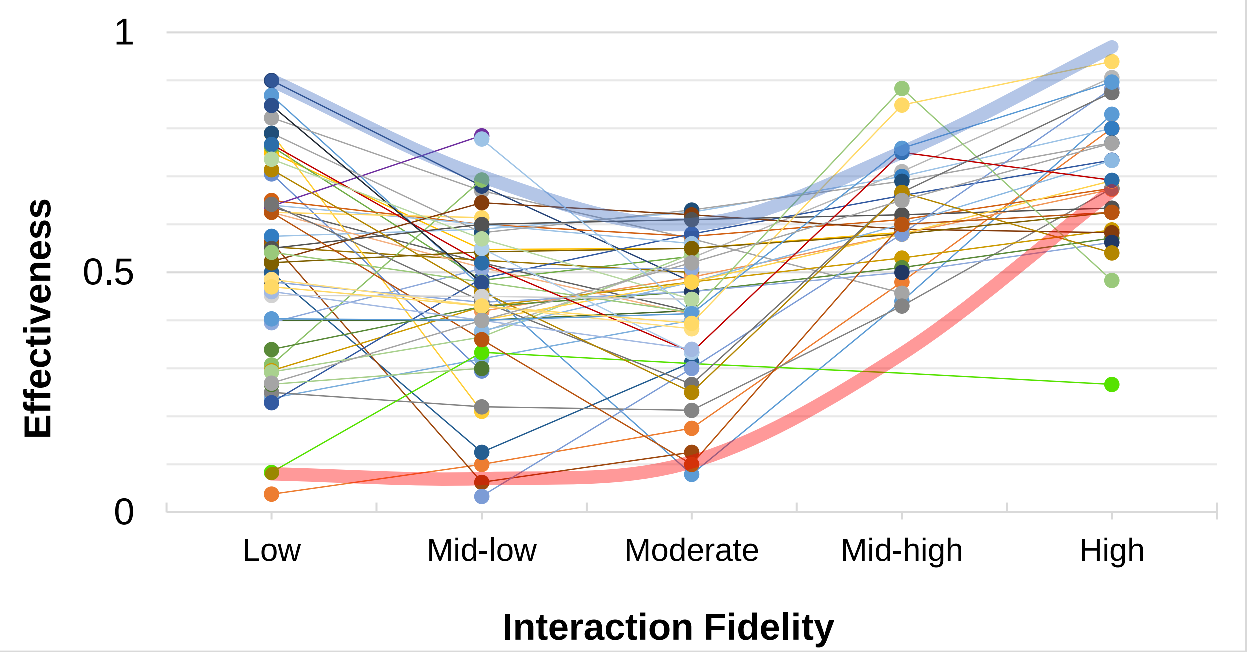


Figure 8.12 – The overlay of all the results from the meta-analysis articles. Thick blue line indicate the higher bound and the thick red line indicate the lower bound of the fidelity-effectiveness hypothesis.

8.4 Characterizing counter-examples

We divided the results into two general categories: examples that provide further evidence for this hypothesis and counter-examples that dispute this idea. Analyzing the counter-examples, we observed that these data are from specific measurements of different tasks. We can characterize these outliers in three categories:

8.4.1 Outliers

Some results *can* be contradictory to our hypothesis. Here, we try to find the reason behind it. As shown in Figure 8.13, the green line (turning error, (McCullough, Xu et al. 2015)) indicates a low level of effectiveness for a high-fidelity interface. In this graph, the interaction fidelity increases to the highest level but the graph stays at a low level of effectiveness even for the high-fidelity technique. The mean values for the three locomotion interfaces (Joystick, Myo arm-swinging and real walking) was approximately 20 to 30 degrees. These values are similar to the results from literature that examines similar tasks (Chance, Gaunet et al. 1998, Nabiyouni and Bowman 2015). The least possible error would be zero degrees, while based on their results the worst possible mean value plus variance was about 30 degrees. This is the method we employed to calculate the worst possible value and it may explain why the normalized value for turning error is so low.

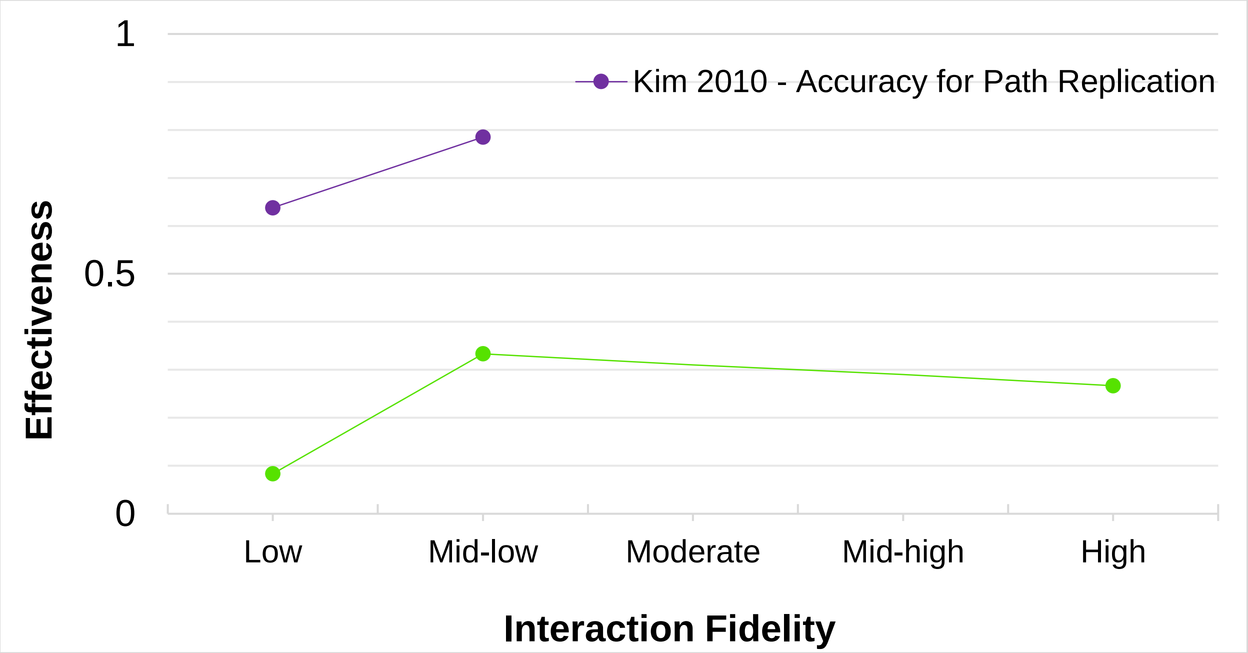


Figure 8.13 – Results from (Kim, Gračanin et al. 2010) and (McCullough, Xu et al. 2015) for path replication and turning error

The purple line (accuracy for path replication, (Kim, Gračanin et al. 2010)) in Figure 8.13, indicates high effectiveness for a mid-low-fidelity interface, which is outside the boundaries of our hypothesis. The pattern is similar to the results for a similar task (Kim, Gračanin et al. 2015), with both interfaces highly effective for this task. A reason for the high effectiveness values might be that the task was too simple for the users and they could perform it well regardless of technique. The delta between the values, however, is similar to the results from (Kim, Gračanin et al. 2015).

8.4.2 Simulator sickness

Mismatch between visual and vestibular cues can cause simulator sickness. Moderate-fidelity interfaces often include leg motions to mimic real walking, and such vestibular cues can be beneficial to simulator sickness. As shown in Figure 8.14, moderate-fidelity interfaces can alleviate simulator sickness compared to low-fidelity interfaces. The results from (Interrante, Ries et al. 2007) show low effectiveness of the moderate-fidelity interface (constant 10x gain), compared to the joystick technique. Using this moderate-fidelity technique, as the user took one step, she was moved 10 steps in the VE. This causes a large mismatch between vestibular and visual cues and might be the reason for users experiencing more simulator sickness using this specific technique.

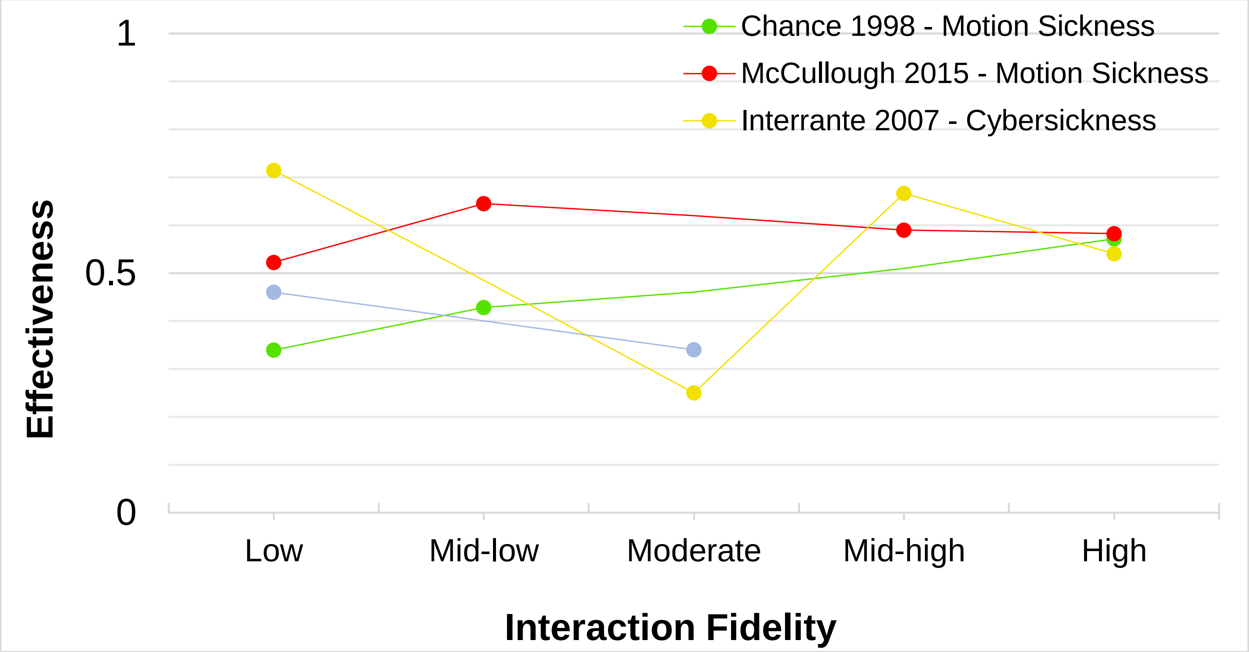


Figure 8.14 – Simulator sickness results.

As shown in Figure 8.14, the overall shape of these graphs stays at the same moderate level of effectiveness for both moderate- and high-fidelity interfaces and does not expose an increasing level of effectiveness with increasing fidelity from medium to high (Chance, Gaunet et al. 1998, Interrante, O'Rourke et al. 2007, McCullough, Xu et al. 2015). There are several factors in the real-walking interaction technique at play here that are different from walking in real world, such as latency, field of view, form factor and not being able to see your feet. Also, distance estimation can be different in the VE compared to the real world. Such factors can affect and contribute to simulator sickness, and we believe this might be the reason behind the low level of effectiveness for high-fidelity techniques in these articles.

8.4.3 Subjective Measures

Specific subjective measures such as:

- Overall Impression
- Would you buy it?
- How frequently would you use it?

are shown in Figure 8.15. The moderate-fidelity interfaces are often novel and most of the users have not used them before. Employing a novel and different interface in the context of VR can create a pleasant experience, regardless of the effectiveness and performance of the interface. The user can have *fun* using this device and enjoy experiencing a novel interaction. Therefore, as can be seen in Figure 8.15, moderate-fidelity interfaces can create results equal or better than high- and low-fidelity interfaces, for such measures.

The four points in Figure 8.15 for high-fidelity real walking (Interrante, O'Rourke et al. 2007, McCullough, Xu et al. 2015), are almost at the same level as the mid-low-fidelity interfaces and based on these graphs, the high level of interaction fidelity does not imply high levels of effectiveness. Several system specifications, such as latency, display resolution, field of view and other factors, such as how interesting the task is, or how cumbersome it is to wear an HMD, can affect the user experience. We believe that such factors might be the reason for low levels of user experience for the aforementioned measurements from these articles. However, results from other subjective measures such as ease of use, subjective accuracy and perceived naturalness shows high effectiveness of the high-fidelity interfaces and support our hypothesis.

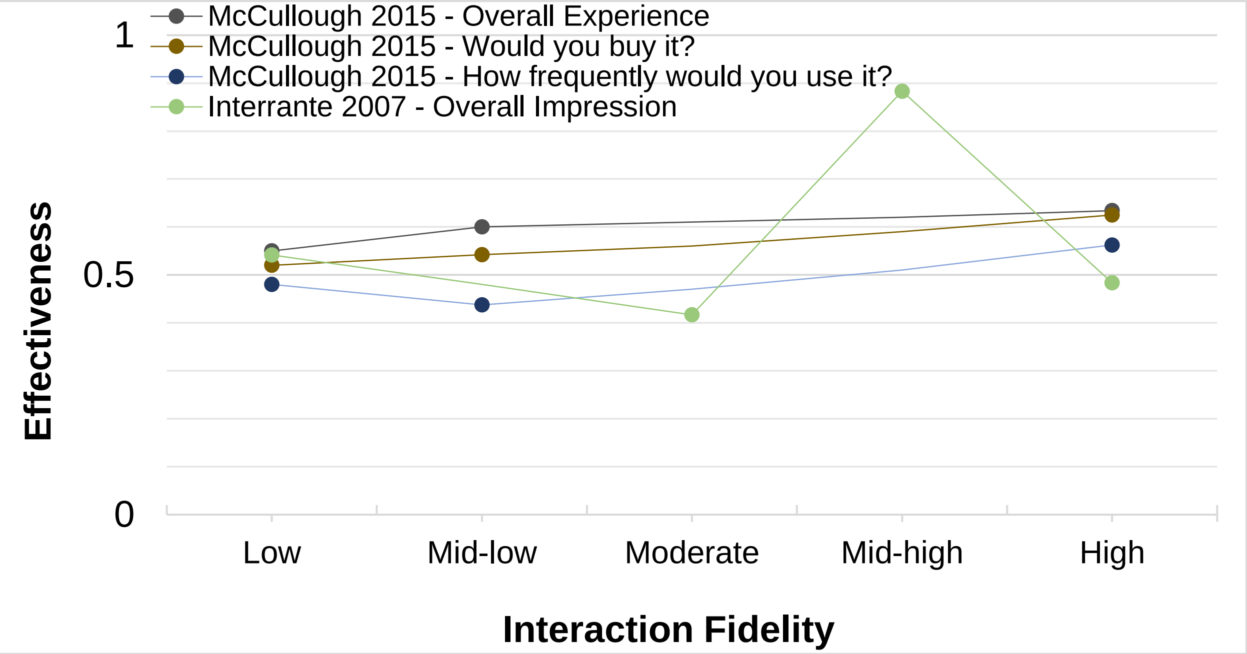


Figure 8.15 – results from subjective measures such as, overall impression, would you buy it and how frequently would you use it.

8.5 User experience measures that fit into our hypothesis:

As we observed in our meta-analysis, various performance measures and subjective user experience measures do fit into the concepts of our hypothesis. Such measures include:

- Performance measures
    - Completion time
    - Response time
    - Movement and maneuvering accuracy
    - Movement speed

  - Speed control
  - Distance estimation
  - Orientation estimation
  - Cognitive load: spatial and verbal memory task
  - Progress through course
  - Head trajectory
  - Balance control
  - Tactile sensation
- Subjective user experience measures
  - Presence (Questionnaire Scores)
  - Subjective evaluation
  - Perceived naturalness
  - Ease of use
  - Subjective accuracy
  - Most liked interface
  - Involvement

For the aforementioned measures, high-fidelity interfaces lead to high levels of effectiveness. The reason is likely that such interfaces mimic real-world actions closely, and the user is inherently familiar and skillful with such actions. Therefore, the user can perform the tasks well and generally has a good experience (Figure 8.16). Low-fidelity interfaces that are well-designed and employ good design paradigms can be easy to learn and easy to use and can create superior results. However, it is possible that depending on the tasks and design of the interface low-fidelity interfaces may cause low levels of effectiveness (Figure 8.16).

Moderate-fidelity interfaces, on the other hand, introduce themselves as natural interfaces and users try to use real-world actions to employ such interfaces. Because of the differences in the control, forces and movements in moderate fidelity interfaces, the user needs to change the way she walks and to some extent unlearn what she has been doing in the real world while learning the new walking method. This may cause the user to have inferior performance and experience with the moderate fidelity interfaces. As can be seen in the Figure 8.17, most of the lines from moderate to high levels of fidelity have a positive slope, indicating that corresponding points from the high-fidelity group have higher effectiveness.

Since the moderate-fidelity interfaces change the way the user has to walk, she will be challenged to newly understand her walking and control her movement. Thus, performance measures such as completion time, accuracy and speed control will be affected. Since walking actions are changed in the moderate-fidelity interfaces, the user needs to control and think about her walking. This increases the cognitive load of locomotion and will influence tasks such as word recognition and memory tasks. Since the walking with moderate-fidelity interfaces requires more cognitive resources than walking in the real world, a user's spatial understating might also be affected negatively. Difficulty in performing locomotion will cause an inferior user experience and since the user needs to be aware of her walking, it will reduce presence. Therefore, as we can see in Figure 8.17, for previously mentioned performance and subjective user experience measures, moderate-fidelity interfaces have inferior effectiveness compared to the other two ends of the fidelity spectrum.

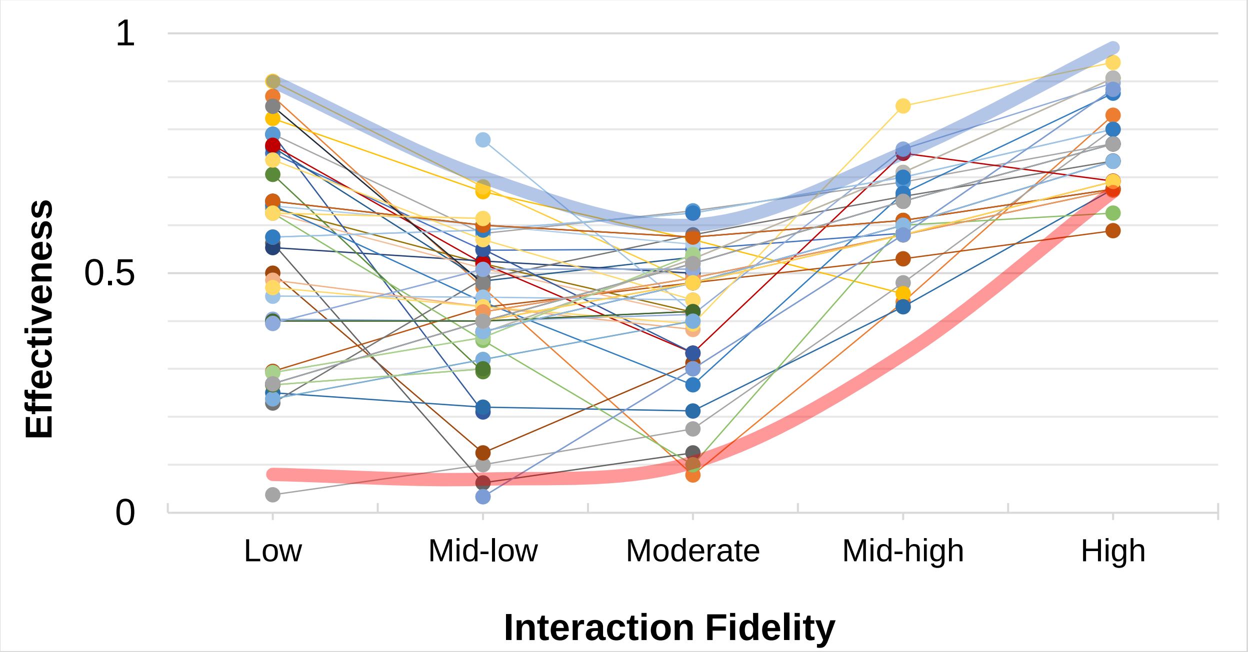


Figure 8.16 – Results from performance measures such as, completion time, accuracy, speed control, cognitive load, spatial understanding and subjective measures such as ease of use, perceived naturalness, subjective accuracy and presence.

All the techniques that fit into our hypothesis (presented in chapter 8.5) have high effectiveness for high-fidelity techniques. However, as shown in Figure 8.16, for some measures effectiveness increases by increasing the level of fidelity while others have low effectiveness for moderate-fidelity techniques and high effectiveness for low-fidelity one and form a U-shaped uncanny valley. We can further characterize the measures based on this fact.

8.5.1 Increasing Effectiveness with Increasing Level of Interaction Fidelity

For some measures in Figure 8.16, effectiveness increases by increasing the level of fidelity. Such techniques have high effectiveness for high-fidelity techniques and low effectiveness for low-fidelity techniques. We further analyzed the results of the literature and learned that specific measures have this characteristic, such as:

- Performance measures
    - Orientation Estimation
    - Cognitive load: spatial memory task
    - Head trajectory: Natural head movement during locomotion
    - Tactile sensation
- Subjective user experience measures
    - Presence (Questionnaire Scores)
    - Overall Involvement

These techniques are shown in Figure 8.17. For the orientation estimation and spatial understanding, higher levels of fidelity provide more proprioceptive sensory information to the user, and the user can more accurately understand her spatial orientation with increasing levels of interaction fidelity. Additionally, spatial understanding uses the same cognitive resources as the locomotion interaction (Chance, Gaunet et al. 1998), and therefore we observe the same positive slope pattern for the cognitive load measure when spatial memory tasks were involved. Using lower levels of interaction fidelity, the user receives less proprioceptive sensory information and therefore likely has a less accurate understanding of their spatial position. An increase in the level of effectiveness when the level of interaction fidelity increases, is therefore understandable.

Using high-fidelity interaction techniques, with the user physically walking, she will feel tactile sensations at her feet and will experience natural head bobbing and head trajectories similar to real-world walking. Increasing levels of interaction fidelity increase the natural movements and sensations. Although the user's movements are different using the moderate-fidelity interfaces, these movements are considerably more natural than the low fidelity techniques such as gamepad or joystick. The natural movements create more natural head movements and tactile sensations using the moderate-fidelity interfaces compared to low-fidelity techniques and positively influence effectiveness for these two measures.

For subjective user experience measures, such as overall involvement and presence, as the interaction fidelity level increases, the interaction naturalness increases, and this improves the sense of presence and perceived naturalness. Therefore, for the aforementioned measures, we observe a line with positive slope from low levels to high levels of fidelity.

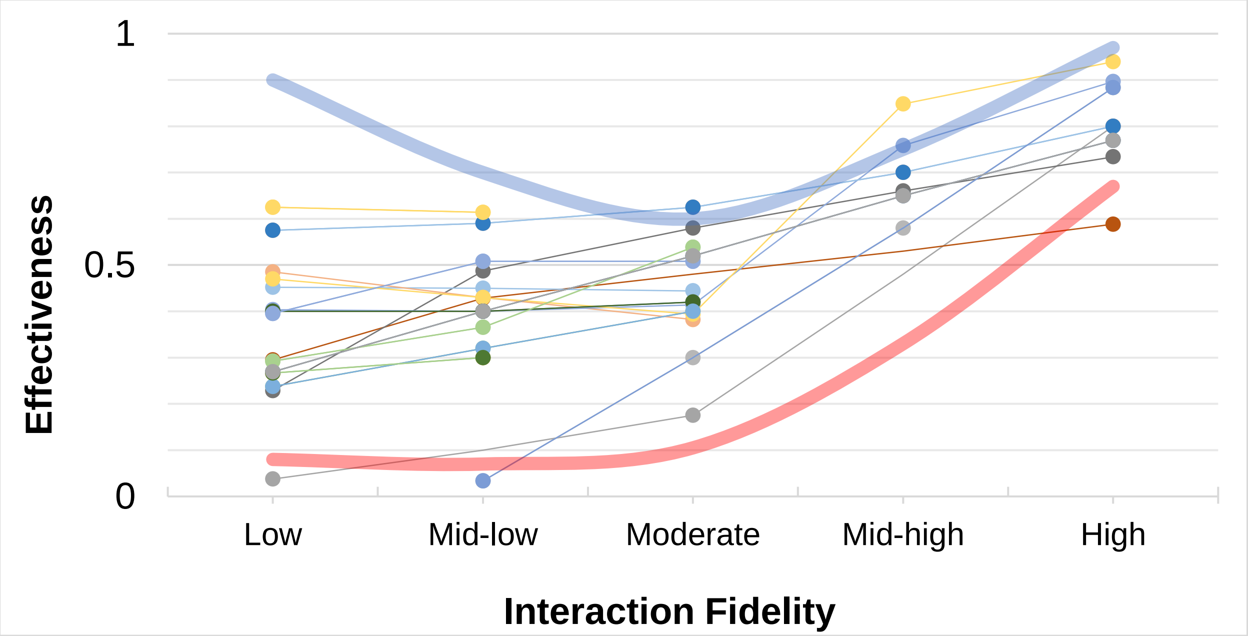


Figure 8.17 – Effectiveness increases by increasing the level of interaction fidelity for measures such as orientation estimation, cognitive load, tactile sensation, overall involvement and presence.

In general, we observe that as the interaction fidelity increases, the user receives higher levels of proprioceptive cues and this positively affect measures and tasks that require proprioceptive cues, such as orientation estimation and spatial memory tasks. Additionally, the increasing level of proprioceptive sensory cues increase the sense of presence and involvement of the user in the VR experience. The more natural movements and sensations with moderate-fidelity interfaces, as compared to low-fidelity interfaces, create a higher level of effectiveness for tasks and measures based on movements and sensations.

8.5.2 U-shape Change of Effectiveness with Increasing Level of Interaction Fidelity

On the other hand, some other measures can form a U-shape uncanny valley by increasing the level of fidelity (Figure 8.18), such as:

- Performance measures
    - Completion time
    - Response time
    - Movement and maneuvering accuracy
    - Progress through course
    - Movement speed
    - Balance control
    - Cognitive load: verbal memory task
    - Distance estimation
- Subjective user experience measures
    - Ease of use
    - Most liked interface
    - Subjective accuracy
    - Subjective evaluation

Low-fidelity techniques are very dissimilar to real walking and the user needs to learn a new technique. However, well-designed low-fidelity techniques are easy to learn and easy to use and users can easily understand them and use them. Moderate fidelity techniques on the other hand introduce themselves as natural techniques and the user tries to use her natural skills. However, since such techniques employ different forces, movements or transfer functions compared to real world actions, the user will have difficulty employing her natural skills with these techniques and struggle to learn the new way of walking with these interfaces, and therefore she might have lower level of effectiveness.

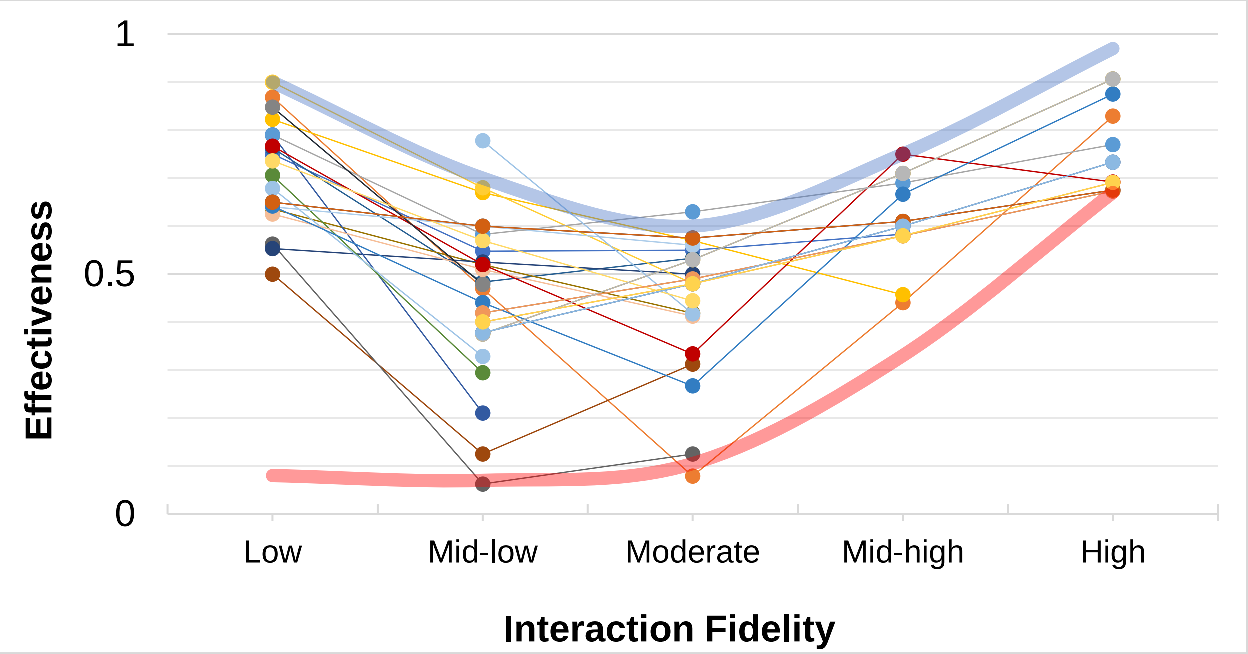


Figure 8.18 – Effectiveness forms a U-shape uncanny valley, by increasing the level of interaction fidelity for measures such as completion time, accuracy, distance estimation, movement speed, balance control, ease of use, subjective accuracy and subjective evaluation.

When the user struggles to understand her walking using the moderate-fidelity techniques, her completion time, accuracy, walking speed, progress through course, and movement speed are affected negatively using such techniques. On the other hand, well-designed low-fidelity interfaces are easy to understand, easy to learn and easy to use. This will allow the user to effectively employ such interfaces and have a high level of effectiveness for such measures and tasks.

The response time depends on the design of the technique and the control system used in the technique. Well-designed low-fidelity interfaces often use a simple and responsive control system, which provides the user with the ability to quickly interact and perform different actions such as start and stop and have a good response time (e.g., mouse and keyboard, gamepad). On the other hand, moderate fidelity interfaces often employ a more complicated control system which takes some time to start detecting gestures or feet movements. This will cause the moderate-fidelity interfaces not to be responsive and the user's response time will suffer (e.g., Virtusphere, Omni Directional Treadmill, Walking-in-place).

Cognitive load for verbal memory tasks, unlike the spatial memory task presented in Section 8.5.1, does not require proprioceptive cues. The easy-to-use nature of well-designed low-fidelity interfaces imposes less cognitive load on the user, and the user can more easily remember objects and perform memory tasks. Moderate fidelity interfaces are often not as easy to use and require the user to focus on her walking and interaction with these devices, and think about and learn the new way of walking. Consequently, user will have fewer free cognitive resources to focus on the memory tasks and will have lower effectiveness for such tasks.

The proprioceptive cues provide useful information for distance estimation. However, well-designed low-fidelity interfaces are easy to learn and use, and the user can focus more on the visual sensory cues from the environment for the distance estimation and achieve higher effectiveness. When well-designed low-fidelity interfaces employ good HCI design principles, the user can easily use them and will have a good experience with such interfaces and therefore, they will be highly effective in terms of ease of use, subjective accuracy, and subjective evaluation.

8.5.3 Perceived Naturalness

Some subjective measures are sensitive in terms of how the user might or can interpret them, or what might influence the user's answers. Naturalness is one such measure. Other measures, such as familiarity or ease of use, can influence the user's subjective opinion about the naturalness of the interface. We believe that that is the reason we see different patterns for the perceived naturalness in our meta-analysis (Figure 8.19).

We have results from three articles for comparing various levels of interaction fidelity in terms of perceived naturalness (Figure 8.19). The green line shows the results from (Interrante, Ries et al. 2007), for comparing gamepad (low-fidelity), constant 10x gain (moderate-fidelity), Seven League Boots (mid-high- fidelity) and real walking (high-fidelity). In these results, the moderate-fidelity interface maps each user step to a distance, 10 times larger. This greatly disturbs the user's distance judgment and movement speed and therefore causes a sense of unnatural locomotion for the user. The low-fidelity interface is easy to use, understandable, and familiar to the user, and that might be the reason they perceived this interface as more natural. The blue line in Figure 8.19 shows the results from (Marsh and Kluss 2015), which compares the torso-directed Virtusphere (mid-low-fidelity) with the normal Virtusphere (moderate-fidelity). The torso-directed Virtusphere allows the user to move in the direction her torso indicates, rather than the Virtusphere's movement direction. This provides a better experience and better distance estimation, and the user understands and employs it more easily. Therefore, it is perceived as being more natural.

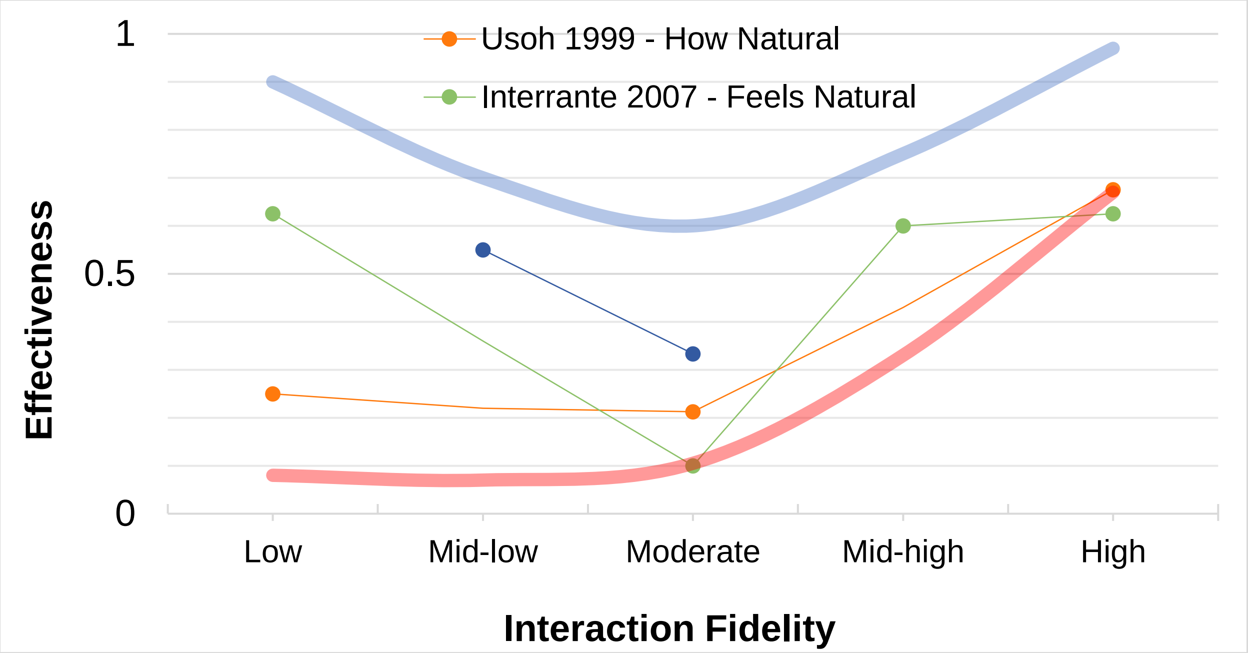


Figure 8.19 – Results from three articles for comparing various levels of interaction fidelity in terms of perceived naturalness (Interrante, Ries et al. 2007).

The results from Usoh et al. (Usoh, Arthur et al. 1999) are indicated by the orange line in Figure 8.19. The low-fidelity interface uses flying for travel. Compared to the moderate-fidelity interface of walking in place, it is less natural to fly for locomotion. On the other hand, the walking-in-place technique is more difficult to use than flying, and therefore the user may perceive these techniques as having similar naturalness.

8.6 Conclusion

We performed a meta-analysis of research results from the literature to further investigate the relationship between the level of interaction fidelity and effectiveness. We analyzed the results from articles which compared two or more locomotion interfaces with different levels of interaction fidelity. We observed that for most of the tasks and measures, the locomotion interface evaluations follow our hypothesis. For simulator sickness and for some subjective user experience measures (such as overall impression, would you buy it, how frequently would you use it), the graphs are more flat and high interaction fidelity does not lead to higher effectiveness. We believe that these measures are more dependent on other system features rather than the level of interaction fidelity.

We further characterized the measures and tasks that fit our hypothesis into two groups. The first group exhibits an increasing level of effectiveness with increasing levels of interaction fidelity. These measures include performance measures, such as orientation estimation, cognitive load (spatial memory task), head trajectory (natural head movement during locomotion), and tactile sensation, as well as subjective user experience measures, such as presence (questionnaire scores) and overall Involvement. These measures partly depend on proprioceptive cues from the interaction techniques, and by increasing the level of interaction fidelity, the user receives higher level of proprioceptive sensory information. Thus, the effectiveness will increase.

In the second group, the graphs form a U-shape uncanny valley with low levels of effectiveness for the moderate-fidelity interfaces. Such measures include performance measures, such as completion time, response time, movement and maneuvering accuracy, progress through course, movement speed, balance control, cognitive load (verbal memory task), and distance estimation, as well as subjective user experience measures, such as ease of use, most-liked interface, subjective accuracy, and subjective evaluation. These measures are more dependent on the ease of learning and ease of use of the interface, and therefore well-designed low-fidelity interfaces can outperform their moderate-fidelity counterparts. The results regarding perceived naturalness seem to include both these features and require further investigation in the future for a deeper understanding of this measure.

9 A Taxonomy for Walking-Based Travel Techniques

To address RQ5 about developing a design space for classification of locomotion techniques, we developed a taxonomy to extract various characteristics of walking-based locomotion. As an example to show how to employ this taxonomy, we chose various options from these characteristics, to design a novel locomotion interface.

Walking-based travel techniques include phases similar to the human walking gait cycle. Walking-based locomotion can increase immersion, reduce simulator sickness and provide a better user experience (Steinicke, Visell et al. 2013). Therefore, it is important to better understand the characteristics of walking-based locomotion techniques and learn how to design for such techniques. Due to their importance and lack of prior systematic classification, we aimed to develop a taxonomy of walking-based locomotion techniques for VR. We exclude lower fidelity, non-natural travel techniques, since these have been studied extensively (Bowman, Koller et al. 1997, Bowman, Koller et al. 1998, Arns 2002, Bowman, Kruijff et al. 2004, Steinicke, Visell et al. 2013). In addition, we exclude natural techniques based on other sorts of real-world travel metaphors, such as driving a vehicle, cycling, or swimming, because these techniques have very different properties than walking-based techniques.

In the taxonomy presented here and shown in Figure 9.1, we break walking-based locomotion techniques into finer-grained components. These components¬—movement range, walking surface, transfer function, properties sensed—represent distinct design decisions for walking-based locomotion techniques, although not all of the decisions are completely independent.

9.1 Motivation

Natural locomotion in virtual reality (VR) increases immersion, lessens simulator sickness, and improves user experience (Steinicke, Visell et al. 2013). Thus, in recent years, natural walking-based locomotion has been a popular topic among VR researchers.

Unlimited walking-based locomotion in VR has been addressed by developing various devices such as omni-directional treadmills (ODT) (Darken, Cockayne et al. 1997), robotic tiles(Iwata, Yano et al. 2005), stepping systems (Hollerbach, Xu et al. 2000), sliding-based surfaces (Iwata and Fuji 1996, Goetgeluk 2013) and human-sized hamster balls (Nabiyouni, Saktheeswaran et al. 2015). Such devices employ stationary or moving surfaces to keep the user in a limited physical space while allowing infinite walking in VR. Other techniques, such as walking-in-place (WIP) (Nilsson, Serafin et al. 2013), redirected walking (RDW) (Razzaque, Kohn et al. 2001, Suma, Bruder et al. 2012) and seven-league boots (Interrante, Ries et al. 2007), also enable the user to explore a large or (in some cases) unlimited virtual environment (VE). These techniques are based on normal human walking on the ground, without a device, and are meant to allow users to explore a VE larger than the physical environment.

Unfortunately, these walking-based locomotion techniques suffer from a lack of generality (not applicable to all VEs or physical setups), a degraded user experience, or both, compared to real-world walking (Nabiyouni, Saktheeswaran et al. 2015) and require further improvements (Nabiyouni, Scerbo et al. 2015). The ideal walking-based locomotion technique for VR has not yet been designed. To improve such interfaces, researchers require an in-depth understanding of the design components of these techniques. A taxonomy can enable us to design new techniques and improving existing ones by providing a means to analyze characteristics of these interfaces.

In this chapter, we present a taxonomy that extracts components of walking-based locomotion techniques and presents choices for each component. Together, the components define the specifications of a technique. This taxonomy can be used either to define novel locomotion techniques by composing various choices of components, or to analyze and improve existing ones. Locomotion interfaces with higher effectiveness can improve navigation though VEs for applications such as immersive analytics, entertainment and therapy. Improvements on navigating method, can contribute to data visualization and analysis technologies. An effective and natural navigation method, can increase immersion and reduce cognitive load for travel through the visual data.

This organization is not purely a scholarly pursuit. It will be useful to enable designers to analyze flaws and weaknesses in current designs, to evaluate ideas that haven't been tried yet, and to design experiments that allow comparisons of fundamental components of techniques, as opposed to simply comparing the whole techniques against one another.

9.2 Previous Taxonomies

Studying and analyzing human travel and motion control is beneficial for designing more effective travel techniques in VR by improving performance and user experience (Warren and Wertheim 2014). We distinguish travel from walking-based locomotion. As defined by Bowman et al. (Bowman, Koller et al. 1998), travel can be considered as the task of setting the position and orientation of one's viewpoint in the 3D space. We define walking-based locomotion as the task of traveling through VEs by performing actions similar to human walking. While general travel techniques include metaphors based on flying or driving a vehicle, or mappings using a handheld controller, walking-based locomotion will be based only on the human gait cycle.

Bowman et al. (Bowman, Koller et al. 1997) presented a categorization of travel techniques based on three components: direction/target selection, velocity/acceleration selection, and input condition. They further improved this framework (Bowman, Koller et al. 1998) by adding task, environment, user and system characteristics into their methodology to allow analysis of technique components alongside other variables that might affect the user experience.

Another taxonomy categorized travel techniques by dividing them into subtasks: start to move, indicate position, indicate orientation and stop moving (Bowman, Kruijff et al. 2004). This viewpoint can provide additional information about techniques such as ODT (Darken, Cockayne et al. 1997), WIP (Nilsson, Serafin et al. 2013) or Virtusphere (Latypov 2006) in which the user experience of starting, continuing, and stopping walking might be different.

Arns (Arns 2002) presented a revised taxonomy based on (Bowman, Koller et al. 1998), suggesting that the choices of interaction and display devices can often be controlled by the VE designer and are essential to the travel technique. Arns considered rotation and translation separately, and further divided techniques into physical and virtual subcategories.

These existing taxonomies attempt to provide a classification of all VR travel techniques. Thus, such taxonomies are broad and general by design and are not always able to capture the subtle differences between similar techniques. In particular, many walking-based techniques would be classified together in these taxonomies, but our prior work and experience has shown us that subtle differences in the design of such techniques can greatly impact the user experience (References removed for blind review).

Suma et al. (Suma, Bruder et al. 2012) described a taxonomy specifically for techniques based on redirected walking. They considered reposition and reorientation as two main subtasks which can be continuous or discrete. They also included two subcategories of subtle and overt manipulation. Although this taxonomy is useful for RDW researchers, it does not address other walking-based techniques.

Riecke et al. (Riecke and Schulte-Pelkum 2013) and Ruddle (Ruddle 2013) developed frameworks that attempted to organize and explain prior findings. Riecke's framework (Riecke and Schulte-Pelkum 2013) explains how different factors related to VE travel affect the user's perception of walking for a specific application. Ruddle (Ruddle 2013, Steinicke, Visell et al. 2013) reviewed prior comparisons of travel techniques, and summarized how technique factors affect navigation performance, distance estimation, and direction estimation. These frameworks differ from our taxonomy in that they attempt to extract important features of techniques in order to make sense of prior observations, while we aim to classify techniques based on their fundamental features in order to provide a design space.

9.3 Taxonomy of Walking-Based Locomotion Techniques

Walking-based locomotion techniques include phases similar to the human walking gait cycle. Walking-based locomotion can increase immersion, reduce simulator sickness and provide a better user experience (Steinicke, Visell et al.). Therefore, it is important to better understand the characteristics of walking-based locomotion techniques and learn how to design for such techniques. Due to their importance and lack of prior systematic classification, we aimed to develop a taxonomy of walking-based locomotion techniques for VR. We exclude lower fidelity, non-natural travel techniques, since these have been studied extensively (Steinicke, Visell et al.) (Bowman, Koller et al. , Bowman, Koller et al.) (Arns , Bowman, Kruijff et al.). In addition, we exclude natural techniques based on other sorts of real-world travel metaphors, such as driving a vehicle, cycling, or swimming, because these techniques have different properties than walking-based techniques.

In the taxonomy presented here and shown in Figure 1, we break walking-based locomotion techniques into finer-grained components. These components¬—movement range, walking surface, transfer function, properties sensed—represent distinct design decisions for walking-based locomotion techniques, although not all of the decisions are completely independent.

9.3.1 Movement Range

Natural walking techniques differ in movement range, which determines the amount of physical space necessary to implement the technique. For example, a WIP (Nilsson, Serafin et al.) technique can be used with any amount of space, since the user remains in one location, while RDW (Razzaque, Kohn et al. , Suma, Bruder et al.) requires a large, open tracked space. Techniques such as WIP (Nilsson, Serafin et al.) and VirtuixOmni (Goetgeluk) use a practically stationary center of mass, while users of techniques such as ODT (Darken, Cockayne et al. 1997) and robotic tiles (Iwata, Yano et al. 2005) have a small movement range (often less than 1m radius). RDW (Razzaque, Kohn et al. 2001), Real Walking (Nabiyouni, Saktheeswaran et al. 2015) and seven-league boots (Interrante, Ries et al. 2007) require a large movement range which is typically several meters in radius.

9.3.2 Walking Surface

The walking surface used by a locomotion technique can be flat or curved. A flat surface is more natural than a curved surface, and techniques requiring a large range of movement require a flat walking surface. Curved surfaces, on the other hand, can help to slide the user's feet back into the center (e.g., VirtuixOmni (Goetgeluk 2013)) or can be part of a rotating sphere (e.g., Virtusphere (Nabiyouni, Saktheeswaran et al. 2015)). Curved surfaces can change the forces used in walking (Nabiyouni, Saktheeswaran et al. 2015); they often disturb the user's balance and might

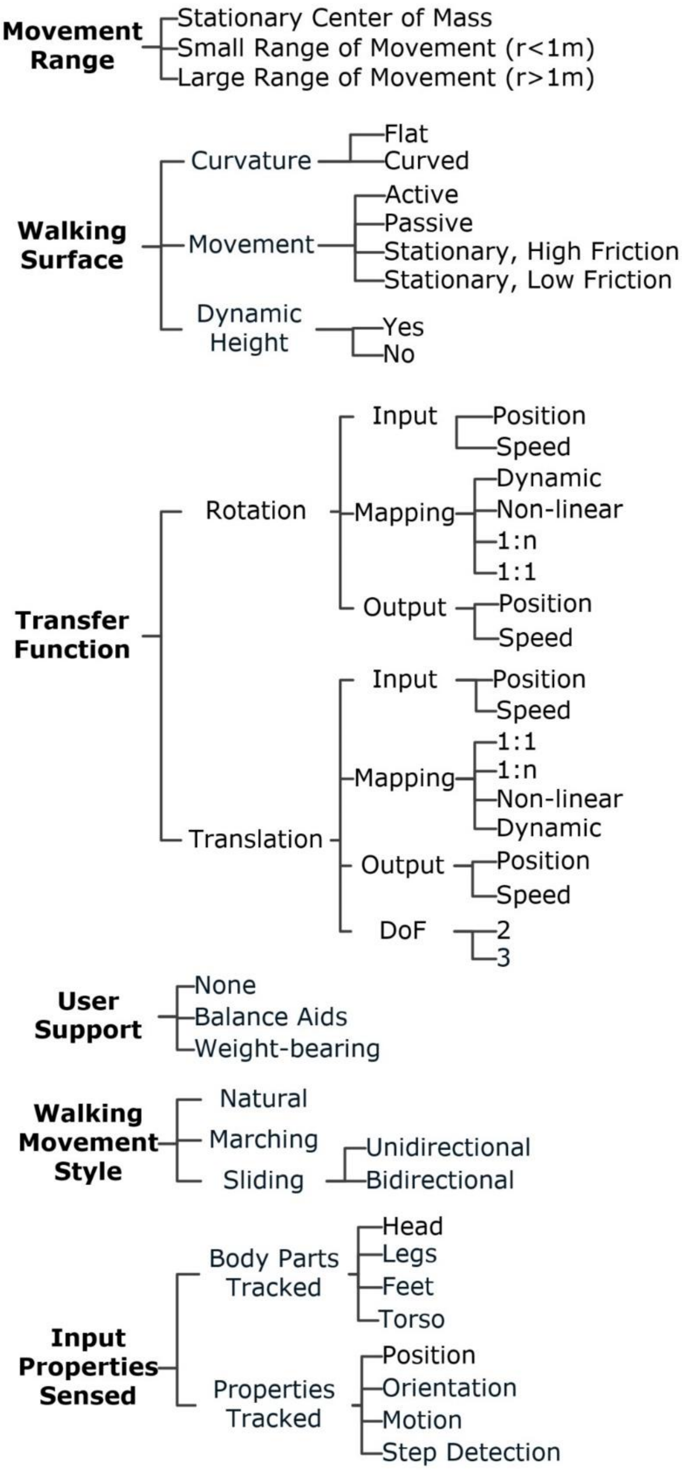


Figure 9.1: Components of the Walking-Based Travel Techniques Taxonomy.

require a stand or harness for balance assistance. A curved surface can only be used for techniques that also use a stationary center of mass or a small movement range.

In addition, walking surfaces can be either moving or stationary. Stationary surfaces can have high friction, such as in natural walking or RDW (Razzaque, Kohn et al. 2001), or low friction, as in sliding-in-place techniques (VirtuixOmni (Goetgeluk 2013) or virtual perambulator (Iwata and Fuji 1996)). Techniques with a large movement range can only employ stationary high-friction surfaces. A low-friction surface can be detrimental to the user's balance if the user does not use any type of weight support or harness. Some stationary low-friction interfaces, such as Virtuix Omni (Goetgeluk 2013) employ specialized shoes to reduce friction.

Moving surfaces are used by some techniques to keep the user in the center of the device. The movement may be active (e.g., ODT (Darken, Cockayne et al. 1997)) or passive (e.g., Virtusphere (Nabiyouni, Saktheeswaran et al. 2015)). Active moving surfaces are motorized and often require a complex control system to detect and predict the user's movement direction, in order to adjust the surface movement accordingly. On the other hand, passive moving surfaces use human force to start moving and often require the user to move some distance before the surface begins to move, which might cause the user to lose her balance (Nabiyouni, Saktheeswaran et al. 2015). Surfaces with passive or active movement require normal friction.

Finally, some walking surfaces can have dynamic height, giving them the potential to simulate uneven surfaces or terrain. Robotic tiles (Iwata, Yano et al. 2005) and stepping systems such as the Sarcos Treadport (Hollerbach, Xu et al. 2000) can offer dynamic height features.

9.3.3 Transfer Function

A locomotion technique's transfer function describes the mapping between its input and its output. Both translation and rotation control have transfer functions, which can potentially be different (e.g., seven-league boots (Interrante, Ries et al. 2007), RDW (Razzaque, Kohn et al. 2001)). The transfer function includes an input, an output and a mapping function.

Either position or speed can be the input to the mapping function. While most locomotion techniques employ position as the input for the transfer function and map it to the output position (e.g., real walking (Nabiyouni, Saktheeswaran et al. 2015)), some techniques, such as seven-league boots (Interrante, Ries et al. 2007), use the user's speed as an input parameter and map it to the output speed.

The most common mapping function is a direct 1:1 mapping of the input to the output, as in ODT (Darken, Cockayne et al. 1997) and real walking (Nabiyouni, Saktheeswaran et al. 2015), or a 1:n mapping that applies a constant scale factor to the input, as in WIP (Razzaque, Kohn et al. 2001). The mapping can also be non-linear and change the scale factor based on the input (e.g., seven-league boots (Interrante, Ries et al. 2007)). Finally, the mapping can be dynamic based on the requirements of the locomotion algorithms, as in RDW techniques (Razzaque, Kohn et al. 2001, Suma, Bruder et al. 2012).

A final aspect of the transfer function is the number of degrees of freedom of the virtual movement. Translation in most walking-based locomotion techniques (e.g., WIP (Razzaque, Kohn et al. 2001)) has 2

DoF. However, in some other techniques, such as real walking in buildings with physical stairs, the user can move in the up/down dimension as well.

9.3.4 User Support

Locomotion techniques can employ aids to compensate for part or all of the users' weight and help them improve their balance. For example, the handlebar in the Virtusphere (Latypov 2006) and virtual perambulator (Iwata and Fuji 1996), can improve user experience by providing a physical balance aid. Weight-bearing user support allows users to "sit" and walk, or walk in mid-air (as in (Templeman, Denbrook et al. 1999)). A technique with a large range of movement does not typically employ a user support method. Techniques like RDW (Razzaque, Kohn et al. 2001) and real walking fall into the no user support category.

9.3.5 Walking Movement Style

Normal walking movements include the whole stance and swing phases (Steinicke, Visell et al. 2013) in the gait cycle, but the gait cycle used in locomotion techniques does not always use a completely natural style. Marching movements involve feet moving in the vertical direction, almost perpendicular to the ground, with no foot movements parallel to the ground surface, such as in WIP (Razzaque, Kohn et al. 2001). In the Wizdish interface (Swapp, Williams et al. 2010), the user can slide her feet parallel to the ground and move them back and forth to simulate a walking action. We call this a bidirectional sliding movement. In interfaces such as the virtual perambulator (Iwata and Fuji 1996) or VirtuixOmni (Goetgeluk 2013), the sliding motion is only in the direction opposite to user movement, and the feet are lifted off the surface for the forward movement. Therefore, we call this unidirectional sliding. Note that in this style, the user's foot is not stationary on the walking surface during the stance phase; therefore, this movement style is different than natural walking.

9.3.6 Input Properties Sensed

Various walking-based locomotion techniques track different body parts, and different properties of the motion of those body parts. Techniques such as real walking (Nabiyouni, Saktheeswaran et al. 2015) or RDW (Razzaque, Kohn et al. 2001, Suma, Bruder et al. 2012) can track either the user's head or her feet. Techniques such as WIP (Razzaque, Kohn et al. 2001) often need to track the user's legs or feet to activate translation, and may employ the user's torso or head direction for rotation. Therefore, we considered head, legs, feet and torso as body parts that can be tracked.

In most walking-based locomotion techniques, position and orientation of the body part being tracked is needed. However, in the Wizdish technique (Swapp, Williams et al. 2010), the back and forth motion of the user's feet will be tracked. Finally, techniques such as WIP (Razzaque, Kohn et al. 2001) require the tracking of complete steps taken by the user. This often results in a lag at the initiation or termination of the walking movement, since no virtual movement occurs until a complete step has been detected.

9.3.7 External Factors

Beyond the core components of walking-based locomotion techniques, designers have other choices to make that affect the user experience of the locomotion in a VE. Designers need to choose an appropriate type of display, according to the design requirements of their technique. For example, techniques with a large range of movement are more suited to head-mounted displays than surround-screen displays. Similarly, sensor technology can greatly affect the effectiveness of a technique, and designers need to consider an appropriate option. For example, tracking the user's feet with an optical tracking system might work well for WIP (Razzaque, Kohn et al. 2001), but might be more challenging with RDW (Razzaque, Kohn et al. 2001, Suma, Bruder et al. 2012), since more occlusion might occur.

Finally, designers need to consider the virtual environment. Depending on the application, it may be possible to design an environment that matches the desired locomotion technique. If the environment is determined by the application, designers need to select a technique that is well suited to that environment. Environment characteristics have been discussed in more detail in (Warren and Wertheim 2014).

9.4 How to Use This Taxonomy

Designers and researchers can employ our taxonomy to analyze the components of walking-based locomotion techniques for:

1. Classifying existing techniques to understand their similarities and differences.
2. Designing novel techniques by making and combining choices for each of the components, especially in areas of the design space that have not been well explored.
3. Designing experiments that vary particular components systematically and independently, to understand the effects of individual design choices on user experience.
4. Incorporating walking-based navigation into emerging applications of VR such as Immersive Analytics.

So far, we have presented a taxonomy of walking-based VR locomotion techniques with components representing design decisions that characterize such techniques. The taxonomy can be used as a design space for understanding and comparing existing techniques as well as designing new ones. We expect to use this taxonomy to explore new locomotion techniques that may overcome some of the limitations of existing approaches.

9.5 An Example to Employ the Taxonomy: Prototyping a Novel Locomotion Interface

We employed the locomotion taxonomy to design this interface. Using this taxonomy, we made choices among various characteristics of the locomotion interfaces and combined these choices to design the novel interface. These choices are shown in Figure 9.2.

In terms of walking surfaces, based on our experience, curved surfaces (such as used by the Wizdish or the Virtusphere) not only disturb the user's balance, but also disturb the natural feeling of walking on a flat surface. Therefore, we decided against it and chose a flat surface (Figure 9.2). Similarly, both active and passive moving surfaces change the ground forces and might interfere with the user's balance. We chose to keep the user stationary while performing locomotion to overcome the physical workspace limitation. Therefore, we chose a low-friction surface to decrease fatigue. To improve the user's balance and reduce fatigue, we decided to use a weight-bearing user support to compensate for part of the user's weight. This helps reducing friction as well.

In techniques such as Walking-In-Place (WIP), the user will not be using the same muscles as natural walking and this will cause fatigue as well as lower the level of naturalness. Our new interface was designed to engage the same muscles and forces used in natural walking. However, the amount of forces might be different. We hypothesize that an accurate imitation of walking forces will result in improved effectiveness over other locomotion interfaces with medium level of fidelity. We used a natural 1:1 transfer function for both translation and rotation. We chose a unidirectional sliding movement style to allow the user to slide in place and simulate the walking movements. We employ a touch surface to accurately detect the user's feet position and orientation and map the corresponding movements to the viewpoint control in the VE.

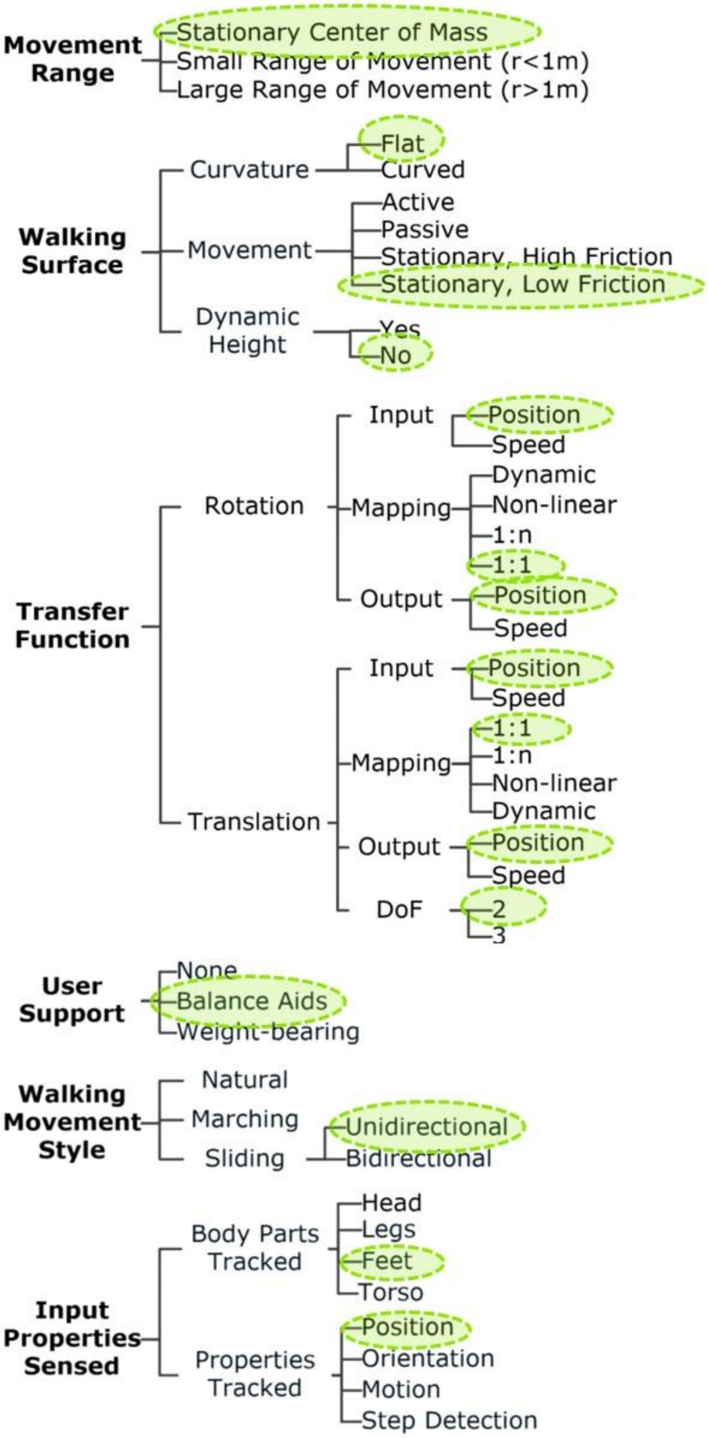


Figure 9.2: Choices made using the taxonomy to design a novel locomotion interface.

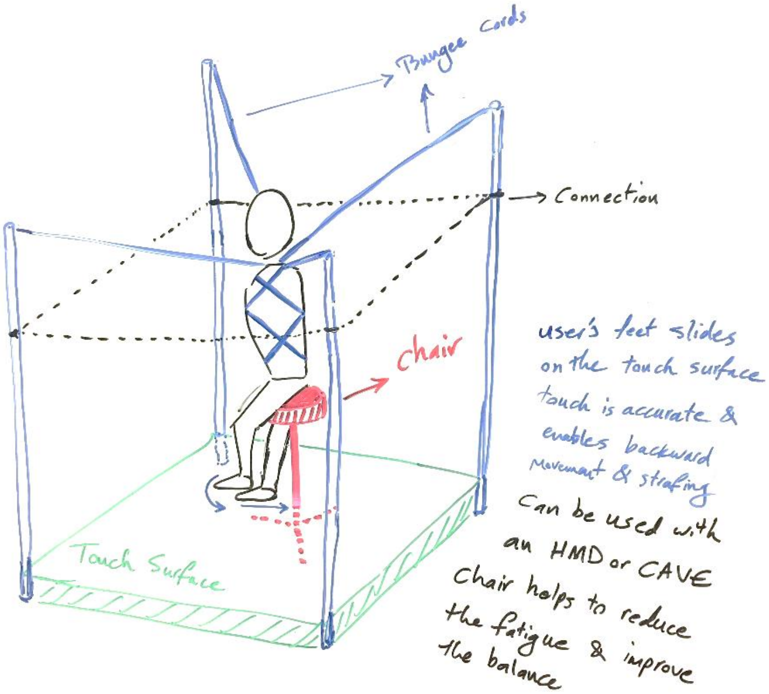


Figure 9.3: The initial idea for the novel locomotion interface prototype.

Our novel interface employs an adjustable and relatively tall stool and the stool has a narrow seat without a back rest. Therefore, the user's feet will be straight, similar to a standing position. This interface makes the user sit straight and not lean back, like in a chair. Therefore, the user will be using similar muscles than when walking. The stand will help compensate part of the user's weight. As the user is walking and sliding her feet, she will have less friction with the ground similar to walking in mid-air. However, the user's feet will have enough friction with the ground to engage the muscles normally used while naturally walking. The setup will require the user to apply backward forces to the ground as well as provide haptic feedback. Therefore, the user will have some proprioceptive cues similar to natural walking. We initially designed a set of bungee cords (Figure 9.3) to help the user keep her balance and compensate for her weight. Finally, we decided against this idea since it would be cumbersome to wear and could negatively affect the user

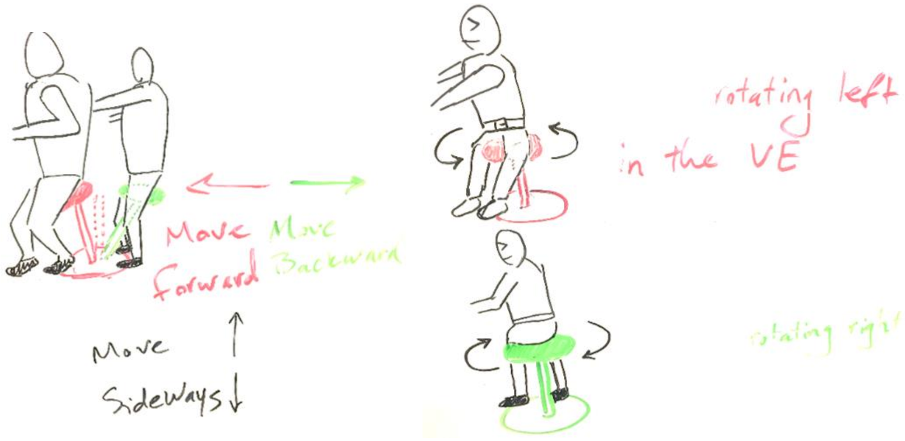


Figure 9.4: Sketches for the novel locomotion interface prototype.

experience. The final idea does not include bungee cords and just relies on the seat to bear the user's weight (Figure 9.4).

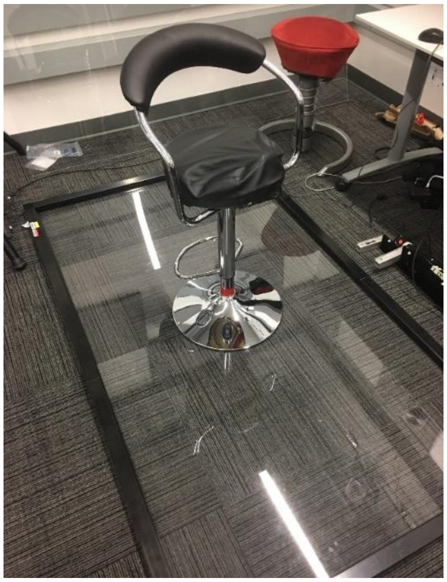


Figure 9.5: The initial version of physical prototype of the novel locomotion interface.

This interface employs a touch surface to detect the user's feet movements accurately (Figure 9.5). As the user walks and slides her feet on the surface, her feet movement is detected and employed for virtual movement in the VE. The stool-like base is able to rotate, therefore, to rotate in the VE, the user will be rotating physically. The stool-like base will have certain degrees of freedom to let the user's body move forward, backward and sideways (Figure 9.6). So, as the user starts walking in a certain direction for the first step or two her body will be moved in the same direction. Moreover, the user's head will be tracked, and even small head or body movements will be transferred into the VE. Therefore, the user will receive

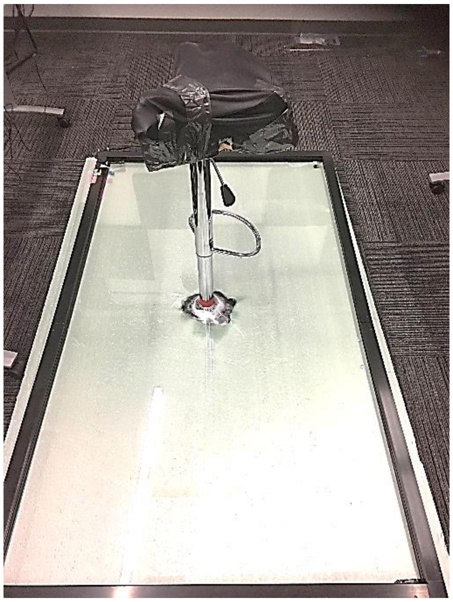


Figure 9.6: The final physical prototype of the novel locomotion interface.

vestibular cues similar to real world to improve the immersiveness of this interfaces. We have implemented this idea and a physical prototype is shown in Figure 9.7.

Figure 9.7: The final version of physical prototype of the novel locomotion interface working with an HMD display.

9.5.1 Biomechanical Analysis of the Idea

Our analysis of forces for the Virtusphere (Nabiyouni, Saktheeswaran et al. 2015) provided some insight for the reasons behind the shortcomings of the Virtusphere and helped us better understand semi-natural locomotion interaction and design effective training methods to improve performance (Nabiyouni, Scerbo et al. 2015). Similarly, an analysis of the forces in this novel interface might provide some insight about different ways to improve the effectiveness of this interface and lead to an effective design. As shown in Figure 9.8.A, during the push-off phase of real-walking, as the foot applies downward and backward forces, the ground applies the same amount of force in the opposite direction, causing the user to move

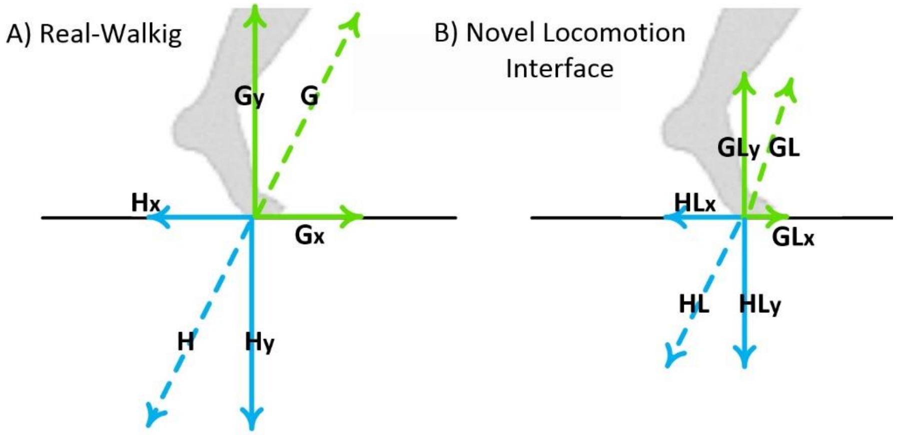


Figure 9.8 – Forces applied by the human foot (H, HL) during gait are shown in blue. Reaction force elements from the ground (G) and the Novel Locomotion interface (GL) are shown in green. A) Forces in real-walking. B) Forces when using the Novel Locomotion interface.

forward. However, walking on the low friction surface used in this interface will not result in the same reaction forces. Walking on this interface, as the user applies the backward force, the lack of friction will result in a smaller reaction force parallel to the ground. Therefore, the ground reaction force in the forward direction (GL_x) will be smaller than the user's force in the backward direction (HL_x), which will cause the user's foot move backwards (Figure9.8.B). On the other hand, since a part of the user's weight is supported by the stool that the user is sitting on, the upward reaction force (GL_y) will be smaller than that of real-walking (G_y).

9.6 Conclusion

We designed a taxonomy for walking-based locomotion interfaces. This taxonomy creates a design space and classification of locomotion techniques. This can help designers and researchers gain a deeper understanding of the differences between techniques and it provides a design space for new techniques to be prototyped. This goal-based and practical taxonomy allows designers to make choices among different characteristics of locomotion interfaces. This taxonomy covers various characteristics, such as movement range, walking surface, transfer function, user support, movement style, and input properties sensed. We employed this taxonomy to design a novel locomotion interface. This novel locomotion interface presents an example of how to use, and design with, this taxonomy.

10 Conclusions and Future Work

In this Chapter, we first present an overall summary of this dissertation, our research questions, and how we addressed them. Then, we discuss the contributions of this dissertation. Finally, we present ideas about how to continue this work.

10.1 Summary and Conclusions

In this work, we have presented our hypothesis about the effects of increasing levels of locomotion interaction fidelity on user experience. We posited that high-fidelity locomotion interfaces have a high level of effectiveness and can provide good user experience, due to the closeness to the corresponding real-world actions. Also, well-designed low-fidelity locomotion interfaces can provide good user experiences for most measures due to their easy-to-learn and easy-to-use nature. However, it is possible that low-fidelity interfaces sometimes result in low levels of effectiveness because of design weaknesses, depending on the task. On the other hand, moderate-fidelity locomotion interfaces often have inferior effectiveness and user experience compared to high- and low-fidelity techniques.

The main reason we identified is that such techniques introduce themselves as natural techniques and the users try to employ their real-world interaction skills to make use of these interfaces. However, the interfaces are not fully natural and the difference in their interaction fidelity with the high-fidelity techniques will cause the users to struggle while striving for natural interactions. This will cause the user to unlearn the natural interaction to a certain extent and to try and acclimate to the modified semi-natural actions. As we observed in our studies, and in the literature, this often can result in issues regarding balance control, walking accuracy and walking speed control, which will lead to an inferior user experience. We have utilized a total of thirteen different techniques in this space and evaluated them through four user studies. While we designed some of the techniques, for most of them we implemented an existing technique from the literature, such as real walking (Usoh, Arthur et al. 1999), Gamepad (Iwata 1999) or Seven League Boots (Interrante, Ries et al. 2007).

In our first study (presented in Chapter 4), we compared travel techniques based on an airplane metaphor and a camera-in-hand metaphor. We designed four techniques using the airplane metaphor, with different speed control methods: Bimanual multi-finger, unimanual multi-finger, bimanual gas pedal, and thumb speed control. We found that while the moderate-fidelity camera-in-hand technique could provide faster travel means for an absolute search task, it was significantly less accurate than all airplane metaphor techniques for a path following task. This study made us start thinking about the effects of different levels of interaction fidelity on effectiveness for travel techniques.

In order to compare locomotion techniques with varying level of interaction fidelity, we implemented three techniques with low, moderate, and high level of fidelity (presented in chapter 5). The low-fidelity version used a gamepad, which is completely dissimilar from real walking. The moderate-fidelity version used the Virtusphere device (Latypov 2006), which is similar to walking but the forces and movements are different to some degree. The high-fidelity technique was based on real walking, which mimics walking in the real world, closely. The task included walking on a specified line and reaching targets on the ground. We found that the moderate-fidelity technique was inferior to the high- and low-fidelity techniques for the measures of completion time, accuracy and subjective user experience. This user experiment provided evidence to support our hypothesis. Our third study (presented in Chapter 6) had two goals: understanding the effect of different components of fidelity and the effects of hyper-natural techniques. While the second study already gave us insight about the effects of interaction fidelity, fidelity consists of various components, and we need to know how different components of interaction fidelity affect user experience. In addition, the previous techniques were semi-natural and unnatural techniques respectively (see Chapter 1), and we need to learn more about the effects of hyper-natural (see Chapter 1) techniques. We designed a third user experiment, in which we studied the effects of biomechanical and transfer function components of interaction fidelity on user experience. We designed four techniques, including Seven League Boots (Interrante, Ries et al. 2007) (employing a hyper-natural transfer function), the jump boots technique (employing hyper-natural biomechanics), Seven Jump Boots (employing hyper-natural biomechanics and transfer function) and real walking (natural). To evaluate various aspects of locomotion, we developed a testbed that provides variability in tasks of path following, speed control, maximum speed, and spatial understanding.

The results from the third study showed that changing the biomechanics of walking will be detrimental to some user experience parameters. The users could not accurately walk on the specified line and had less user comfort. We found a hyper-natural transfer function to be beneficial for movement speed, allowing users to explore a larger area and have a better experience. However, changing the transfer function reduced the accuracy for more difficult path following tasks. Nonetheless, it did not affect simpler path following tasks. In addition, the combination of hyper-natural elements in both biomechanics and transfer function reduced overall effectiveness drastically and was detrimental to movement accuracy, speed control, and maximum speed, as well as most of the subjective user experience parameters.

In order to resolve the issue of improving user experience for moderate-fidelity locomotion interfaces, we designed the fourth study (presented in Chapter 7). Training has been shown to improve the effectiveness of moderate-fidelity interfaces (Marsh, Hantel et al. 2013). In this study, we designed a technique which employed a visual acclimation aid to improve the effectiveness of the acclimation phase. We used the Virtusphere as our moderate-fidelity device, and the visual cue we designed showed a virtual sphere rotating around the user as she walked in the Virtusphere. We had two groups: one trained with the visual cue and the other trained without the visual cue during the acclimation phase. During the assessment phase neither group received any visual cue. Our results showed that the group trained with the visual cue could walk more accurately and perceived less difficulty during the assessment phase. The visual cue helped the user better understand their walking and learn the differences of walking inside the Virtusphere and walking in the real world.

Our user studies (presented in Chapters 5, 6 and 7) support the fidelity-effectiveness hypothesis. However, we need to know if other studies in the literature also support this hypothesis, what measures support it, and what counter examples and outliers exist, as well as the reasons behind those. Therefore, we performed a thorough literature review to find research that compared two or more locomotion interfaces with varying levels of fidelity. The tasks and measurements in the various experiments are often very different. We normalized the results regarding the effectiveness of the locomotion techniques on a scale of zero to one, so that we could summarize and compare all the results on the same scale. Results from performance measures such as completion time, movement and maneuvering accuracy, movement speed, spatial understanding, cognitive load, balance control, and subjective user experience metrics such as perceived naturalness, ease of use, presence, and subjective accuracy fit with our hypothesis.

We also designed a taxonomy of walking-based locomotion techniques (presented in Chapter 9). A detailed taxonomy of walking-based locomotion techniques is beneficial to better understand, analyze, and design walking techniques for virtual reality. We present a taxonomy that can help designers and researchers investigate the fundamental components of locomotion techniques. Researchers can create novel locomotion techniques by making choices from the components of this taxonomy, analyze and improve existing techniques, or perform experiments to evaluate locomotion techniques in detail using the organization we present. In addition, as an example of how to employ this taxonomy, we used it to design a novel locomotion technique by making and combining choices for each of the components. This novel interface uses similar muscle groups to those being used during real walking and can accurately detect a user's feet movements and map them to walking motions in the VE.

10.2 Research Questions

We started out with five main research questions. The completed work in this dissertation correspondingly covered five areas. The first research question was concerned with how the effectiveness of locomotion techniques changes with varying levels of fidelity, and whether increasing interaction fidelity "guarantees" an increase in effectiveness? Chapters 4, 5 and 6 presented evidence to support our hypothesis for RQ1. RQ1 was further investigated by our meta-analysis presented in Chapter 8. We found that for measures that are dependent on proprioceptive sensory information, such as orientation estimation, cognitive load for spatial memory tasks, tactile sensation, natural head trajectory, and sense of presence, the level of effectiveness increases when increasing the level of interaction fidelity. Other measures, which depend more on the ease of learning and ease of use, such as completion time, response time, movement accuracy, balance control, cognitive load for verbal memory tasks, subjective accuracy, and subjective evaluation, form a U-shape uncanny valley. For such measures moderate-fidelity interfaces are often outperformed by low- and high-fidelity interfaces.

The second research question was concerned about how various components of interaction fidelity impact the effectiveness of interaction techniques. The third research question intended to investigate the effect of hyper-naturalism on the effectiveness of locomotion techniques. To address RQ2 and RQ3, in Chapter 6, we studied the influence of biomechanical and transfer function symmetry and the effect of hyper-natural locomotion on user performance. We learned that effective biomechanics are sensitive to changes and that the effects of changing the biomechanics of walking were mostly undesirable in hyper-natural techniques. Changes in the transfer function component were easier for the user to learn and to adopt to. Transfer function choices could improve some locomotion aspects but they were detrimental to accuracy to some degree.

The fourth research question was about improving the level of effectiveness in moderate-fidelity locomotion interfaces. To cover RQ4, we employed an effective training method to improve the effectiveness of a semi-natural locomotion interface. We observed that training can improve the level of effectiveness. We learned that providing a visual cue during the acclimation phase can help users better understand their walking in moderate-fidelity interfaces and improve their effectiveness.

The fifth research question was about developing a meaningful design space and a classification of locomotion techniques to aid a deeper understanding of the differences between different techniques and to provide a design space for new techniques to be tried. To address RQ5, we developed a taxonomy for walking-based locomotion techniques. Using this taxonomy, we extracted and discussed various characteristics of locomotion interaction. As an example of the use of this taxonomy, we employed it for designing a novel locomotion interface.

10.3 Contributions

Our main contributions can be summarized as follows:

- A better understanding of the fidelity-effectiveness relationship
    - Presented evidence for the fidelity-effectiveness hypothesis
- A deeper understanding of the effects of hyper-natural techniques
- A deeper understanding of the effects of components of interaction fidelity
    - Biomechanical symmetry
    - Transfer function symmetry
- Investigated benefits of using a visual cue for training
    - Demonstrated how to improve effectiveness
- A meta-analysis of the effects of interaction fidelity on user experience
- A detailed taxonomy for walking-based travel techniques

We believe that our fidelity-effectiveness hypothesis should be considered when designing novel locomotion techniques or using existing ones. Through our four user studies in addition to our meta-analysis, we have shown that moderate-fidelity locomotion interfaces often lead to inferior user experience compared to high- and low-fidelity interfaces, and that the effectiveness of these interfaces can be improved by more effective training. This hypothesis can help predict the results of using different levels of interaction fidelity before going through the high-cost process of designing, implementing, and evaluating techniques.

10.4 Future work

There are many directions that could be taken in future studies on the effects of fidelity. For example, our hypothesis can be studied for tasks other than locomotion. The same arguments may hold true for tasks other than locomotion. Moreover, in the future, we can extend this research to further study the concrete shape of the interaction fidelity-performance curve and find more evidence from novel interaction techniques. More interaction techniques can be studied to address the question of how much fidelity is needed to achieve performance similar to the real world.

While we learned about the effects of manipulating the biomechanical and transfer function components of interaction fidelity in this dissertation, other components, such as latency, still need to be studied.

Additionally, our results can be compared to those obtained by semi-natural locomotion techniques (e.g., Virtuix Omni), using the same testbed and metrics. One can further extend this direction and study the potential of design approaches not based on real-world actions (non-natural and super- natural) to produce effective locomotion techniques.

Another way to continue this work would be to further investigate how to improve the level of effectiveness of moderate-fidelity VR techniques. For example, with the Virtusphere, one could decrease its mass, lower the static friction, provide a more appropriate level of dynamic friction (perhaps with mechanical assistance), and train users on simple strategies to walk more proficiently in the device. In addition, other types of sensory cues (e.g., audio or haptic cues) can be studied for improving acclimation. Some of our studies, such as the work presented in Chapter 7, were specific to the Virtusphere device. One can also extend this work and study effectiveness of acclimation aids for other locomotion devices.

The taxonomy we developed here can be used as a design space for understanding and comparing existing techniques, as well as for designing new ones. Researchers can use this taxonomy to explore new locomotion techniques that may overcome some of the limitations of existing approaches.

Finally, the novel locomotion technique we developed can be evaluated by a user experiment. The overall goal of the experiment would be to improve the performance of interfaces with a moderate level of interaction fidelity. Such an evaluation could help determine the characteristics of semi-natural techniques which have the strongest effects on user performance. Similar to our first experiment (Nabiyouni, Saktheeswaran et al. 2015), this interface could be compared to interfaces with high and low levels of interaction fidelity. There would be three independent variables for such a controlled environment: technique (real-walking, novel locomotion interface, gamepad), task (path following, maximum speed, speed control, orientation estimation, distance and orientation estimation, and cognitive workload) and task difficulty for some tasks (path following, speed control, and cognitive workload). Studying and analyzing this and other novel interfaces may lead to several new insights, including:

- Providing additional evidence for the fidelity/performance hypothesis.
- Better understanding how novel locomotion techniques can improve existing interfaces (e.g., the Virtusphere).
- Helping researchers and users of the novel locomotion interfaces better understand how the interfaces work, how they can be used and what to expect from them.

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11 Appendix I: Abbreviations

HCI: Human-Computer Interaction

VR: Virtual Reality

AR: Augmented Reality

MR: Mixed Reality

VE: Virtual Environment

3DUI: 3D User Interfaces

UI: User Interface

FOV: Field of View

FOR: Field of Regard

WIP: Walking-in-Place

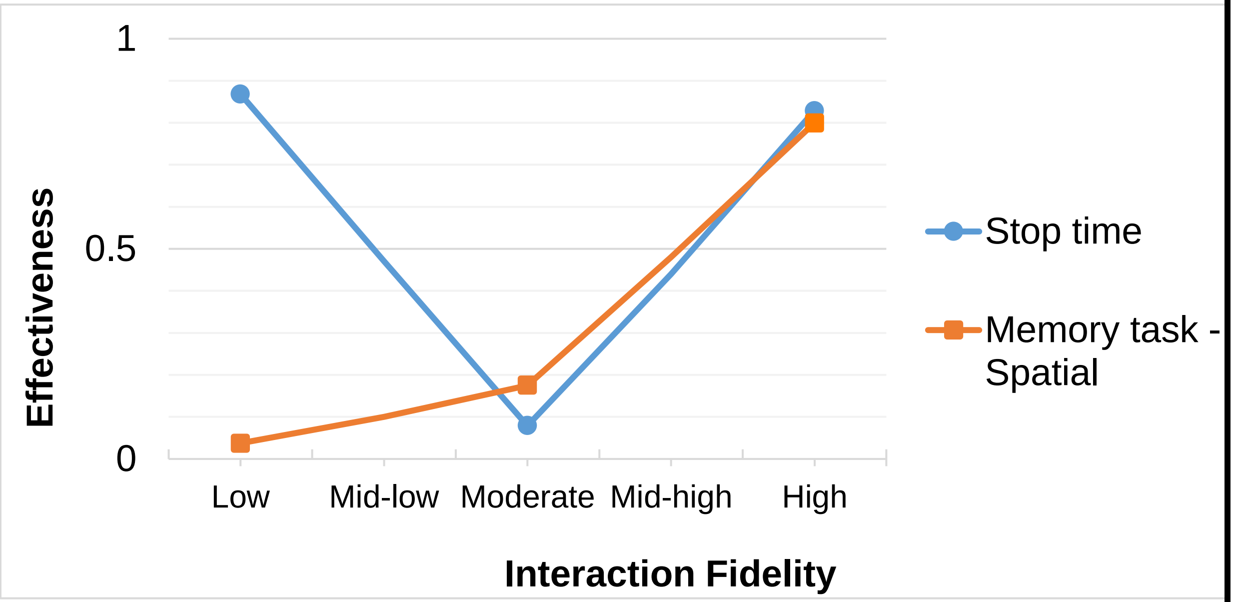
RDW: Redirected Walking

WIM: World-in-Miniature

12 Appendix II: Meta-Analysis papers

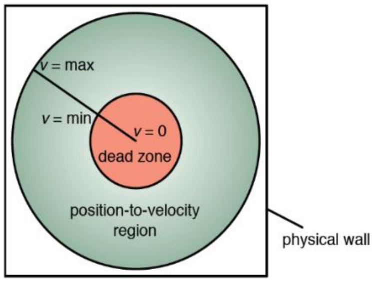
12.1 Marsh, Putnam et al. 2012

Graph



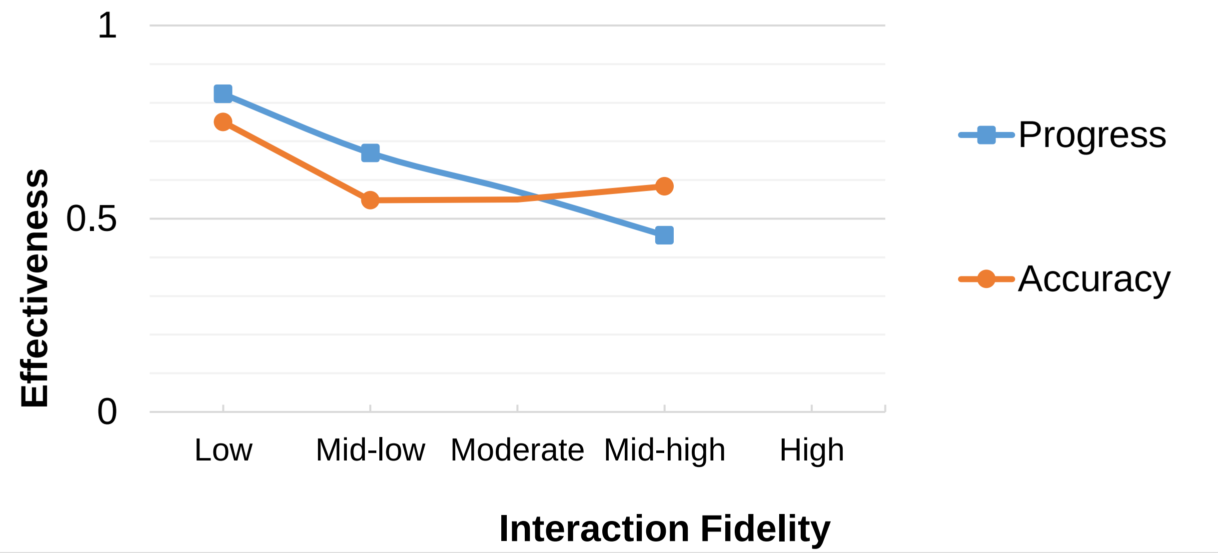
FIFA framework analysis of interaction fidelity

	Joystick	Human Joystick	Real Walking Technique
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to step on curved surface	Move thighs, legs, and feet to translat entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces	Large vertical and shear ground force
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-speed	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Walk back to the neutral zone	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Tracking system	Tracking system
Input Precision	Standard Joystick	Tracking system	Tracking system
Latency	Joystick handle	Tracking system	Tracking system
Form Factor	Keep Jostick in hands	N/A	Wearing a headset, not able to see your feet

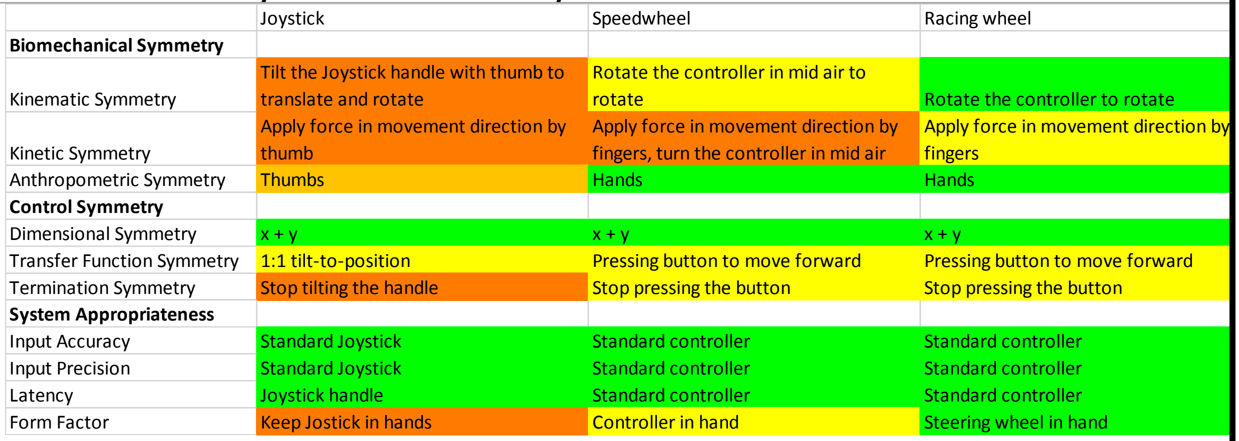
Interfaces	Gamepad	P2V (Human joystick)	Real Walking	**Image**
Measures	Memory task: Memory items missed during memory task Stop time: Time taken by the user to stop navigation			

12.2 McEwan, Blackler et al. 2014

Graph



FIFA framework analysis of interaction fidelity

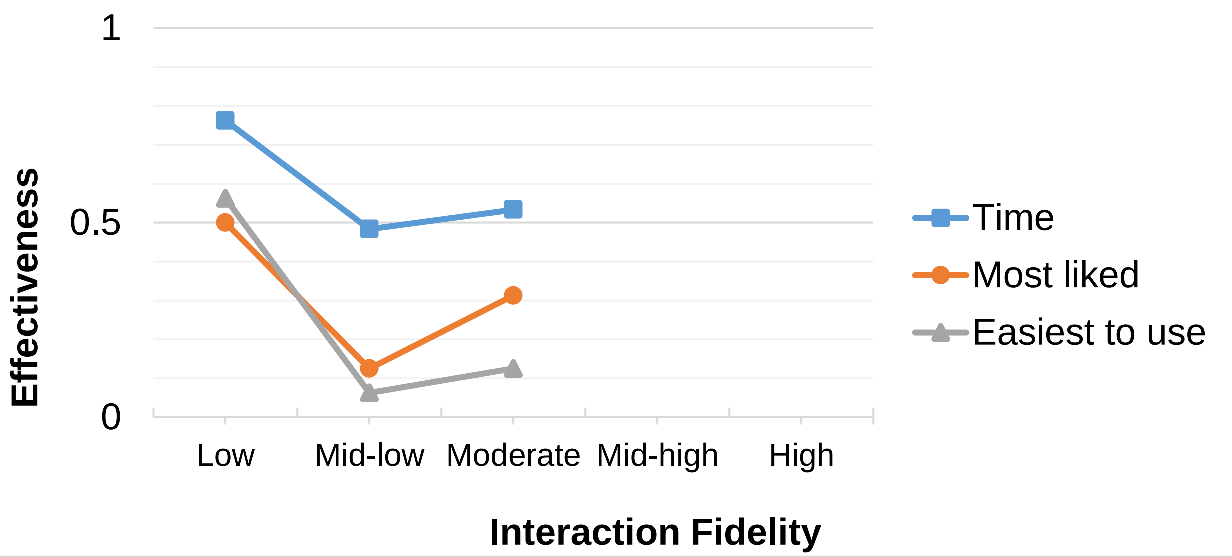


	Joystick	Speedwheel	Racing wheel
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Rotate the controller in mid air to rotate	Rotate the controller to rotate
Kinetic Symmetry	Apply force in movement direction by thumb	Apply force in movement direction by fingers, turn the controller in mid air	Apply force in movement direction by fingers
Anthropometric Symmetry	Thumbs	Hands	Hands
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	Pressing button to move forward	Pressing button to move forward
Termination Symmetry	Stop tilting the handle	Stop pressing the button	Stop pressing the button
System Appropriateness			
Input Accuracy	Standard Joystick	Standard controller	Standard controller
Input Precision	Standard Joystick	Standard controller	Standard controller
Latency	Joystick handle	Standard controller	Standard controller
Form Factor	Keep Jostick in hands	Controller in hand	Steering wheel in hand

Interfaces	Controller	Speed Wheel	Racing Wheel	**Image**
Measures	Progress through racing game: progress in a racing game before the time runs out		Accuracy: Times user hit the sides or flipped the car	

12.3 McMahan, Alon et al. 2010

Graph



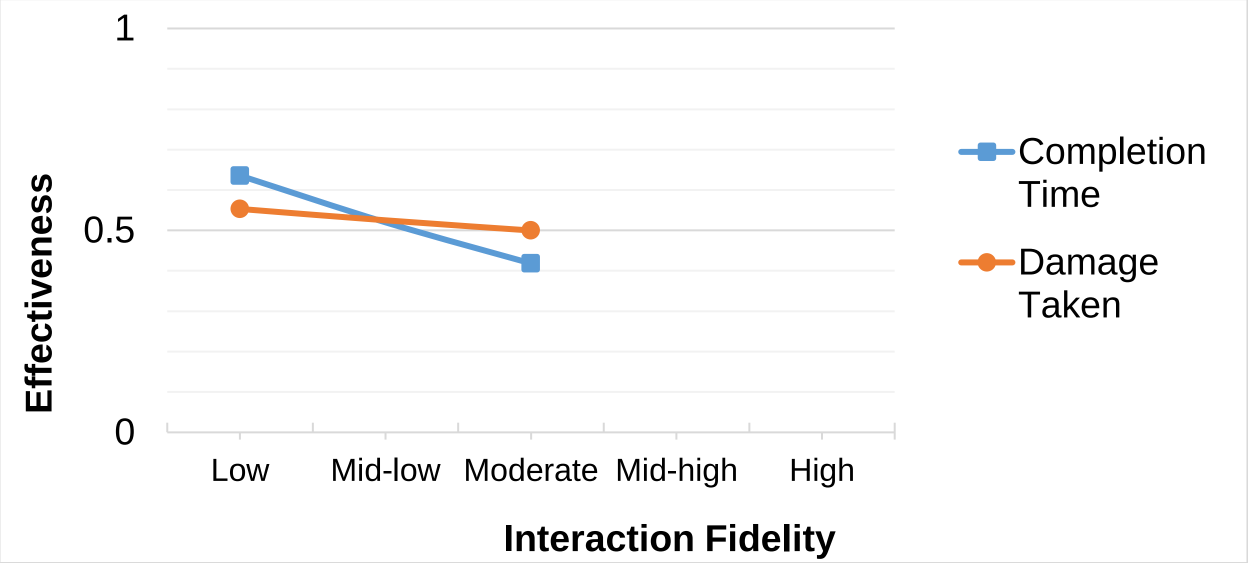
FIFA framework analysis of interaction fidelity

	Mouse and keyboard	Wii remote	Wii wheel
Biomechanical Symmetry			
Kinematic Symmetry	Press buttons and handle mouse to translate and rotate	Rotate the controller in mid air to rotate	Rotate the controller in mid air to rotate
Kinetic Symmetry	Apply force to button in movement direction by finger	Apply force in movement direction by fingers, turn the controller in mid air	Apply force in movement direction by fingers, turn the controller in mid air
Anthropometric Symmetry	Finger	Hands	Hands
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 button press-to-position	Pressing button to move forward	Pressing button to move forward
Termination Symmetry	Stop pressing the button	Stop pressing the button	Stop pressing the button
System Appropriateness			
Input Accuracy	Standard mouse and keyboard	Standard controller	Standard controller
Input Precision	Standard mouse and keyboard	Standard controller	Standard controller
Latency	Standard mouse and keyboard	Standard controller	Standard controller
Form Factor	Keep mouse and keyboard in hand	Controller in hand	Steering wheel in hand

Interfaces	Gamepad	Wii Remote	Wii Wheel	**Image**
Measures	Time: Completion time for the game	Most liked	Easiest to use	

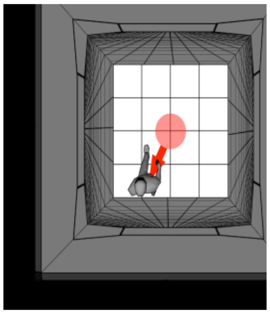
12.4 McMahan, Bowman et al. 2012

Graph



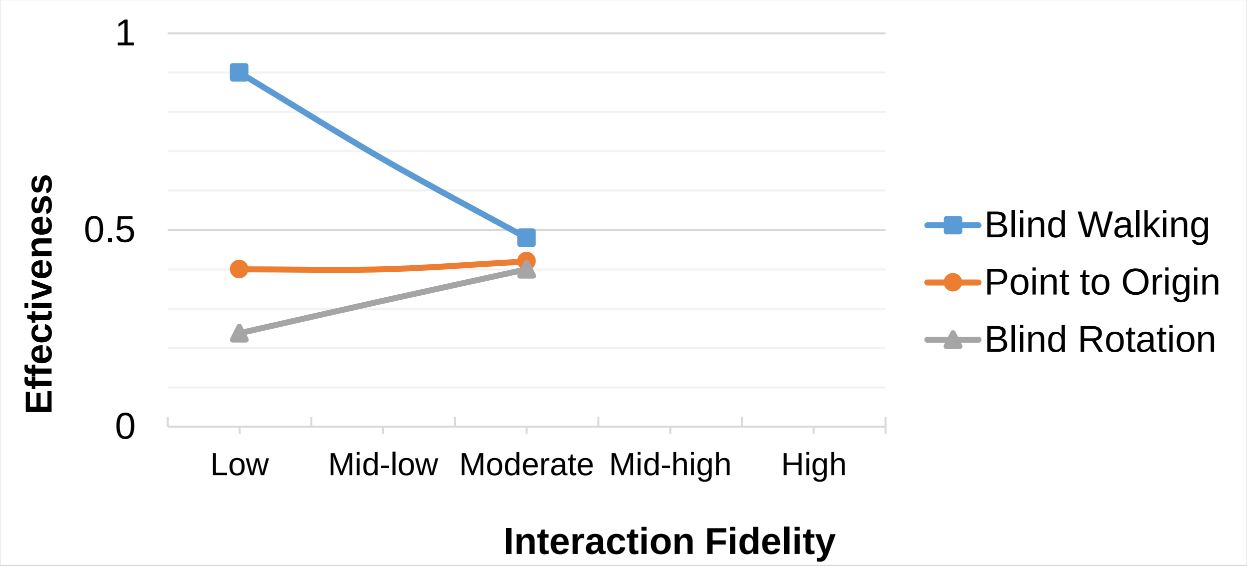
FIFA framework analysis of interaction fidelity

	Mouse and keyboard	Human Joystick
Biomechanical Symmetry		
Kinematic Symmetry	Press buttons and handle mouse to translate and rotate	Move thighs, legs, and feet to step on curved surface
Kinetic Symmetry	Apply force to button in movement direction by finger	Large vertical and shear ground forces
Anthropometric Symmetry	Finger	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 button press-to-position	1:1 position-to-speed
Termination Symmetry	Stop pressing the button	Walk back to the neutral zone
System Appropriateness		
Input Accuracy	Standard mouse and keyboard	Tracking system
Input Precision	Standard mouse and keyboard	Tracking system
Latency	Standard mouse and keyboard	Tracking system
Form Factor	Keep mouse and keyboard in hand	N/A

Interfaces	Mouse and Keyboard	Human Joystick	**Image**
Measures	Completion Time: game completion time	Damage Taken: Damage user take during the game	

12.5 Sibert, Templeman et al. 2008

Graph



FIFA framework analysis of interaction fidelity

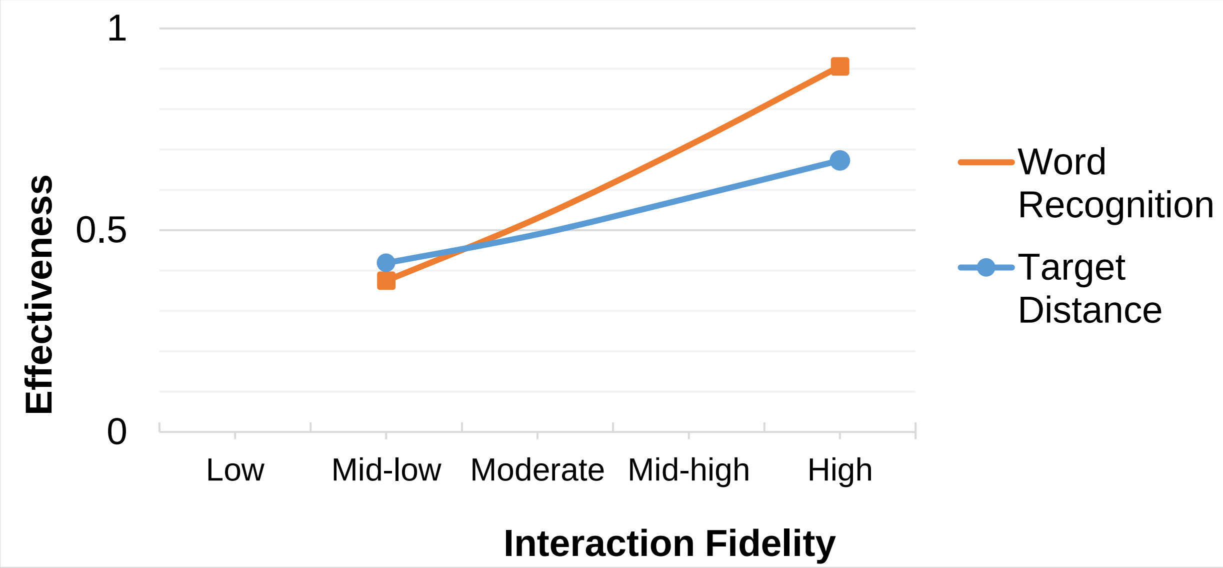
	Joystick	Walking In Place
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to step in place
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Head tracker
Input Precision	Standard Joystick	Head tracker
Latency	Joystick handle	Head tracker and neural network
Form Factor	Keep Jostick in hands	N/A

Interfaces	Desktop Joystick + The Rifle-Mounted Joystick	Gaiter (Walking-in-place)	
Measures	Blind Walking	Point to Origin	Blind Rotation

Image

12.6 Suma, Finkelstein et al. 2010

Graph



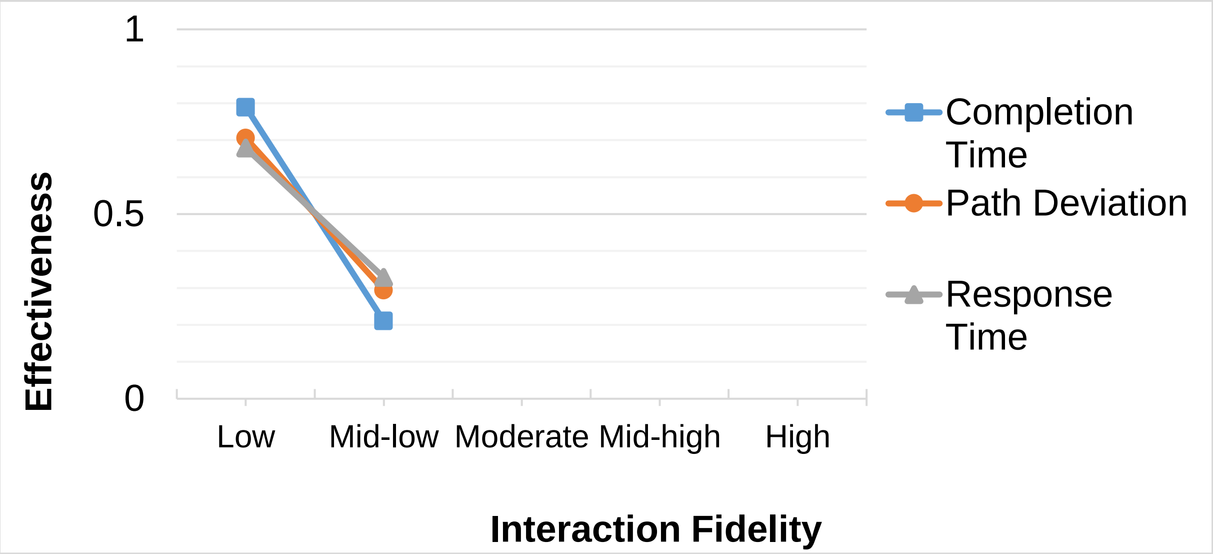
FIFA framework analysis of interaction fidelity

	Joystick + Gaze or Torso Directed	Real Walking Technique
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate, face the direction to rotate	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Tracking system
Input Precision	Standard Joystick	Tracking system
Latency	Joystick handle	Tracking system
Form Factor	Keep Jostick in hands	Wearing a headset, not able to see your feet

Interfaces	Torso/point Directed + Gaze-Directe	Real Walking	**Image**	
Measures	Target Distance: Follow the moving object as closely as possible. There were straight line movements and 90 degree turns	Word Recognition: See words during the locomotion task, how many did they remember after the task		

12.7 Yan, Lindeman et al. 2016

Graph



FIFA framework analysis of interaction fidelity

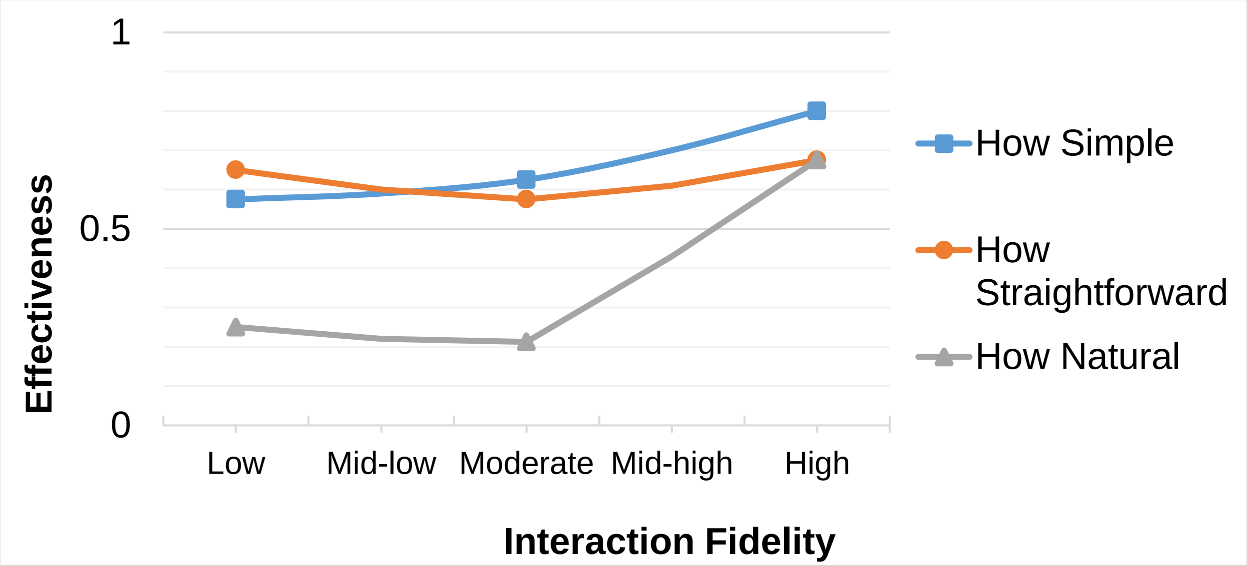
	Joystick	Finger Walking
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move fingers similar to walking movements
Kinetic Symmetry	Apply force in movement direction by thumb	Apply forces parallel to the ground with fingers
Anthropometric Symmetry	Thumbs	Fingers
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Touch surface
Input Precision	Standard Joystick	Touch surface
Latency	Joystick handle	Touch surface
Form Factor	Keep Jostick in hands	N/A

Interfaces	Gamepad	Finger Walking (ForcePad)	
Measures	Completion Time	Path Deviation	Response Time

Image

12.8 Usoh, Arthur et al. 1999

Graph



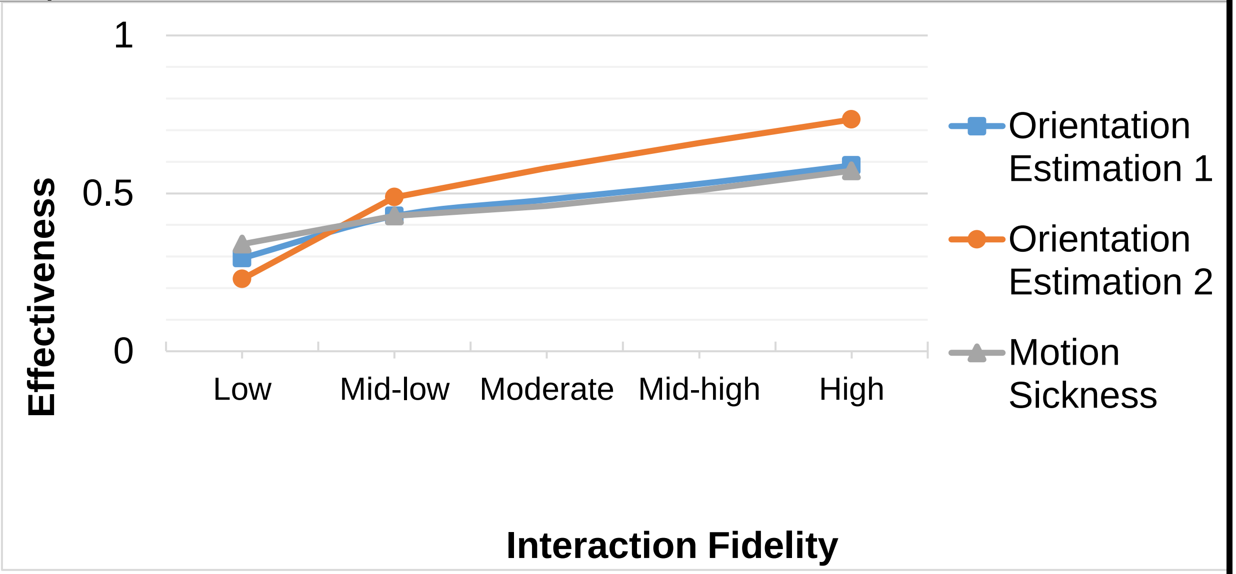
FIFA framework analysis of interaction fidelity

	Flying	Walking In Place	Real Walking Technique
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to step in place	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical ground forces	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Head tracker	Tracking system
Input Precision	Standard Joystick	Head tracker	Tracking system
Latency	Joystick handle	Head tracker and neural network	Tracking system
Form Factor	Keep Jostick in hands	N/A	Wearing a headset, not able to see your feet

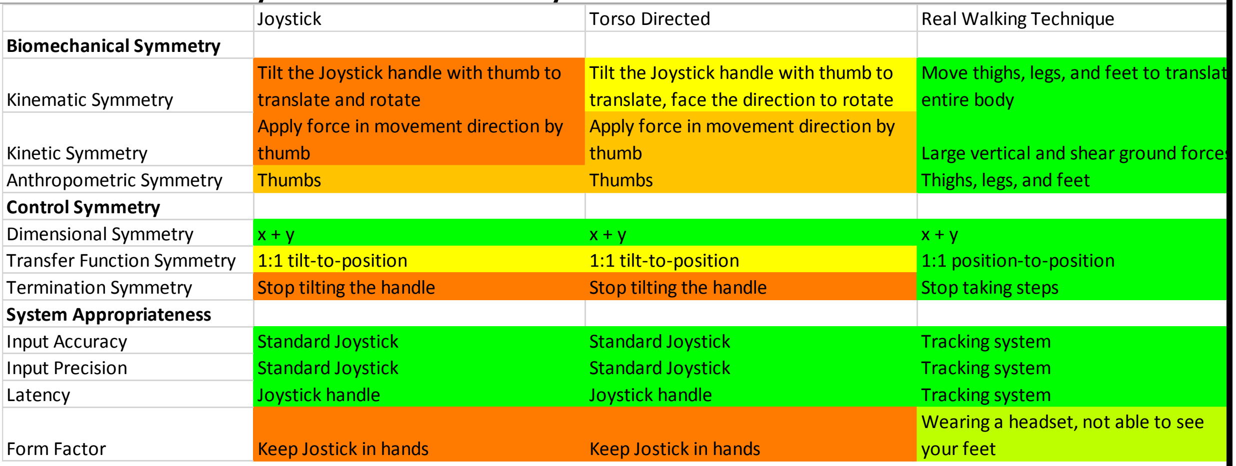
Interfaces	Flying	WIP Walking-in-Place	Walking	**Image**
Measures	How Simple	How Straightforward	How Natural	

12.9 Chance, Gaunet et al. 1998

Graph



FIFA framework analysis of interaction fidelity

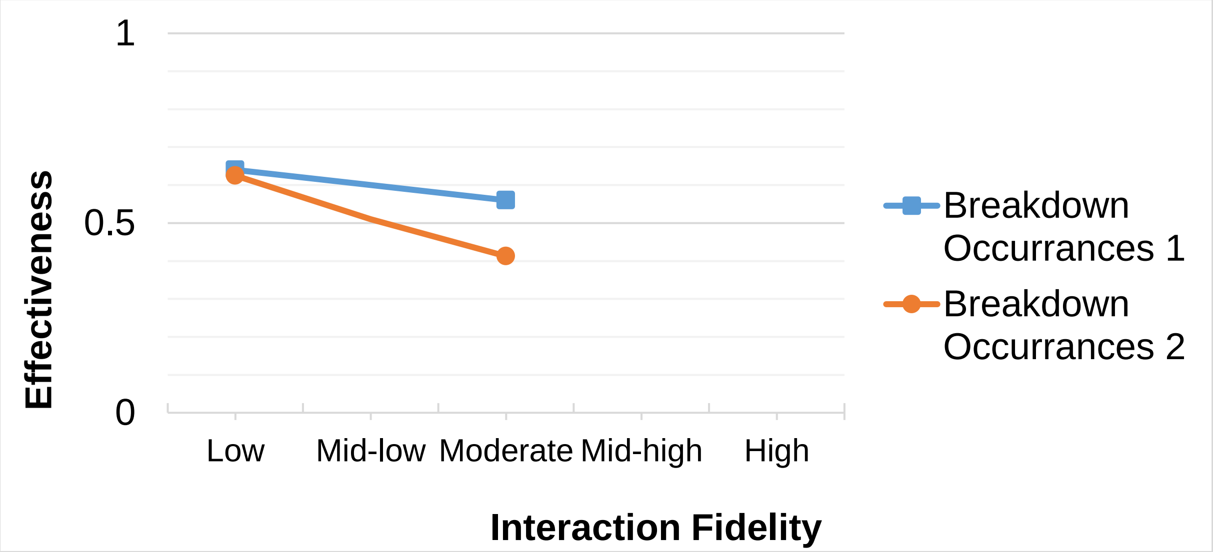


	Joystick	Torso Directed	Real Walking Technique
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Tilt the Joystick handle with thumb to translate, face the direction to rotate	Move thighs, legs, and feet to translat entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Apply force in movement direction by thumb	Large vertical and shear ground force
Anthropometric Symmetry	Thumbs	Thumbs	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop tilting the handle	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Standard Joystick	Tracking system
Input Precision	Standard Joystick	Standard Joystick	Tracking system
Latency	Joystick handle	Joystick handle	Tracking system
Form Factor	Keep Jostick in hands	Keep Jostick in hands	Wearing a headset, not able to see your feet

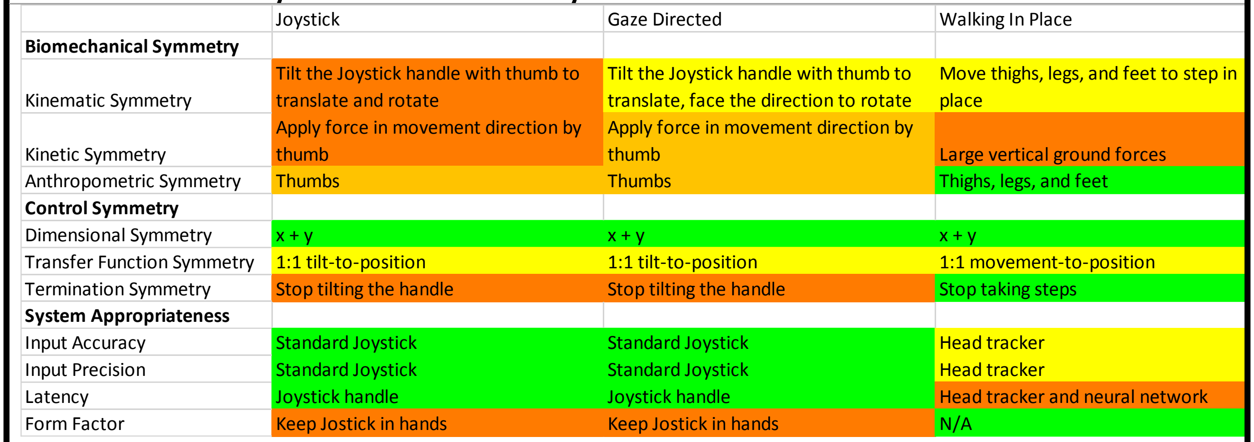
Interfaces	Visual turn with joystick + constant speed	Physical turn with body direction + constant speed	Real Walking
Measures	Orientation Estimation 1: orientation estimation for course 1	Orientation Estimation 2: orientation estimation for course 2	Motion Sickness

12.10 Gamberini, Spagnolli et al. 2013

Graph



FIFA framework analysis of interaction fidelity

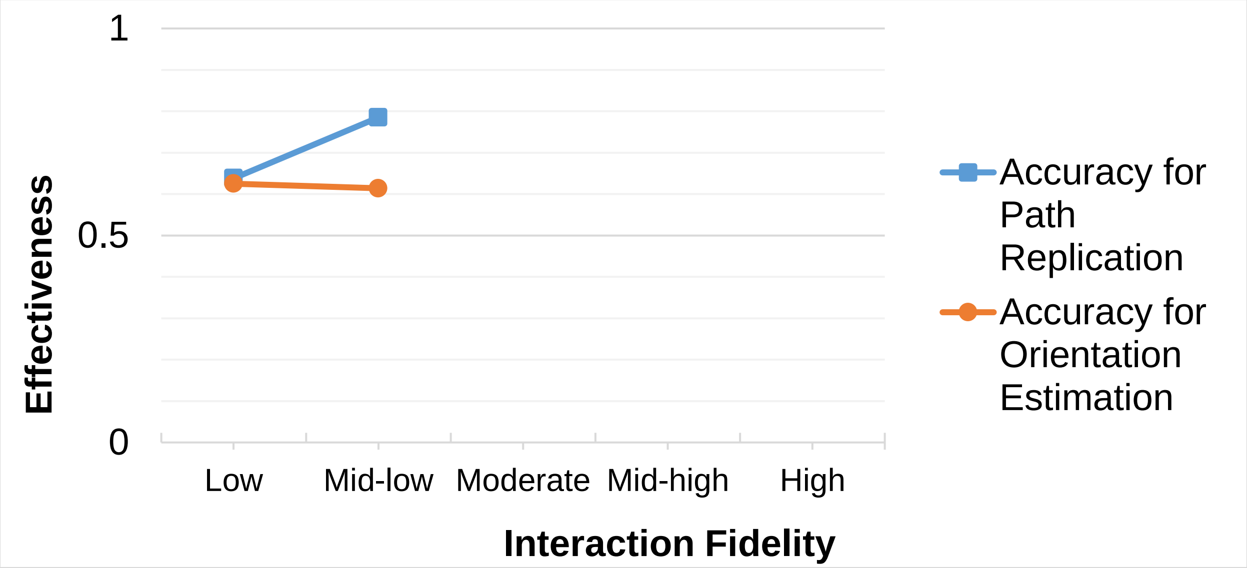


	Joystick	Gaze Directed	Walking In Place
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Tilt the Joystick handle with thumb to translate, face the direction to rotate	Move thighs, legs, and feet to step in place
Kinetic Symmetry	Apply force in movement direction by thumb	Apply force in movement direction by thumb	Large vertical ground forces
Anthropometric Symmetry	Thumbs	Thumbs	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 tilt-to-position	1:1 movement-to-position
Termination Symmetry	Stop tilting the handle	Stop tilting the handle	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Standard Joystick	Head tracker
Input Precision	Standard Joystick	Standard Joystick	Head tracker
Latency	Joystick handle	Joystick handle	Head tracker and neural network
Form Factor	Keep Jostick in hands	Keep Jostick in hands	N/A

Interfaces	Joypad (Game pad)	Superfeet + Head-based Rotation	Superfeet (WIP rotation by feet direction)+ Superfeet with Head Rotation	**Image**
Measures	Breakdown Occurrences 1		Breakdown Occurrences 2	

12.11 Kim, Gračanin et al. 2010

Graph



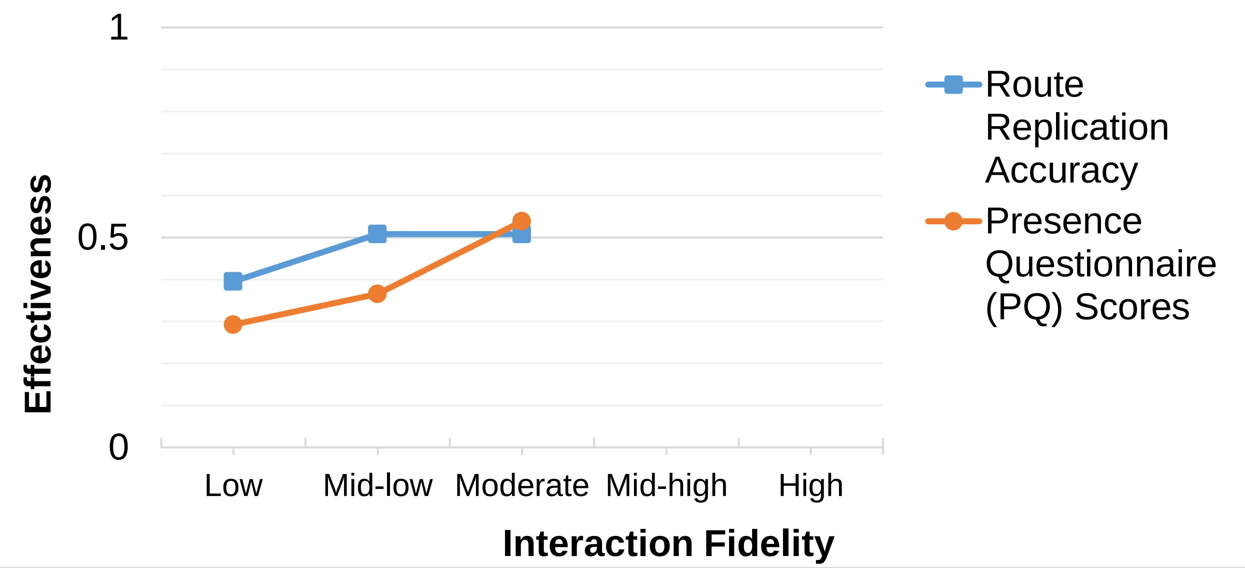
FIFA framework analysis of interaction fidelity

	Joystick	Finger Walking
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move fingers similar to walking movements
Kinetic Symmetry	Apply force in movement direction by thumb	Apply forces parallel to the ground with fingers
Anthropometric Symmetry	Thumbs	Fingers
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Touch surface
Input Precision	Standard Joystick	Touch surface
Latency	Joystick handle	Touch surface
Form Factor	Keep Jostick in hands	N/A

Interfaces	Joystick flying	FWIP Finger Walking-In-Place
Measures	Accuracy for Path Replication: The route error is measured as area between the optimal route (from the first marker to the last marker) and the path taken by the subject in the route replication tasks	Accuracy for Orientation Estimation: The orientation estimation error is measured as area between the straight-line path (from the entrance to the exit) and the direct path taken by the subject

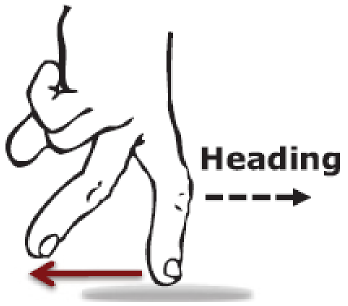
12.12 Kim, Gračanin et al. 2015

Graph



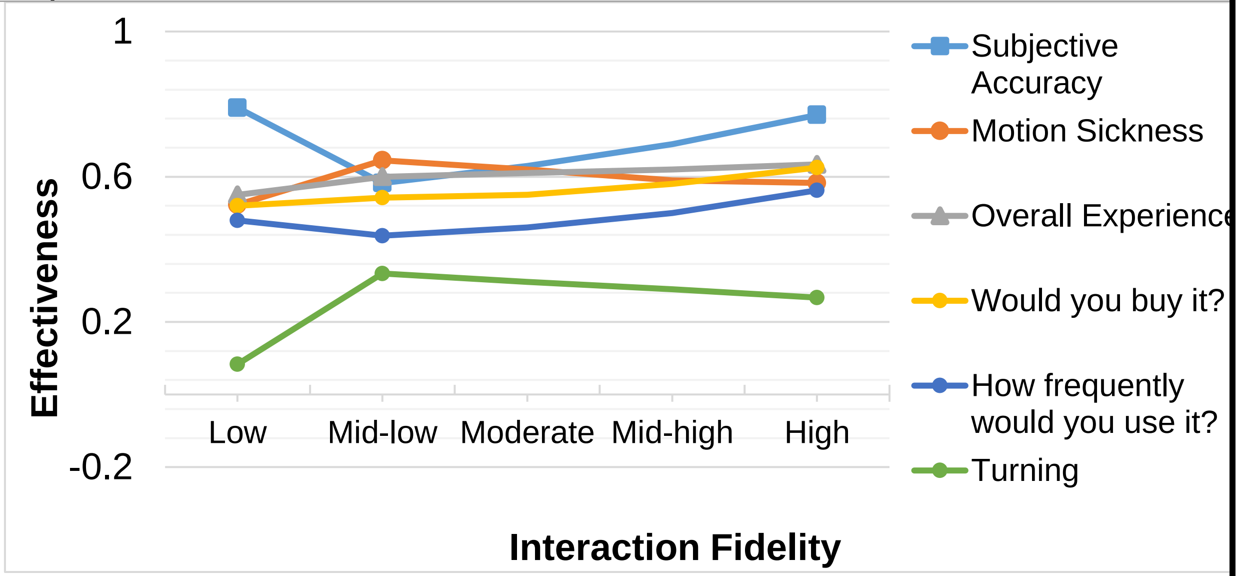
FIFA framework analysis of interaction fidelity

	Joystick	Finger Walking	Walking In Place
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move fingers similar to walking movements	Move thighs, legs, and feet to step in place
Kinetic Symmetry	Apply force in movement direction by thumb	Apply forces parallel to the ground with fingers	Large vertical ground forces
Anthropometric Symmetry	Thumbs	Fingers	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position	1:1 movement-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Touch surface	Head tracker, feet/leg tracker
Input Precision	Standard Joystick	Touch surface	Head tracker, feet/leg tracker
Latency	Joystick handle	Touch surface	Tracker and start/stop latecnies
Form Factor	Keep Jostick in hands	N/A	N/A

Interfaces	Joystick flying	F-WIP Finger Walking-In-Place	Walking-In-Place SF-WIP	**Image**
Measures	Route Replication Accuracy		Presence Questionnaire (PQ) Scores	

12.13 McCullough, Xu et al. 2015

Graph

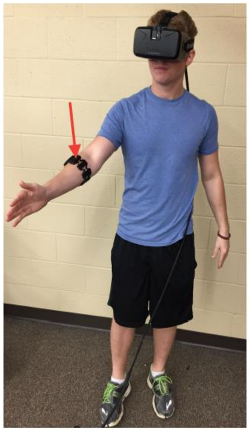


FIFA framework analysis of interaction fidelity

	Joystick	Myo arm-swinging	Real Walking Technique
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move arm, to simulate walking	Move thighs, legs, and feet to translat entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large horizontal forces	Large vertical and shear ground force
Anthropometric Symmetry	Thumbs	Arms	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Tracking system	Tracking system
Input Precision	Standard Joystick	Tracking system	Tracking system
Latency	Joystick handle	Tracking system	Tracking system
Form Factor	Keep Jostick in hands	N/A	Wearing a headset, not able to see your feet

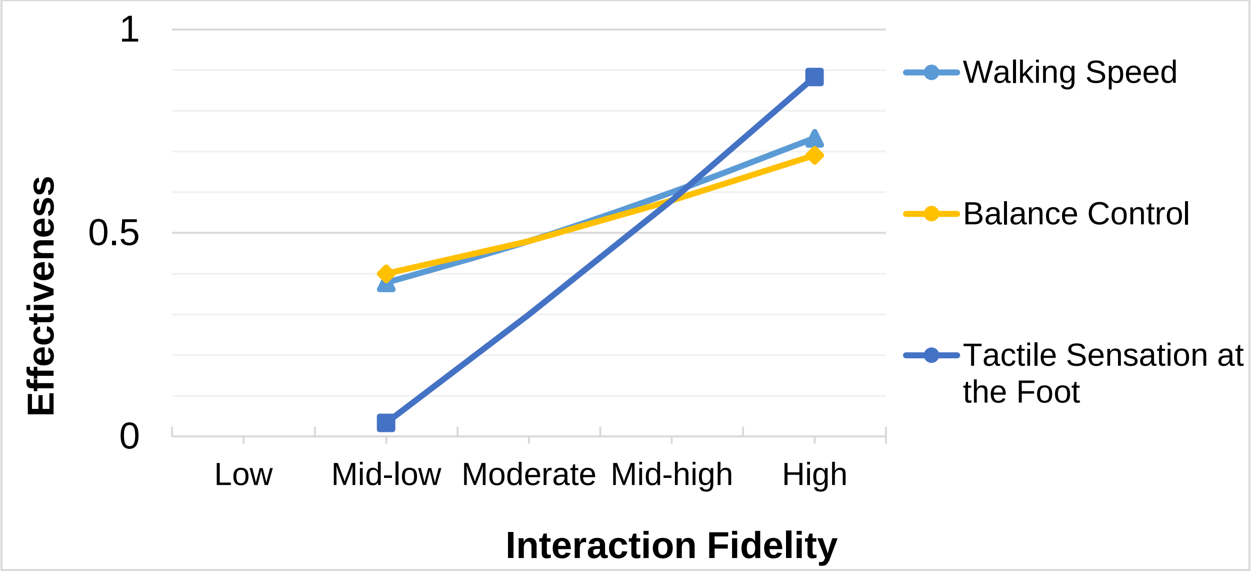
Interfaces	Joystick	Myo arm–swinging	Walking
Measures	Did your movements feel accurately translated into the environment? Did you experience any motion sickness or vertigo while using this equipment? Overall, how would you rate your experience with this machine? If this device was within your price range, would you buy it? If you owned this device, how frequently would you use it?		
	Spatial orientation: Turning error for the orientation estimation task		

Image



12.14 Shimabukuro, Kato et al. 2015

Graph



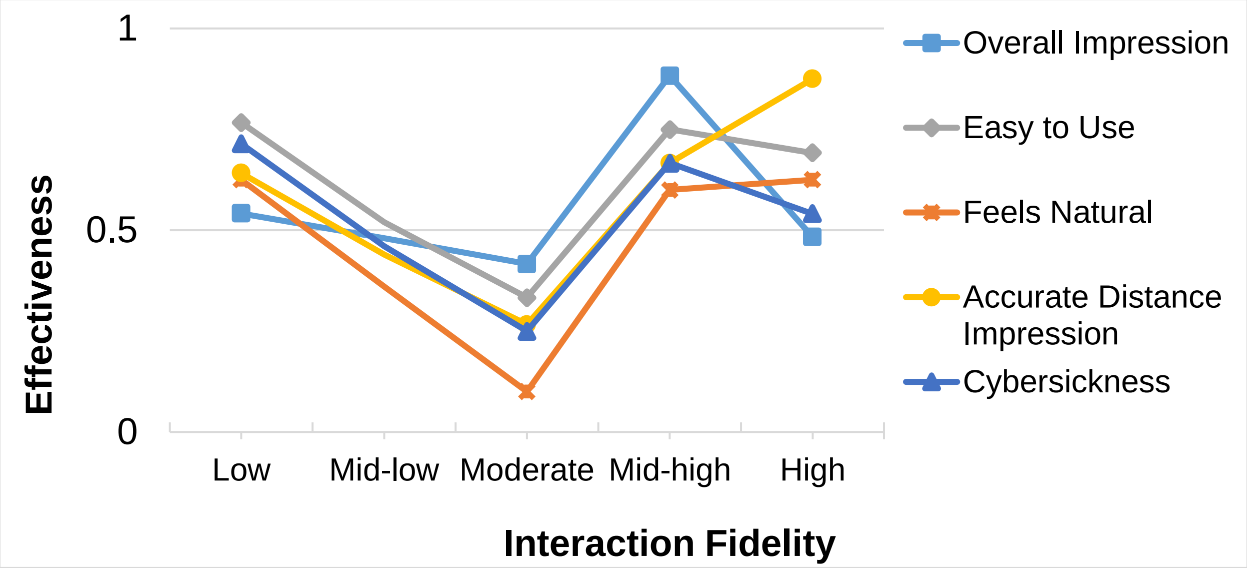
FIFA framework analysis of interaction fidelity

	Motion Seat (3 DoF)	Real Walking Technique
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the seat to translate and rotate	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by body	Large vertical and shear ground forces
Anthropometric Symmetry	whole body	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the seat	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Tracking system
Input Precision	Standard Joystick	Tracking system
Latency	Motion seat	Tracking system
Form Factor	Seat on a chair	Wearing a headset, not able to see your feet

Interfaces	Motion Seat (3 DoF)		Real Walk	**Image**
Measures	Walking Speed	Balance Control	Tactile Sensation at the Foot	

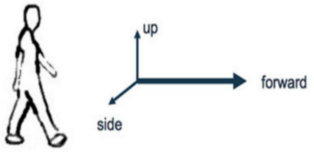
12.15 Interrante, O'Rourke et al. 2007

Graph



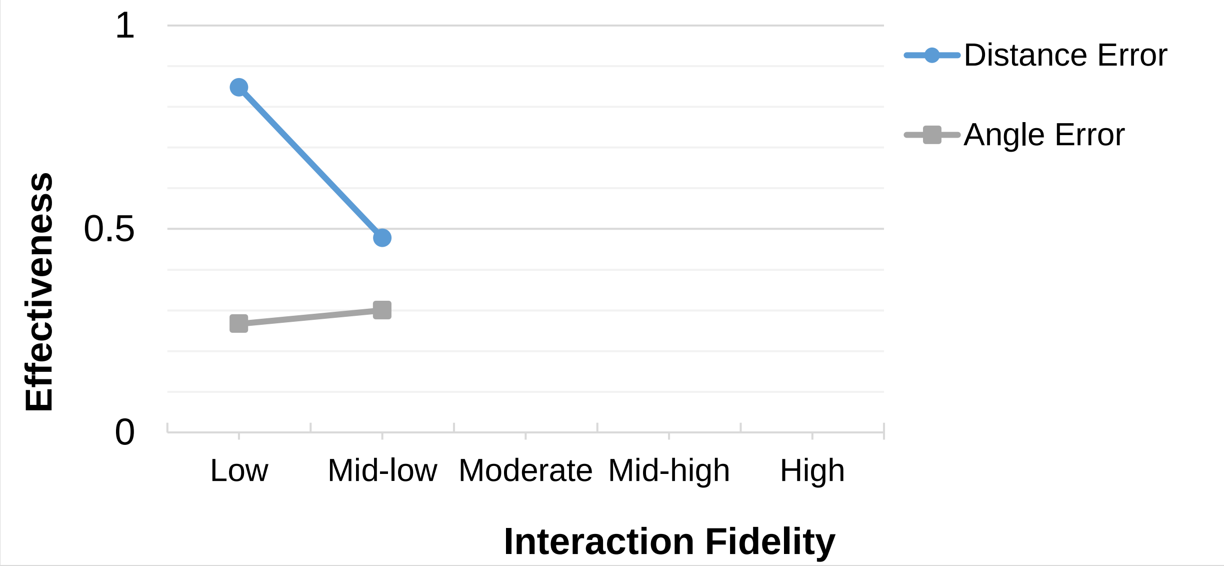
FIFA framework analysis of interaction fidelity

	Joystick	Constant Gain (10x)	Sevel League Boots	Real Walking Technique
Biomechanical Symmetry				
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to translate entire body	Move thighs, legs, and feet to translate entire body	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces	Large vertical and shear ground forces	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet	Thighs, legs, and feet	Thighs, legs, and feet
Control Symmetry				
Dimensional Symmetry	x + y	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:10 position-to-position	1:n position-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps	Stop taking steps	Stop taking steps
System Appropriateness				
Input Accuracy	Standard Joystick	Tracking system	Tracking system	Tracking system
Input Precision	Standard Joystick	Tracking system	Tracking system	Tracking system
Latency	Joystick handle	Tracking system	Tracking system	Tracking system
Form Factor	Keep Jostick in hands	Wearing a headset, not able to see your feet	Wearing a headset, not able to see your feet	Wearing a headset, not able to see your feet

Interfaces	Joystick	Gain (10x)	7League Boots	Walking	**Image**
Measures	Overall Impression Easy to Use Feels Natural Accurate Distance Impression Cyber-sickness				

12.16 Iwata 1999

Graph



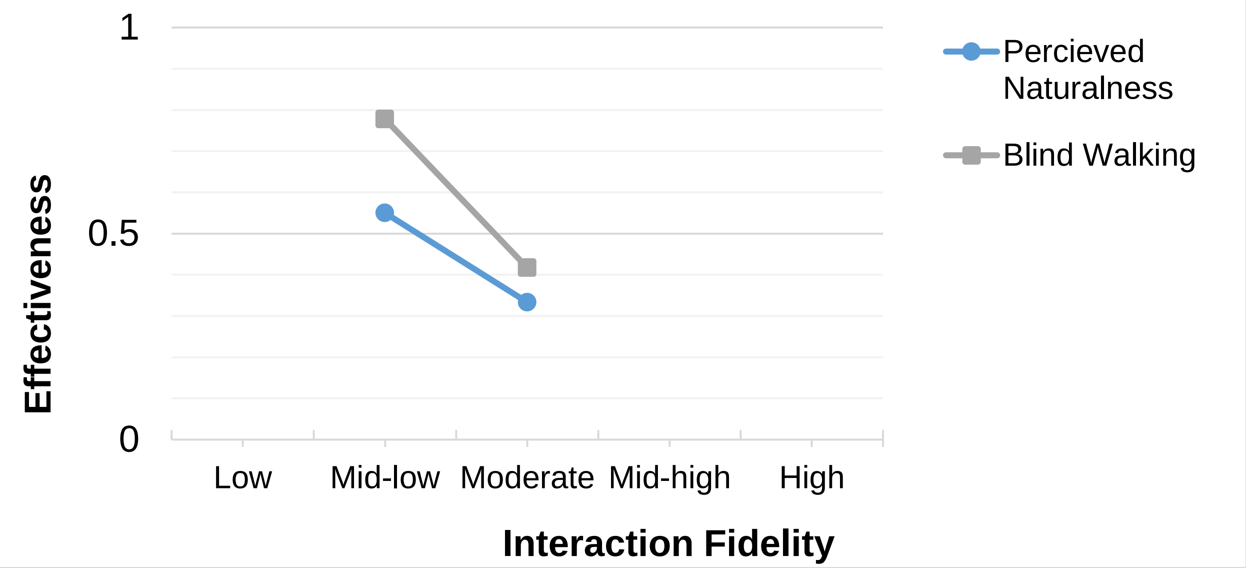
FIFA framework analysis of interaction fidelity

	Joystick	Omni Directional Threadmill
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces; Belt forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Head tracker
Input Precision	Standard Joystick	Head tracker
Latency	Joystick handle	Head tracker and belts
Form Factor	Keep Jostick in hands	Belts and balance harness

Interfaces	Joystick	Motion base	**Image**
Measures	Distance Error	Angle Error	

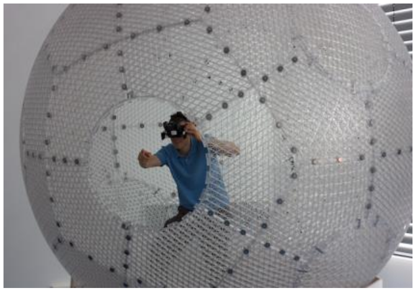
12.17 Marsh and Kluss 2015

Graph



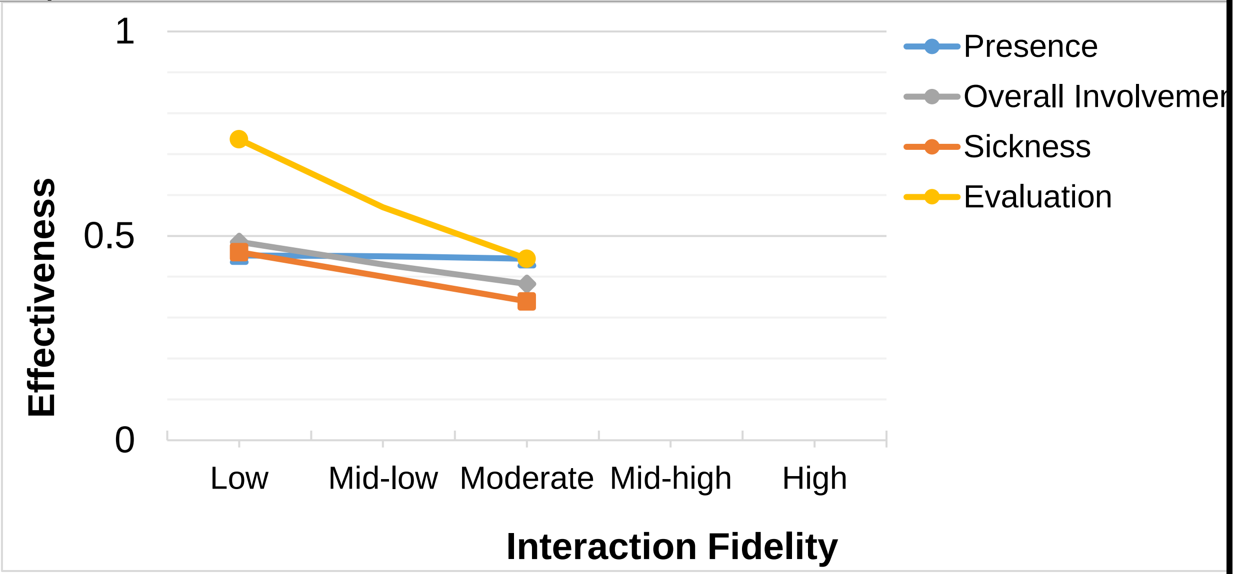
FIFA framework analysis of interaction fidelity

	Virtusphere, Torso Directed	Virtusphere, Movement Directed
Biomechanical Symmetry		
Kinematic Symmetry	Move thighs, legs, and feet to step on curved surface	Move thighs, legs, and feet to step on curved surface
Kinetic Symmetry	Large vertical and sheare ground forces; force toward walking direction	Large vertical and sheare ground forces; force toward walking direction
Anthropometric Symmetry	Thighs, legs, and feet	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 position-to-position	1:1 position-to-position
Termination Symmetry	Stop taking steps; Apply force to reverse direction	Stop taking steps; Apply force to reverse direction
System Appropriateness		
Input Accuracy	Virtusphere movement sensor	Virtusphere movement sensor
Input Precision	Virtusphere movement sensor	Virtusphere movement sensor
Latency	Virtusphere movement sensor	Virtusphere movement sensor
Form Factor	Closed area; Curved surface	Closed area; Curved surface

Interfaces	Virtusphere (Torso directed)	Virtusphere (normal)	**Image**
Measures	Perceived Naturalness	Blind Walking Turning Error	

12.18 Skopp, Smolenski et al. 2014

Graph



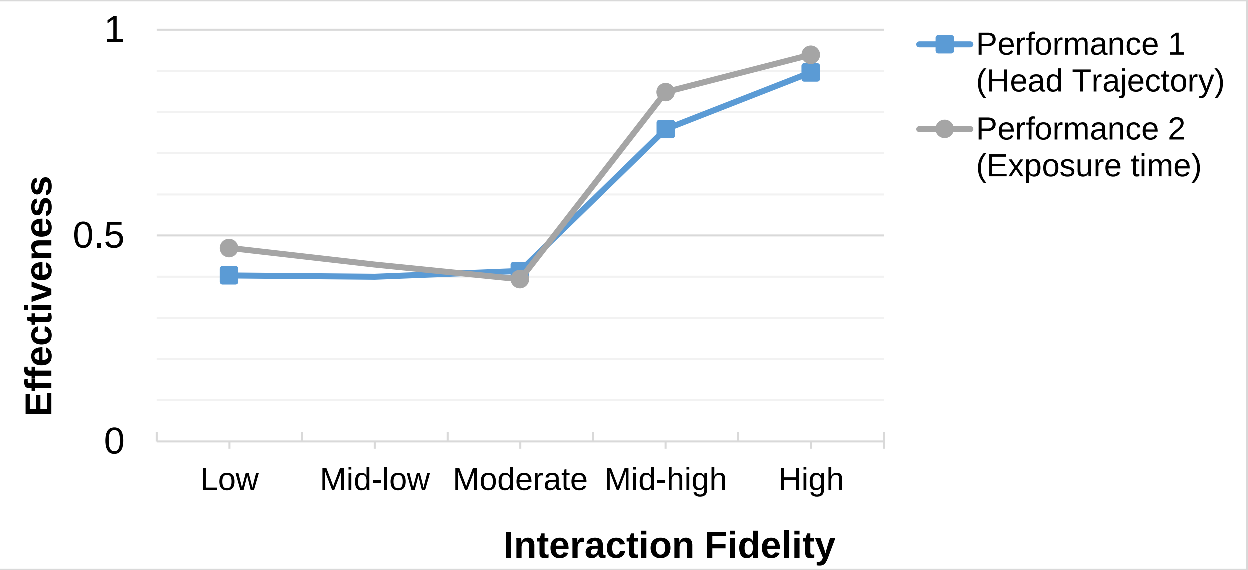
FIFA framework analysis of interaction fidelity

	Joystick	Virtusphere, Movement Directed
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to step on curved surface
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and sheare ground forces; force toward walking direction
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps; Apply force to reverse direction
System Appropriateness		
Input Accuracy	Standard Joystick	Virtusphere movement sensor
Input Precision	Standard Joystick	Virtusphere movement sensor
Latency	Joystick handle	Virtusphere movement sensor
Form Factor	Keep Jostick in hands	Closed area; Curved surface

Interfaces	Game Console	Virtusphere
Measures	Presence Questionnaire Overall Involvement/Control Simulator/Motion Sickness Evaluation (Virtual Iraq Feedback Form)	

12.19 Feasel, Whitton et al. 2008

Graph



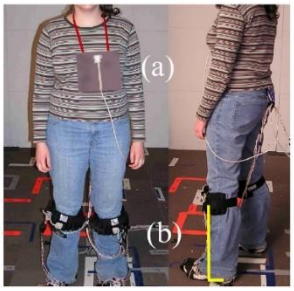
FIFA framework analysis of interaction fidelity

	Joystick	Walking In Place	Real Walking Technique
Biomechanical Symmetry			
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to step in place	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical ground forces	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet	Thighs, legs, and feet
Control Symmetry			
Dimensional Symmetry	x + y	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 movement-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps	Stop taking steps
System Appropriateness			
Input Accuracy	Standard Joystick	Head tracker	Tracking system
Input Precision	Standard Joystick	Head tracker	Tracking system
Latency	Joystick handle	Head tracker and neural network	Tracking system
Form Factor	Keep Jostick in hands	N/A	Wearing a headset, not able to see your feet

Interfaces	Joystick	WIP-LLCM (Walking-in-place low latency continuous motion)	VRWalk (Real Walking)	Real (Physical walking in physical world)

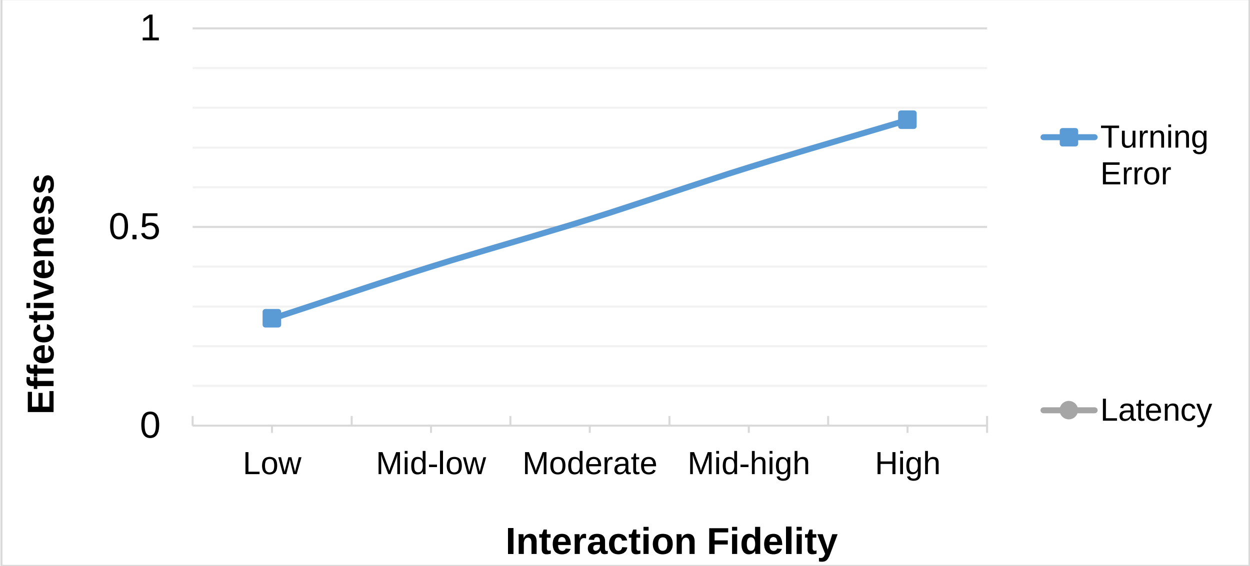
Measures	Performance 1 (Head Trajectory): Length of Head Trajectory during Gunfire	Performance 2 (Exposure time): Average Total Exposure per Trial

Image



12.20 Williams, Bailey et al. 2011

Graph



FIFA framework analysis of interaction fidelity

	Joystick	Real Walking Technique
Biomechanical Symmetry		
Kinematic Symmetry	Tilt the Joystick handle with thumb to translate and rotate	Move thighs, legs, and feet to translate entire body
Kinetic Symmetry	Apply force in movement direction by thumb	Large vertical and shear ground forces
Anthropometric Symmetry	Thumbs	Thighs, legs, and feet
Control Symmetry		
Dimensional Symmetry	x + y	x + y
Transfer Function Symmetry	1:1 tilt-to-position	1:1 position-to-position
Termination Symmetry	Stop tilting the handle	Stop taking steps
System Appropriateness		
Input Accuracy	Standard Joystick	Tracking system
Input Precision	Standard Joystick	Tracking system
Latency	Joystick handle	Tracking system
Form Factor	Keep Jostick in hands	Wearing a headset, not able to see your feet

Interfaces	Joystick	Walking	**Image**
Measures	Turning Error