Exploring the Effects of Higher-Fidelity Display and Interaction for Virtual Reality Games

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ABSTRACT

In recent years, consumers have witnessed a technological revolution that has delivered more-realistic experiences in their own homes. Expanding technologies have provided larger displays with higher resolutions, faster refresh rates, and stereoscopic capabilities. These advances have increased the level of display fidelity—the objective degree of exactness with which real-world sensory stimuli are reproduced by a display system. Similarly, the latest generation of video game systems (e.g., Nintendo Wii and Xbox Kinect) with their natural, gesture-based interactions have delivered increased levels of interaction fidelity— the objective degree of exactness with which real-world interactions can be reproduced in an interactive system. Though this technological revolution has provided more realistic experiences, it is not completely clear how increased display fidelity and interaction fidelity impact the user experience because the effects of increasing fidelity to the real world have not been empirically established.

The goal of this dissertation is to provide a better understanding of the effects of both display fidelity and interaction fidelity on the user experience. For the context of our research, we chose virtual reality (VR) games because immersive VR allows for high levels of fidelity to be achieved while games usually involve complex, performance-intensive tasks. In regard to the user experience, we were concerned with objective performance metrics and subjective responses such as presence, engagement, perceived usability, and overall preferences.

We conducted five systematically controlled studies that evaluated display and interaction fidelity at contrasting levels in order to gain a better understanding of their effects. In our first study, which involved a 3D object manipulation game within a three-sided CAVE, we found that stereoscopy and the total size of the visual field surrounding the user (i.e., field of regard or FOR) did not have a significant effect on manipulation times but two high-fidelity interaction techniques based on six degrees-of-freedom (DOF) input outperformed a low-fidelity technique based on keyboard and mouse input. In our second study, which involved a racing game on a commercial game console, we solely investigated interaction fidelity and found that two low-fidelity steering techniques based on 2D joystick input outperformed two high-fidelity steering techniques based on 3D accelerometer data in terms of lap times and driving errors.
Our final three studies involved a first-person shooter (FPS) game implemented within a six-sided CAVE. In the first of these FPS studies, we evaluated display fidelity and interaction fidelity independently, at extremely high and low levels, and found that both significantly affected strategy, performance, presence, engagement, and perceived usability. In particular, performance results were strongly in favor of two conditions: low-display, low-interaction fidelity (representative of desktop FPS games) and high-display, high-interaction fidelity (similar to the real world). In the second FPS study, we investigated the effects of FOR and pointing fidelity on the subtasks of searching, aiming, and firing. We found that increased FOR affords faster searching and that high-fidelity pointing based on 6-DOF input provided faster aiming than low-fidelity mouse pointing and a mid-fidelity mouse technique based on the heading of the user. In the third FPS study, we investigated the effects of FOR and locomotion fidelity on the subtasks of long-distance navigation and maneuvering. Our results indicated that increased FOR increased perceived usability but had no significant effect on actual performance while low-fidelity keyboard-based locomotion outperformed our high-fidelity locomotion technique developed for our original FPS study.

The results of our five studies show that increasing display fidelity tends to have a positive correlation to user performance, especially for some components such as FOR. Contrastingly, our results have indicated that interaction fidelity has a non-linear correlation to user performance with users performing better with “traditional”, extremely low-fidelity techniques and “natural”, extremely high-fidelity techniques while performing worse with mid-fidelity interaction techniques. These correlations demonstrate that the display fidelity and interaction fidelity continua appear to have differing effects on the user experience for VR games.

In addition to learning more about the effects of display fidelity and interaction fidelity, we have also developed the Framework for Interaction Fidelity Analysis (FIFA) for comparing interaction techniques to their real-world counterparts. There are three primary factors of concern within FIFA: biomechanical symmetry, control symmetry, and system appropriateness. Biomechanical symmetry involves the comparison of the kinematic, kinetic, and anthropometric aspects of two interactions. Control symmetry compares the dimensional, transfer function, and termination characteristics of two interactions. System appropriateness is concerned with how well a VR system matches the interaction space and objects of the real-world task (e.g., a driving simulator is more appropriate than a 2D joystick for a steering task).

Although consumers have witnessed a technological revolution geared towards more realistic experiences in recent years, we have demonstrated with this research that there is still much to be learned about the effects of increasing a system’s fidelity to the real world. The results of our studies show that the levels of display and interaction fidelity are significant factors in determining performance, presence, engagement, and usability.
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1 INTRODUCTION

1.1 Motivation

In recent years, new technologies have provided more-realistic experiences for consumers. Televisions with larger displays, higher resolutions, faster refresh rates, and stereoscopic capabilities produce sensory stimuli that better match real-world stimuli than televisions manufactured a decade ago [1]. Videogame consoles that use motion-sensitive controllers provide natural, gesture-based interactions by matching body movements to real-world tasks [2], in contrast with traditional game controllers that use 2D joysticks and buttons for interactions.

Essentially, these technological advances are providing more-realistic experiences by increasing the fidelity or objective degree of exactness with which real world experiences are reproduced [3]. Televisions have improved with increases in their display fidelity, the objective degree of exactness with which real-world sensory stimuli are reproduced by a display system [4]. Similarly, videogames have advanced with increases in interaction fidelity, the objective degree of exactness with which real-world interactions can be reproduced in an interactive system [5].

Proponents of these technological advances have claimed increases in fidelity provide users with richer entertainment experiences [6]. Moviegoers are attending more 3D films than ever before [7], which has been attributed to advances in stereoscopic projection technology [8]. The recent increases in fidelity for the videogame industry have been credited with creating a larger and broader demographic of players [2]. Additionally, proponents have conjectured that users learn how to use products with increased fidelity faster than traditional counterparts due to embodied interaction [9].

Though claims advocating increasing fidelity seem reasonable, there are also arguments for opposing such technological advances. For instance, the stereoscopic technologies fueling 3D visual content have been shown to cause visual fatigue and viewer discomfort due to mismatches in convergence and accommodation stimuli [10], which are not problems for 2D visual content [11]. Similarly, current gesture-based interactions used by videogame consoles have been demonstrated to lack the precision of control that “hardcore” gamers are provided by traditional game controllers [12, 13].

Before recent consumer-level advances, fidelity was the focus of the virtual reality (VR) community since the 1960s. In 1965, Ivan Sutherland described “The Ultimate Display” [14]. In this visionary paper, he foresaw that users would use their whole bodies, tracked by a computer, to interact with highly realistic virtual worlds. Three years later, Sutherland published the first...
paper describing a tracked head-mounted display (HMD), which allowed use of natural head movements to view virtual and augmented 3D environments [15]. Over the next 30 years, VR research continued sporadically until the 1990s, when interest in VR boomed with the emergence of futuristic VR systems in popular culture [4]. Since then, researchers have investigated VR with the goal to let users experience high fidelity, computer-generated worlds.

1.2 Problem Statement

To a large degree, VR researchers have succeeded in providing users with realistic virtual experiences by developing systems and technologies that afford extremely high levels of fidelity. Demonstrations of these high-end technologies show that a high level of fidelity can cause users to behave and feel differently [16]. Clearly, using a high-fidelity system is a unique experience and different from interacting with a 3D application on a desktop computer or gaming console.

Despite the unique experiences that high-fidelity systems can offer, the number of production applications—Fred Brooks’ term for real-world systems used frequently for the results they provide [17]—are limited [4]. One potential reason is that high-fidelity technologies, such as HMDs, multiscreen stereoscopic projection displays, high-precision 3D tracking systems, and advanced input devices, are still quite expensive. If all that these high-fidelity technologies provide for the user were oohs and ahs and a unique user experience, it would be difficult to justify their development and cost. Hence, in order to defend future developments of high-fidelity technologies, it is important to determine the benefits of using such high-fidelity systems, beyond strong subjective reactions.

In addition to high-fidelity systems, it is also important to understand how increasing fidelity in consumer-level products affects the general population. Only recently has the majority of the public been introduced to systems that provide more fidelity than just keyboards, mice, and game controllers. Like high-fidelity systems, these technological advances have provided the general population with oohs and ahs, but the benefits of these advances are unknown beyond that. More importantly how the introduction of higher-fidelity technologies will impact the way users work, future product designs, and society in general is unknown.

Therefore, in order to better understand the potential benefits of high-fidelity systems and the possible impacts of higher-fidelity consumer products, it is necessary to determine the effects of increasing fidelity. Additionally, it would be intellectually interesting to know how increased fidelity affects user performance, understanding, and engagement.
1.2.1 Practical Evaluations of Fidelity

Some researchers have already begun exploring the effects of increasing fidelity by conducting practical evaluations. Practical evaluations of fidelity normally involve the direct comparison of systems that drastically differ in their level of fidelity, to empirically demonstrate that a high-fidelity system is significantly different from a low-fidelity system for a particular task or experience [4]. A common approach for conducting practical evaluations is to compare high-fidelity VR systems to low-fidelity desktop computers.

Head-mounted displays, which normally offer a full 360-degree visual field surrounding the user (i.e., field of regard or FOR) and stereoscopic capabilities, have been compared to traditional desktop computers by several researchers. For example, Ruddle et al. compared a head-tracked HMD to a standard desktop computer with a monitor, mouse, and keyboard for navigating large-scale virtual environments (VEs) [18]. They found that users were faster at wayfinding and could better estimate distances to other locations with the HMD. In addition to objective performance metrics, researchers have also compared HMDs to traditional desktops with concern for changes in subjective responses. Pertaub et al. evaluated the effects of using an HMD on speaker confidence while giving a presentation to a virtual audience [19]. The researchers found that the HMD caused larger decreases in speaker confidence when dealing with a negative audience than the desktop did, which indicates the HMD likely heightened the users’ sense of presence or “being there” [20].

In addition to using HMDs, researchers have also compared CAVEs [21] (rear-projected displays that partially or fully surround the user) to traditional desktop computers. Arns et al. compared a four-sided CAVE with six-degrees-of-freedom (6-DOF) input devices to a desktop computer for analyzing statistical data in three dimensions [22]. They found that the CAVE was better for identifying clusters of data and radial sparseness than the desktop. For a different type of task (well-path editing), Gruchalla conducted a similar evaluation by comparing a four-sided CAVE with 6-DOF input to a desktop computer with a stereoscopic monitor [23]. He found that using the CAVE was faster for editing 3D well paths than using the desktop setup with its mouse and keyboard.

Using practical evaluations, researchers have demonstrated that there are some significant benefits to using high-fidelity systems compared to low-fidelity counterparts. However, the results of practical evaluations are limited for three reasons. First, because these types of evaluations compare such different systems, the results of practical evaluations are not generalizable due to the high number of confounding variables (or confounds) between the systems. For instance, considering the practical evaluation by Arns et al., any one or combination of the differences between their CAVE system and desktop setup (e.g., stereoscopy, increased FOR, 6-DOF input) could have contributed to the better performance of the CAVE.
Second, again due to comparing such different systems, practical evaluations cannot indicate whether moderate levels of fidelity between the high-fidelity VR systems and low-fidelity computing systems would provide the same significant benefits as the high-fidelity VR systems. For example, in Gruchalla’s practical evaluation, it is theoretically possible that 3-DOF input could be significantly better than the low-fidelity mouse and keyboard while not being significantly different from the 6-DOF input used in the high-fidelity CAVE.

Third, because some practical evaluations involve complex applications and interdependent tasks, it is difficult to generalize the results of these evaluations for other applications or tasks. Reconsider the practical evaluation by Gruchalla. The complex well-path editing tasks involved the subtasks of navigating around, selecting, positioning, and rotating well paths. Hence, Gruchalla’s results cannot be properly generalized for another application task unless that task also involves the same set of subtasks.

### 1.2.2 Controlled Evaluations of Fidelity

Due to the limitations of practical evaluations, researchers have also begun exploring the effects of increasing fidelity by conducting controlled evaluations. Controlled evaluations of fidelity usually involve the direct comparison of similar systems or setups while controlling one or more components of fidelity to determine their effects and possible interactions. By comparing similar systems or setups, the number of confounds in controlled evaluations are reduced or even eliminated.

One type of controlled evaluation is a univariate evaluation, where a single component of fidelity is controlled to determine its effects. Researchers have conducted a number of univariate evaluations for different aspects of fidelity. One aspect has been the display fidelity component of stereoscopy. Ware and Mitchell evaluated the presence and absence of stereoscopy for discerning paths between nodes in 3D network graphs and found that stereoscopy improved response times. In addition to evaluating single components of display fidelity, researchers have also conducted univariate evaluations for aspects of interaction fidelity. For instance, Pausch et al. evaluated view control by comparing natural head tracking to a hand-based view-control technique. They found that the high-fidelity head tracking technique was faster than the low-fidelity hand-based technique when searching for non-present targets within a virtual room.

Another type of controlled evaluation is a multivariate evaluation in which two or more components of fidelity are controlled to determine their effects and possible interactions. For example, Scribner and Gombash evaluated both stereoscopy and field of view (FOV) for a teleoperated driving task. They found that stereoscopy reduced driving errors while FOV did not. They also found no significant interactions between the two display fidelity components.
Some multivariate evaluations have also examined aspects of both display fidelity and interaction fidelity. For instance, Narayan et al. evaluated stereoscopy and head tracking for completing a collaborative object manipulation task [28]. The researchers found that stereoscopy significantly reduced manipulation times and errors while head tracking did not, and they did not report any significant interactions between the two components.

Despite having better generality and fewer confounds than practical evaluations of fidelity, prior controlled evaluations have also had limitations. Technology has been one of those limitations. Prior evaluations involving HMDs (e.g., Pausch et al.) were usually limited by small fields of view and low display resolutions (total pixels) while many evaluations involving CAVEs (e.g., Narayan et al.) were limited by fields of regard smaller than 360 degrees and low spatial resolutions (pixels per inch). Similarly, several early evaluations involving 6-DOF tracking systems suffered from low positional accuracies, incorrectly reported orientations, and cumbersome wires connecting trackers and sensors [17].

### 1.2.3 Components of Fidelity

Consider the flow of information that occurs when a user interacts with a simulation. First, the user likely uses a piece of hardware as an input device to generate some type of data. That data is then interpreted by software as some meaningful effect, which the simulation decides how to handle based on the physics of the virtual world and the model data. Software then renders a view of the current state of the simulation, which is then displayed to the user through a hardware device. This information loop is shown in Figure 1.1.

Considering the user-simulation information loop, we associate the realism of the input devices and interpretation software with interaction fidelity. Similarly, we associate the verisimilitude of the rendering software and display devices with display fidelity. Between the two, we refer to the plausibility of the simulation and the associated model data as simulation fidelity, which we define as the objective degree of exactness with which real-world physics and characteristics are reproduced in a simulation. *(NOTE: Exploring simulation fidelity was beyond the practical scope of this research, so we are not considering it in this dissertation beyond defining it here.)*
The primary reason that researchers use controlled evaluations instead of practical comparisons is to identify the factors that cause significant differences. Many prior controlled evaluations have investigated factors or components of display fidelity, in particular visual display fidelity (i.e., the objective degree of exactness with which visual real-world sensory stimuli are produced by a display system). From these numerous controlled evaluations, a framework of visual display fidelity components has been defined in earlier work [4], including

- **stereoscopy** – the display of different images to each eye to provide an additional depth cue,
- **field of view (FOV)** – the size of the visual field (in degrees of visual angle) that can be viewed instantaneously by the user,
- **field of regard (FOR)** – the total size of the visual field (in degrees of visual angle) surrounding the user,
- **display resolution** – the total pixels displayed on the screen or surface,
- **display size** – the physical dimensions of the display screen or surface,
- **refresh rate** – how often the display draws provided rendered data, and
- **frame rate** – how often rendered data is provided to the display.

In addition to visual (sight) aspects, display fidelity also comprises auditory (hearing), haptic (touch), olfactory (smell), and gustatory (taste) aspects. Lists of components, similar to the above
list, could be compiled for these other aspects of display fidelity by examining prior controlled evaluations and by considering the rendering software and display devices that are used to present these sensory stimuli to the user. (*NOTE: Non-visual aspects of display fidelity are beyond the practical scope of this research, so from this point forward, we are referring to visual display fidelity when using the term “display fidelity”.*)

By considering interaction fidelity depends on the input devices and interpretation software, and reviewing prior controlled evaluations investigating interaction fidelity, a list of interaction fidelity components can be suggested. This list of components might include

- *positional accuracy* – how accurately an input device estimates a position,
- *rotational accuracy* – how accurately an input device estimates an orientation,
- *force accuracy* – how accurately an input device estimates an applied force,
- *form factor* – the shape of a held input device,
- *device location* – the location of the input device relative to the user,
- *button location* – the location of buttons on an input device,
- *refresh rate* – how often the input device reports surveyed data,
- *update rate* – how often surveyed data is interpreted by the system,
- *number of control dimensions* – how many DOF are interpreted,
- *integration of dimensions* – how the DOF are interpreted together, and
- *button mappings* – how button data is interpreted as commands.

Unlike the prior list of display fidelity components, we consider this list of components as a flawed approach to describing the level of interaction fidelity for two reasons. First, even though these components can be used to provide gesture-based interactions, they cannot properly describe the differences between two gestures. For example, in the game *Wii Sports*, the accelerometers within the Wii Remote [29] are used to provide the high-fidelity gesture of swinging a baseball bat, but because these sensors are only used to estimate the orientation and force applied to the Wii Remote, the low-fidelity gesture of flicking the wrist can be interpreted as a high-fidelity bat swing. Hence, different gestures may be indistinguishable if described using this list of components.

Second, for this list of interaction fidelity components, a higher level of an individual component does not necessarily equate to a higher level of fidelity, unlike the prior list of display fidelity components. For example, providing stereoscopy results in a higher level of display fidelity. Increasing FOV also results in a higher level of display fidelity. The same applies to the components of FOR, display size, display resolution, refresh rate, and frame rate. Now consider the list of interaction fidelity components. Increasing positional accuracy does not result in a higher level of interaction fidelity if the reproduced interaction is void of position changes (e.g. turning or orienting a stationary steering wheel). Similarly, when reproducing the interaction of swinging a tennis racket, if the proper location for a 6-DOF device is in the user’s hand,
attaching the device to the user’s elbow does not intuitively result in any higher level of fidelity than attaching the device to the user’s shoulder, despite being closer to the proper location.

Alternative lists of interaction components could be derived from the input device taxonomies developed by Card et al. [30] or Froehlich et al. [31]. Card et al. identified several control dimensions with their taxonomy by distinguishing the physical properties (position, movement, force, and delta force) of the linear axes (x, y, z) and the physical properties (angle, delta angle, torque, and delta torque) or the rotary axes (rX, rY, rZ) [30]. Similarly, Froehlich et al. identified multiple degrees of freedom that could be controlled using isotonic, elastic, or isometric sensors [31]. Like the prior list of interaction components, these taxonomies also suffer from the inability to address the differences between two gestures and increased components not yielding increased interaction fidelity.

As we have pointed out, there are difficulties with using a list of components to describe the level of fidelity for an interaction. Hence, for researchers to conduct controlled evaluations that can be generalized regardless of these inefficiencies, an alternative method for describing the fidelity of an interaction is necessary.

1.2.4 Contexts of Prior Research

Prior practical and controlled evaluations have explored the effects of fidelity in several different contexts, domains, and tasks. Considering just the examples we have already discussed, the results are spread across the contexts of wayfinding (Ruddle et al.), public speaking (Pertaub et al.), abstract data analysis (Arns et al.), geology (Gruchalla), network analysis (Ware and Mitchell), visual search (Pausch et al.), teleoperated driving (Scribner and Gombash), and collaborative object manipulation (Narayan et al.).

Due to significant differences between two contexts, prior researchers have sometimes arrived at seemingly contradictory results. For example, Pausch et al. determined that head tracking was a significant factor in predicting performance while Narayan et al. determined that it was not. Considering the contexts of the two experiments, this contradiction seems logical, as head tracking is probably more important for visual searches than collaborative object manipulation.

Hence, it is difficult to generalize the results of prior research on the effects of fidelity due to the numerous contexts, domains, and tasks that researchers have explored.

1.3 Research Questions

The problem statement above demonstrates the importance of further exploring the effects of increasing fidelity on the user experience. Considering the recent advances in display fidelity and interaction fidelity that consumers have experienced, we defined three research questions that we
addressed through the research presented in this dissertation, in hopes of providing a better understanding of the effects of display fidelity and interaction fidelity.

1. What are some of the significant effects of increasing display fidelity on the user experience?

Considering the numerous components of display fidelity that had been identified, we decided to focus on only two components in depth as opposed to broadly surveying several components. We chose to evaluate stereoscopy and FOR because we considered these the display fidelity components that distinguished most high-fidelity VR systems from low-fidelity systems in many of the prior practical evaluations of fidelity.

With regard to the user experience, we wanted to address limitations of some prior controlled evaluations by evaluating both objective and subjective metrics. For objective metrics, we were concerned with the effects of stereoscopy and FOR on user performance. For subjective metrics, we chose to investigate a wide range of measures, including preference, presence, engagement [32], and perceived usability.

We hypothesized that both stereoscopy and FOR would have positive significant effects on our objective and subjective metrics, based on prior practical [18, 19, 22] and controlled evaluations [24, 33].

2. What are some of the significant effects of increasing interaction fidelity on the user experience?

As mentioned in the problem statement, unlike display fidelity, the components of interaction are not suitable for describing the level of interaction fidelity. Hence, in order to answer this question, our research also had to explore interaction fidelity in general to define a better method for describing it. We did this by comparing high-fidelity interaction techniques to low-fidelity techniques and by investigating some mid-fidelity interaction techniques. These investigations led to the development of our Framework for Interaction Fidelity Analysis (FIFA), which is an initial attempt at a method for describing the level of interaction fidelity.

As with our first research question, we wanted to address the limitations of some prior controlled evaluations by considering both objective and subjective metrics. Again, we chose to focus on user performance, preference, presence, engagement, and perceived usability.

We hypothesized that increasing interaction fidelity would have positive significant effects on our objective and subjective metrics, based on prior practical [23, 34] and controlled evaluations [25, 35].
3. What are some of the significant interaction effects between the components of display fidelity and the components of interaction fidelity on the user experience?

Considering that most practical evaluations of fidelity compared systems that drastically differed in terms of display fidelity and interaction fidelity, we wanted to investigate if there were any significant interactions between our chosen display fidelity components (stereoscopy and FOR) and the various high, mid, and low-fidelity interaction techniques we would be evaluating. We accomplished this by using a multidimensional methodology, which we describe in section 1.4.1.

We hypothesized that increasing display fidelity and increasing interaction fidelity would result in the best user performances, preferences, presence, engagement, and perceived usability, based on prior practical and controlled evaluations [18, 23, 36].

1.4 Approach

The research presented in this dissertation was carried out using a multidimensional methodology for evaluating the effects of display fidelity and interaction fidelity together, which we describe in section 1.4.1. In order to address the previously mentioned issue of contradictory results due to contrasting contexts, we chose to apply this methodology to a single domain—video games—which we further discuss in section 1.4.2.

1.4.1 Methodology

Instead of using a three-step methodology for answering our three research questions (one step per research question), we chose to primarily use a one-step, multidimensional methodology that would simultaneously address all three questions.

The concept of our multidimensional methodology was to simultaneously evaluate display fidelity and interaction fidelity by controlling each independently at differing levels. By independently controlling display fidelity, this methodology addressed our first research question. By independently controlling interaction fidelity, this methodology also addressed our second research question. Finally, by independently controlling both at the same time, it also addressed our third research question.

Early in our research, our objective was to determine if the level of fidelity, for each aspect, had a significant effect on the user experience. To accomplish this objective, we used our methodology to investigate extremely high and low levels of display fidelity and interaction fidelity. Over the course of our first three studies, we found that both the level of display fidelity and the level of interaction fidelity had significant effects on the user experience, particularly
performance. In our third study, we also found that there were significant interaction effects between the two aspects of fidelity.

Later in our research, our objective was to determine if moderate levels of fidelity were significantly different from high and low levels of fidelity. To accomplish this objective, we used our methodology to investigate high, low, and mid levels of display fidelity and interaction fidelity. From our fourth and fifth studies, we found there were significant differences among the levels for display fidelity and interaction fidelity. We also found that the level of display fidelity had a positive linear effect on user performance while the level of interaction fidelity had a nonlinear effect on performance, similar to Mori’s uncanny valley theory [37].

Finally, to fully address our second research question, we developed the Framework for Interaction Fidelity Analysis (FIFA) as an initial attempt at a better method for describing levels of interaction fidelity. We developed this framework based on our own experiences and the observations and results of our five studies.

1.4.2 Context of Experiments

As previously mentioned, researchers have arrived at seemingly contradictory results likely due to significant differences between their contexts or domains of study. Therefore, it has been difficult to generalize research results not from a single domain. To avoid this issue, we chose to focus only on the domain of videogames for the context of our research approach.

Videogames have a history of being used as research tools to study phenomena such as factual learning [38], skill development [39], aggressive behavior [40], and cultural awareness [41]. One of the earliest examples was the use of Atari’s Army Battlezone as a tactical trainer for the United States Army [42]. In recent years, videogames have been used as cheap, fast, effective, and universal tools for research and other non-entertainment purposes [43]. For example, Larssen et al. used Beat Freak and Kung Foo, two Eyetoy games for the Playstation 2, to investigate aspects of interaction fidelity [44].

One of the primary reasons we chose videogames as the context of our approach was due to their performance-intensive nature. Many videogames require complex interactions, such as racing around a course while avoiding obstacles and other drivers. These types of complex interactions are performance intensive and require increased levels of spatial understanding, awareness, and information processing to be successful. Hence, we expected our videogame context would provide greater potential for significant differences in user performance, for both display fidelity and interaction fidelity.

Another reason we chose videogames was due to their ability to elicit strong subjective responses. The most obvious response they tend to elicit is enjoyment, which is necessary to
keep players playing [45]. In addition to enjoyment, videogames have been shown to elicit engagement, which is the sense of being engrossed [32]. Videogames have also been shown to evoke higher senses of presence [46].

We also chose videogames due to the range of potential interaction tasks involved with such contexts. According to Bowman et al. [47], there are a number of potential interaction tasks including:

- **selection** – indicating an object to manipulate or modify,
- **manipulation** – changing the position and/or orientation of an object,
- **exploration** – moving to learn or inspect unknown objects or locations,
- **searching** – moving to see or reach a known object or location,
- **maneuvering** – moving with small and precise motions,
- **steering** – the continuous control of movement,
- **wayfinding** – the cognitive process of choosing a path of movement,
- **system control** – the issuing of abstract commands to the system, and
- **symbolic input** – the communication of symbolic information to the system.

Through five studies, we were able to evaluate the effects of display fidelity and interaction fidelity on several of these tasks. In our first study, we used a simple game that consisted of selecting and manipulating twenty 3D objects to match corresponding targets as quickly as possible. In our second study, we chose to use Mario Kart Wii, a commercial racing game for the Nintendo Wii that involved steering. For our last three studies, we focused on the context of a custom first-person shooter (FPS) game to strengthen the consistency of our results and to investigate the tasks of selection (aiming and firing), exploration, searching, and maneuvering.

**1.5 Contributions**

We can frame the contributions of this research into four main categories, related to the problem statement presented in section 1.1.

**Effects of Display Fidelity**

1. We have determined that stereoscopy had no significant effect in our studies, but we have attributed this finding to our games not requiring interactions close to the body.
2. We have demonstrated that increasing FOR had a positive effect on user performance, particularly for tasks involving visual search.
3. We have shown that increasing display fidelity can cause positive increases in presence, engagement, and perceived usability.
4. We have observed that the level of display fidelity can influence user strategy.
Effects of Interaction Fidelity

1. We have demonstrated that extremely high levels of overall interaction fidelity provide better user performance than lower levels.

2. We have determined that moderate levels of overall interaction fidelity do not improve user performance and can actually cause decreases in performance.

3. We have provided evidence that the level of control symmetry is a strong indicator to the level of user performance an interaction technique will provide.

4. We have shown that increasing interaction fidelity can cause positive increases in enjoyment, presence, engagement, and perceived usability.

5. We have observed that the level of interaction fidelity can influence user strategy.

6. We have determined that device form factor had no significant effect on user performance in our studies.

Interaction Effects Between Display and Interaction Fidelity

1. We have determined that matching levels of display and interaction fidelity provide better user performances than mixed levels.

2. We have shown that increasing display fidelity and interaction fidelity together will cause the greatest positive increases in presence, engagement, and perceived usability.

3. We have demonstrated that increasing FOR affords more physical turning, thereby increasing interaction fidelity.

Broader Contributions

1. We have developed the Framework for Interaction Fidelity Analysis (FIFA), which provides a method for describing the level of interaction fidelity for a particular interaction technique.

2. We demonstrated that the level of display fidelity often has positive effects on user performance.

3. We provided evidence that the level of control symmetry appears to have positive effects on user performance.

4. We demonstrated that the level of familiarity appears to have positive effects on user performances.
1.6 Dissertation Roadmap

Before discussing our studies, we present a review of the literature pertaining to the effects of fidelity in chapter 2. In chapter 3, we discuss our first study, which used a simple manipulation game to address the effects of fidelity on object manipulation tasks. In chapter 4, we present our second study, which used *Mario Kart Wii* to evaluate steering techniques with different levels of interaction fidelity. In chapter 5, we review the experimental design of our third study, which used a custom FPS game to evaluated extremely high and low levels of both display and interaction fidelity. In chapter 6, we discuss our fourth and fifth studies, which focused on evaluating the effects of FOR and interaction fidelity for the subtasks of our FPS game. In chapter 7, we discuss the Framework for Interaction Fidelity Analysis (FIFA), which we designed based on our review of the literature and the results of our own studies. Finally, we summarize our conclusions and discuss potential future research in chapter 8.
2 LITERATURE REVIEW

2.1 Overview

In this chapter, we provide an extensive (but not exhaustive) review of the literature that pertains to evaluating the effects of visual display fidelity and interaction fidelity. First, we summarize several practical evaluations that compare high-fidelity systems to low-fidelity counterparts (e.g., HMD vs. desktop), high-fidelity systems to other high-fidelity systems (e.g., HMD vs. CAVE), and high-fidelity systems to actual reality (e.g., HMD vs. the real world). Second, we discuss controlled evaluations of display fidelity in regard to the visual display components discussed in chapter one. We then review and categorize controlled evaluations of interaction fidelity by studies involving view control, travel, object manipulation, form factor, and lag. Finally, we discuss the limitations of prior research on the effects of fidelity and explain how our research addresses some of those limitations.

2.2 Practical Evaluations of Fidelity

As mentioned in chapter one, practical evaluations of fidelity normally involve the direct comparison of systems that drastically differ in their level of fidelity, to empirically demonstrate that a high-fidelity system is significantly different from a low-fidelity system for a particular task or experience [4]. In addition to the common approach of comparing a high-fidelity VR system to a low-fidelity desktop system, some researchers have also compared high-fidelity VR systems to each other. Furthermore, a few researchers have compared high-fidelity VR systems to the highest fidelity system (i.e., the real world).

2.2.1 High Fidelity vs. Low Fidelity

The most common approach to conducting a practical evaluation is to compare a high-fidelity VR system to a low-fidelity desktop counterpart. Several researchers have conducted such experiments to determine the effects of fidelity on user performance for tasks that heavily rely on travel (i.e., the “motor component of navigation” [47]). Ruddle et al. compared a head-tracked HMD to a standard desktop computer with a monitor, mouse, and keyboard for navigating large-scale VEs [18]. They found that users were faster at wayfinding and could better estimate distances to other locations with the high-fidelity HMD. Datey conducted a similar experiment for moving around a virtual submarine to identify “radioactive sources” [48]. He found users required less time and committed fewer errors using a high-fidelity HMD, as opposed to a low-fidelity desktop system.
Instead of an HMD, Gruchalla compared a four-sided CAVE to a stereoscopic desktop setup for navigating to and editing well paths, and determined that the high-fidelity CAVE was faster than the low-fidelity desktop [23]. Bayyari and Tudoreanu compared a three-sided CAVE to a desktop computer for navigating a large-scale VE to identify and find virtual pebbles [49]. They found the CAVE provided better user performance than the low-fidelity desktop.

Considering the diversity of tasks involved with these practical evaluations, the common task factor is their heavy dependency on travel. Hence, it appears that high-fidelity VR systems tend to provide better user performance for completing travel-dependent tasks when compared to low-fidelity counterparts. Of course, not all high-fidelity systems will provide better performance for such tasks. For example, Swindells et al. found no significant differences among a four-sided CAVE, a three-screen wall, and a low-fidelity desktop for a navigation-based search task [50].

Researchers have also conducted practical evaluations to determine the effects of high fidelity on perception-based tasks. For instance, Arns et al. compared a four-sided CAVE to a low-fidelity desktop for analyzing statistical data in three dimensions [22]. They found that the high-fidelity CAVE was better for identifying clusters of data and radial sparseness than the low-fidelity desktop. Similarly, Schuchardt and Bowman found that a high-fidelity, four-sided CAVE was better for identifying features of an underground structure than a lower-fidelity, single-screen wall that lacked head tracking and stereoscopic graphics [51]. Using an HMD, Dixon et al. had users judge the heights of objects within a VE, and determined that the HMD afforded the ability to make better judgments than a low-fidelity desktop computer [52]. Similarly, Heineken and Schulte had users judge the sizes and weights of cylinders viewed in a VE, and found that a head-tracked HMD provided for better judgments than two low-fidelity desktop conditions [53]. Overall, these evaluations indicate that high-fidelity VR systems likely afford better spatial understanding [4] than low-fidelity systems.

Memory recall is another type of task for which researchers have investigated the effects of increased fidelity. Slater et al. compared an HMD to a low-fidelity, monitor-based system for the task of remembering which pieces of a 3D chess set were moved and where those pieces were moved [54]. They found the high-fidelity HMD afforded users the best memory recall. Contrastingly, Mania et al. conducted a similar evaluation but found no significant differences between the high-fidelity HMD and the low-fidelity desktop for recalling the positions and shapes of objects within a VE [55]. Based on the limited research, it is unclear if high-fidelity systems afford better memory recall than low-fidelity ones.

In addition to objective tasks, researchers have also compared high-fidelity systems to traditional desktops with concern for changes in subjective responses, in particular presence. Pertaub et al. evaluated the effects of using an HMD on speaker confidence while giving a presentation to a virtual audience and determined that the HMD caused larger decreases in speaker confidence than the desktop, indicating the HMD likely increased the users’ sense of presence [19]. In the
previously mentioned 3D chess study [54], Slater et al. also found that the high-fidelity HMD provided an increased sense of presence. Interestingly, Mania et al. found no effects of high fidelity on presence in their memory recall study [55], indicating that presence may not affect memory recall. Together, these studies demonstrate that high-fidelity systems can create greater senses of presence than low-fidelity systems, but not always.

Using practical evaluations, researchers have demonstrated that there are some significant benefits to using high-fidelity systems compared to low-fidelity counterparts. Considering prior research, high-fidelity systems appear to provide better user performance for travel-dependent tasks and tasks that require spatial understanding. High-fidelity systems may also provide better memory recall and more presence than low-fidelity desktops, but more research is necessary to verify this. Due to the high number of confounds between high-fidelity systems and low-fidelity systems, including aspects of display fidelity and interaction fidelity, these results are not generalizable beyond high-display, high-interaction systems.

2.2.2 High Fidelity vs. High Fidelity

In addition to practical evaluations involving high-fidelity and low-fidelity systems, some researchers have also compared high-fidelity systems to other high-fidelity systems. A few researchers have conducted experiments to determine the differences between HMDs and CAVEs. Bowman et al. used a head-tracked HMD and a four-sided CAVE to determine what type of turning technique (physical or virtual) users preferred [56]. They determined users preferred physically turning in the HMD and virtually turning in the CAVE, which was expected due to the CAVE’s lower FOR. Manek compared an HMD to a four-sided CAVE for an architecture program and found that the HMD was better for selecting objects and moving selected objects from a front position to a back position [57]. Again, this result was expected due to the CAVE’s lower FOR. In another study, Juan and Pérez determined that a four-sided CAVE provided an increased sense of presence and an increased sense of anxiety compared to an HMD [58].

In these practical evaluations comparing HMDs and CAVEs, the primary differences between the systems were components of display fidelity, such as FOV, FOR, display resolution, and brightness. Of these, considering the results of these evaluations, it appears that FOR is the most significant factor. Most CAVEs lack a display screen on one or more of the sides of the cube, which results in a non-360-degree FOR, whereas all head-tracked HMD setups offer a full 360-degree FOR. This lower FOR in turn likely affects how users interact, which explains several of the results presented here.

Another high fidelity vs. high fidelity comparison researchers have investigated involves comparing a CAVE to a “Fish Tank VR” display. Fish Tank VR refers to a display in which the
virtual environment is viewed on a computer monitor using head tracking. The environment can also be viewed monocularly, coupled to a single eye position, or binocularly [59]. Schulze and Forsberg compared a four-sided CAVE to a Fish Tank VR display for placing 3D markers on nodes in a data visualization application, and found that users performed better with the CAVE version and preferred the CAVE to the Fish Tank VR [60]. On the other hand, in a similar study involving 3D marking, Schulze et al. found no significant differences between the CAVE and Fish Tank VR when the data nodes were the same initial size [61]. Interestingly, for a search task concerning protruding surfaces on a handheld object, Demiralp et al. found that users completed the search task faster and with fewer errors when using a Fish Tank VR display as opposed to a four-sided CAVE [62].

In all three of these evaluations, interaction fidelity was held constant between the CAVE and Fish Tank VR setups. Therefore, the results of these comparisons are likely due to display fidelity components, such as FOV, FOR, display resolution, and brightness (like the prior comparisons of HMDs and CAVEs). Unlike the HMD vs. CAVE evaluations, it is not clear which of these components is the likely significant factor causing the differences.

### 2.2.3 High Fidelity vs. True Fidelity

The final type of practical evaluation of fidelity that we have reviewed involves comparing high-fidelity VR systems to the real world, which we call “true fidelity” to convey that reality is the highest level of fidelity possible. In their research for judging the sizes and weights of cylinders [53], Heineken and Schulte also compared their head-tracked HMD to a real world condition. They found no significant differences between the two conditions. In their memory recall research [55], Mania et al. also compared their high-fidelity HMD to a real world condition. They also found no significant differences between high fidelity and true fidelity. Whitton et al. compared walking through a real maze to walking through a virtual maze using a head-tracked HMD, and also found no significant differences between high fidelity and true fidelity [63]. Contrastingly, Ware and Rose compared rotating wooden handles in a VE to the real world, and found that users performed the orientation-matching task significantly faster in the real world than with their high-fidelity Fish Tank VR [64].

Though the study by Ware and Rose demonstrates that VR systems still have room to improve in terms of fidelity, the first two comparisons have demonstrated that high-fidelity systems can be comparable to the real world. While the VR community’s long-term goal to create the “ultimate display” [14] is still unattainable due to current technology, high-fidelity systems can be effectively used to reproduce real world experiences [4]. This helps to explain how VR has been used successfully for phobia therapy [65] and military training [66].
2.3 Controlled Evaluations of Visual Display Fidelity

In chapter one, we discussed how researchers have also conducted controlled studies of fidelity to overcome the confounded nature of practical evaluations. Controlled evaluations normally involve the direct comparison of similar systems or setups while controlling one or more aspects of fidelity to determine their effects and possible interactions [4]. By comparing similar systems or setups, the number of confounds in controlled evaluations are reduced or even eliminated. In this section, we discuss controlled evaluations of visual display fidelity in terms of stereoscopy, FOV, FOR, display resolution, display size, and frame rate.

2.3.1 Stereoscopy

Stereoscopy is the display of different images to each eye to provide an additional depth cue that is interpreted by the brain [4]. Many researchers have investigated the effects of stereoscopy on various aspects of the user experience. Spatial understanding has been the most predominant of those aspects. Yeh and Silverstein evaluated the introduction of stereoscopy for judging depths and altitudes of virtual objects and determined that stereoscopy improved judgments, especially when monocular depth cues were less effective [67]. Ware and Franck determined that stereoscopy significantly reduced the amount of time necessary to determine the number of links between two nodes in a graph [68]. Ware and Mitchell further confirmed this result with their reevaluation of the prior study [24]. Arthur et al. found a similar effect of stereoscopy for a graph-tracing task involving trees of nodes (instead of complex networks of nodes) [69]. In a different type of study, Narayan et al. found a significant effect of stereoscopy for a high-precision 3D manipulation task, which required spatial understanding to succeed [28]. Together, these studies indicate the stereoscopy is an effective component of visual display fidelity when spatial understanding is essential to the task at hand.

In contrast to the prior studies, some researchers have determined that stereoscopy does not improve performance for other types of tasks. Barfield et al. had users select a 2D representation of a 3D wire viewed with and without stereoscopy [70]. The researchers found no significant effect of stereoscopy, but did observe that the task was difficult for all participants to complete. In another study, Raja did not find a significant effect of stereoscopy for search tasks when viewing scatterplots or surface-plot data [36]. Similarly, Mania et al. also did not find a significant effect of stereoscopy for a memory task that involved the recall of positions and shapes of objects in a virtual room [55]. These controlled evaluations appear to show that stereoscopy is not necessary for all tasks that rely on spatial understanding skills, particularly when the virtual objects are farther away from the user.

In addition to user performance studies, researchers have also evaluated the subjective effects of stereoscopy. In the study just mentioned [70], Barfield et al. found that the introduction of
stereoscopy increased presence even though it did not increase user performance. Freeman et al. evaluated the subjective effects of stereoscopy when viewing visual stimuli and found that stereoscopy increased presence and users’ subjective ratings of involvement with the virtual scene, though stereoscopy did not increase users’ sense of vection [71]. In a similar study, IJsselsteijn et al. found that stereoscopy increased presence but not involvement, vection, or even simulator sickness [33]. Based on these studies, it appears that stereoscopy is closely linked to the subjective feeling of “being there” for a VR system.

2.3.2 Field of View (FOV)

The term “field of view” (FOV) is used to refer to “the size of the visual field (in degrees of visual angle) that can be viewed instantaneously” [4]. The term “physical field of view” (PFOV) has been used to refer to the physical visual field (i.e., the portion of the user’s view that the display occupies) [72]. Some researchers have also investigated the “software field of view” (SFOV), which refers to the virtual visual field (i.e., the portion of the virtual environment displayed) [73]. In most VR systems, the PFOV and SFOV are kept the same in order to provide a view of the virtual environment that is correctly sized with respect to the user’s head position, which results in increased fidelity. Because of this, we will use the term “field of view” as an encompassing term that reflects a match between the PFOV and the SFOV. Otherwise, we qualify the term to be explicit about which visual field we are discussing.

Several researchers have conducted controlled experiments to determine the effects of FOV on search tasks. Arthur evaluated FOV in an HMD at 48, 112, and 176 degrees for finding objects outside of the FOV and determined that increasing FOV afforded faster search times [74]. Using single-screen displays, Ni et al. evaluated FOV for finding objects based on perceptual or abstract qualities in an information-rich VE, and determined that 90-degree FOV allowed users to search faster than a 42.8-degree FOV [72]. Using their Peripheral Lenses setup, Robertson et al. also evaluated FOV and determined that a wider FOV improved search times (though this result was not statistically significant) [75]. Using a large tiled configuration of nine monitors (arranged three by three), Ball and North evaluated FOV by comparing nine monitors, four monitors (two by two), and one monitor for two search tasks [76]. They found that the nine-monitor configuration was the best when searching for small targets and that the single monitor was the worst when searching for medium targets to compare. Considering these controlled evaluations of FOV, it appears that searching can be significantly improved by increasing FOV by a large degree.

In addition to evaluating FOV, researchers have also evaluated the effects of PFOV and SFOV on searching. In a second study, Robertson et al. compared their Peripheral Lenses setup to a smaller-PFOV monitor while maintaining the same SFOV [75]. They determined that the larger PFOV significantly increased search times for users compared to the smaller PFOV. In a
different study using a large tiled display configuration, Polys et al. determined that increasing PFOV had no significant effect on searching while increasing SFOV decreased search times [73]. These results indicate that it advantageous to provide a SFOV larger than the PFOV of the display for search tasks because more of the virtual environment is rendered. On the other hand, Polys et al. did determine that an increased SFOV decreases spatial understanding capabilities due to fish-eye distortion [77]. Regardless, as previously mentioned, a mismatch between the SFOV and PFOV will result in a lower level of display fidelity.

In addition to searching, the effects of FOV have been evaluated for a number of other tasks. Using an HMD, Arthur compared 48, 112, and 176 degrees of FOV for avoiding obstacles while walking, estimating distances, and recalling spatial characteristics [74]. He found that increasing FOV allowed users to walk around more efficiently, but found no significant effects of FOV on estimating distances (spatial understanding) or recalling characteristics of the environment (memory recall). Similarly, Dixon et al. evaluated FOV in an HMD and determined it had no effect on the judgment of object sizes (spatial understanding) [52]. Based on these limited results, it appears that FOV most significantly affects tasks that require a large, instantaneous bandwidth of information about the scene, such as searching or navigating tight spaces.

The effects of FOV have been evaluated for another type of objective measure: postural stability. In his research, Arthur found no significant effect of FOV on users’ balance after using an HMD [74]. Concerned with in-session postural stability, Duh et al. determined that increasing FOV caused users to exhibit more dispersion when using a rear-projected display [78]. Hence, FOV may have in-session effects on a user’s balance but probably not after the VR experience.

The effects of FOV on the sense of presence have also been evaluated. In the same HMD studies already mentioned, Arthur also evaluated the effects of wider FOV on users’ sense of presence and simulator sickness [74]. Interestingly, he found no significant effects on either subjective response, even in the 48-degree FOV conditions. Contrastingly, IJsselsteijn et al. evaluated PFOV by controlling a user’s distance from a projection screen without changing the SFOV, and found that increasing PFOV (by standing closer to the screen) resulted in higher presence and subjective vection ratings for moving stimuli [33]. These contradictory results could be due to a number of differences in the studies: display type, environment type, distorted SFOV, lack of interaction, etc.

### 2.3.3 Field of Regard (FOR)

The term “field of regard” (FOR) has been used to refer to “the total size of the visual field (in degrees of visual angle) surrounding the user” [4]. Obviously, FOR and FOV are highly related. A single-screen display with a 90-degree FOV also has a 90-degree FOR. Viewed through CrystalEyes glasses, a two-wall CAVE provides approximately a 120-degree horizontal FOV but
a larger 180-degree horizontal FOR. A Virtual Research V8 display provides a 48-degree horizontal FOV but with head tracking offers a 360-degree horizontal FOR. Due to the close relation between FOR and FOV, it can be difficult to differentiate between a study evaluating FOV and a study evaluating FOR. To address this, if a study evaluates a visual field angle larger than the user’s own perceptive capabilities (approximately 180 degrees) or larger than the visual field afforded by a restrictive component (such as stereoscopic glasses), then we consider the study to evaluate FOR and not FOV, since the user must turn in order to view the entire visual field. In this section, we discuss such studies.

Some researchers have conducted controlled evaluations of FOR to determine its effect on user performance. Raja used a four-sided CAVE (three walls and a floor) to evaluate FOR in two conditions: one wall (90-degree horizontal FOR and vertical FOR) and four sides (270-degree HFOR and 180-degree VFOR) [36]. In his studies, Raja determined that increasing FOR allowed users to search faster and more quickly identify trends in scatter and surface data plots though it did not help with more complicated tasks such as interpretive analysis. Similarly, Bayyari and Tudoreanu used a three-sided CAVE (two walls and a floor) to evaluate FOR in three conditions: one wall (90-degree HFOR and VFOR), one wall and floor (90-degree HFOR and 180-degree VFOR), and all three sides (180-degree HFOR and VFOR) [49]. (Note: Their participants wore stereoscopic glasses and the human VFOV is smaller than 180 degrees; therefore, this was a FOR study and not a FOV study). Bayyari and Tudoreanu found that users were able to navigate to find virtual pebbles significantly faster with the three-sided condition than the lower-FOR conditions, which indicates that horizontal FOR may be more important than vertical FOR for natural VEs (i.e., VEs with a “ground”).

Other researchers have investigated the effects of FOR but not found any significant effects. Swan et al. [79] used a four-sided CAVE (three walls and a floor) to evaluate the same conditions of FOR that Raja did above. For navigating a battlefield visualization, the researchers did not find a significant difference between the two conditions and even observed slightly worse user performance with the higher-FOR condition. In another study, Schulze et al. evaluated the same conditions as Raja and Swan et al., and found no significant effects of FOR on placing 3D markers in a data visualization application [61]. Considering the results of these studies, we speculate that FOR, like FOV, is most relevant for tasks requiring large, instantaneous bandwidths of information.

Aside from user performance, research has also been conducted on the effects of FOR on subjective responses. Lin et al. used a three-screen driving simulator to control HFOR at four levels (60, 100, 140, and 180 degrees viewed with stereoscopic glasses) and determine its effect on presence, enjoyment, and simulator sickness [80]. They determined that users reported higher presence, enjoyment, and simulator sickness scores with increasing FOR. This research indicates that FOR is an important factor for creating a subjectively realistic experience.
2.3.4 Display Resolution

Another component of visual display fidelity that has been investigated is display resolution—the total pixels displayed on a screen or surface [72]. In an early VR study, Watson et al. evaluated display resolution in an HMD at three levels (64 x 48, 192 x 144, and 320 x 240 pixels) for a simple search task [81]. They determined that the lowest resolution was significantly worse than the higher two resolutions for both search time and accuracy. In a more recent study, Ni et al. evaluated display resolution at two levels (1280 x 720 and 2560 x 1440 pixels) for searching an information-rich VE [72]. They found that the high resolution was significantly better than the low resolution for search times. Demiralp et al. evaluated display resolution by comparing a high-resolution Fish Tank VR (1280 x1024 pixels) to a lower-resolution Fish Tank VR (1024 x 768 pixels) for finding a surface extrusion on a handheld object, but did not find any significant differences for search times or errors [62]. Considering these studies on display resolution, it appears that large discrepancies in resolution can result in significantly different user performances, while smaller resolution differences may not.

2.3.5 Display Size

Many researchers have evaluated the effects of “display size” or “screen size,” but in many cases, they have actually evaluated the effects of FOV (e.g., Ni et al. [72], Ball and North [76]) or PFOV (e.g., Polys et al. [73], IJsselsteijn et al. [33]). There have been a small number of studies that have actually evaluated the effects of display size by controlling FOV. Tan et al. evaluated display size by controlling the FOV, display resolution, brightness, and contrast of two displays located at different distances from the user [82]. They determined that the larger display (76 in. x 57 in.) afforded better user performance for a spatial orientation task and greater presence than the smaller display (14 in. x 10.5 in.). In another study, Tan et al. evaluated the same displays for a path integration task, and again determined that the larger display provided better user performance [83]. In a more ecologically valid study, Tan et al. evaluated the same displays again, and determined the large display allowed users to take shorter paths for finding targets in a realistic VE [84]. Based on these results, better user performance and greater presence is provided by increasing the size of the display (even without changing FOV, PFOV, or display resolution).

2.3.6 Frame Rate

Frame rate (or update rate) is the number of times per second that an image or scene is changed [69]. A number of researchers have investigated the effects of frame rate. Ware and Balakrishnan investigated frame rates of 60 Hz, 15 Hz, 10 Hz, 5 Hz, 3 Hz, 2 Hz, and 1 Hz for a Fitts’ Law style task and found that low frame rates cause degradation of user performance [85]. In a similar study, Arthur et al. [69] investigated frame rates of 30 Hz, 15 Hz, and 10 Hz for a graph-tracing
task, but deduced that frame rates did not affect user performance as much as lag (i.e., the time it takes to survey input and interpret it [85]). In a study examining presence in stressful VEs, Meehan et al. evaluated frame rate at 30 Hz, 20 Hz, 15 Hz, and 10 Hz [16]. They determined that presence significantly increased from 15 Hz to 20 Hz, with a similar trend from 20 Hz to 30 Hz. Interestingly, they found 10 Hz gave anomalous results, which they believe were due to the low frame rate creating discomfort in an already stressful environment. Given the results of these controlled evaluations, low frame rates (15 Hz or less) appear to have negative effects on user performance while higher frame rates result in a greater sense of presence.

### 2.3.7 Summary of Visual Display Fidelity Effects

In summary, many of the components of visual display fidelity have been shown to have significant effects on aspects of the user experience. Stereoscopy has been shown to positively effect user performance for tasks that rely heavily on spatial understanding, like graph tracing, while also providing a greater sense of presence. Increasing FOV has been demonstrated to improve user performance for tasks that benefit from large information bandwidths, such as searching and high-precision navigation. Similarly, wider FOR appear to also benefit large information bandwidth tasks, and positively impact presence. For display resolution, researchers have shown that large increases can result in faster search times. Larger display sizes (with the same FOV, display resolution, color brightness, and contrast) appear to benefit simple spatial orientation tasks and navigation while providing increased presence. Low frame rates (15 Hz and less) have been shown to result in poor user performances while increasing frame rates (above 15 Hz) appear to increase users’ sense of presence.

### 2.4 Controlled Evaluations of Interaction Fidelity

In this section, we review a number of controlled evaluations that involve comparing high-fidelity interactions to lower-fidelity counterparts while maintaining the same or similar display systems. We categorize these studies by those that involve view control, travel, object manipulation, form factor, and lag.

#### 2.4.1 View Control

We use the term “view control” to refer to the task of changing one’s view of their immediate surroundings without traveling to a new location. Many researchers have investigated view control by evaluating the effects of head tracking, which is the calculation of a viewing transformation based on the position of the user’s head [69]. Ware et al. evaluated head tracking for tracing a tree of nodes and determined that the presence of head tracking significantly improved completion times and accuracy compared to no head tracking [59]. Similarly, Ware and Franck found that the presence of head tracking significantly improved user performance for
tracing a graph of nodes [68]. Barfield et al. also found head tracking improved user performance for viewing a 3D wire and selecting a 2D representation of the wire [70]. In a perceptual study, Heineken and Schulte found that the presence of head tracking improved user judgments of the sizes and weights of cylinders viewed in a VE [53].

Some researchers have found that the introduction of head tracking does not improve user performance. Raja determined that head tracking had no significant effect for analyzing data in scatterplots and surface-plots (though users were also permitted to travel) [36]. Similarly, Narayan et al. found that the presence of head tracking had no significant effect for an object manipulation task requiring high precision [28]. Considering these results and the prior studies involving head tracking, it appears that head tracking has a significant effect on user performance for tasks that are dependent on spatial understanding, especially when travel is not available.

In addition to the presence and absence of head tracking, researchers have also compared head tracking and other lower-fidelity view control techniques. Pausch et al. compared head tracking to another 6-DOF, hand-based technique [25]. They found that the high-fidelity head tracking was faster than the low-fidelity hand-based technique when searching for non-present targets within a virtual room. Ware and Franck also compared head tracking to a 6-DOF, hand-based technique, but found no significant differences between the two techniques for a graph-tracing task [68]. Similarly, Mania et al. found no significant differences between head tracking and a mouse-based technique for a memory recall task [55]. In another type of view control study, Barfield et al. compared a 6-DOF, hand-based technique to a mouse-based technique and found no significant differences between them when searching for targets within a virtual room [70]. Compared to lower-fidelity view control techniques, head tracking may be most useful for tasks that require processing all of the available information before completion (e.g., Pausch et al.).

2.4.2 Travel

As mentioned, travel is the “motor component of navigation” [47], which involves moving from one location within the VE to a different location. There have been a number of controlled studies of the effects of interaction fidelity on travel. Chance et al. compared real walking, gaze-based steering, and joystick-based steering for navigating to locations within a virtual maze [86]. They determined that the high-fidelity walking technique was significantly better than the low-fidelity joystick technique. In a similar study, Usoh et al. compared real walking, walking in place, and gaze-based flying, and found that real walking afforded the greatest sense of presence with gaze-based flying providing the least [87]. Chung also compared real walking to a number of lower-fidelity techniques for a radiotherapy treatment planning application, but found it performed worse than an “Orbital” technique that leveraged head rotations to move around the tumor [88]. For travel tasks in general, it appears that real walking (the highest fidelity technique
for travel) is better than lower-fidelity travel techniques (though task-specific travel techniques can obviously outperform real walking, as was the case in Chung’s study).

In addition to real walking, researchers have also compared lower-fidelity travel techniques to other lower-fidelity techniques. Bowman et al. compared gaze-based steering to hand-based steering (pointing) and determined that pointing was more accurate for relative motion tasks than gaze-based steering [89]. For gesture-based travel techniques, Swan et al. compared a position-to-position transfer function to a position-to-velocity function, and found a significant interaction between the function and stereoscopy [79]. The position-to-position function with stereoscopic graphics and the position-to-velocity function without stereoscopy performed the best.

2.4.3 Manipulation

Manipulation tasks normally involve the selection, rotation, and/or positioning of objects in 3D space [47]. There are two major input characteristics that dictate how users manipulate objects—how control dimensions (DOF) are provided and how transfer functions interpret input data. Regarding control dimensions, Hinckley et al. compared two 3-DOF devices to two mouse-based techniques for rotating virtual objects, and found that the 3-DOF devices were significantly faster to use than the mouse-based techniques [90]. Balakrishnan et al. conducted a similar study by comparing a mouse-based technique to the “Rockin’Mouse”, which provided two extra DOF by tilting its curved base [91]. For positioning an object in 3D space, they found that the Rockin’Mouse technique was significantly faster than using a standard mouse. These two studies indicate that increasing the number of control dimensions that can be controlled simultaneously should result in increased user performance for tasks involving more than two DOF.

In addition to control dimensions, researchers have also investigated the effects of various transfer functions. Poupyrev et al. compared the virtual hand technique, which used a linear transfer function, to their Go-Go technique, which used a non-linear function, and determined that the virtual hand technique was faster for manipulating local objects than Go-Go [92]. Ware and Rose also evaluated the virtual hand technique by comparing it to a virtual hand technique with an offset of 60cm [64]. They determined that the non-offset virtual hand provided faster rotations than the lower-fidelity offset technique. In a similar study, Mine et al. compared the virtual hand technique to several offset versions (ranging from 10cm to 60cm), and also determined that any offset decreased user performance for 6-DOF manipulations [93]. These studies demonstrate that one-to-one positional mappings tend to provide better user performance than other types of control ratios.

In addition to control ratios, how transfer functions interpret input properties have also been evaluated. Zhai evaluated four types of transfer functions for object manipulations: isotonic position (position-to-position), isotonic rate (position-to-velocity), isometric position (force-to-
position), and isometric rate (force-to-velocity) [94]. He determined that the isotonic position and isometric rate techniques were the best for 6-DOF manipulations. Similarly, Zhai and Milgram compared the isometric rate function (force-to-velocity) to an elastic rate function (position-and-force-to-velocity) [95]. They concluded the elastic rate function was better than the isometric rate function. These controlled evaluations indicate that the type of property measured (by an input device) and how it is interpreted (by the transfer function) will affect user performance.

2.4.4 Form Factor

In addition to evaluating the effects of interaction fidelity for view control, travel, and manipulation tasks, researchers have also investigated the effects of form factor. Form factor is the “shape and size” of the input device used [96]. Zhai et al. evaluated form factor by comparing a 6-DOF ball-shaped device to a glove with a 6-DOF tracker located in the palm [97]. For 3D object manipulations, they determined that the ball-shaped device afforded faster manipulations than the glove, and concluded this result was due to the ability to use the fingers to control the 6-DOF tracking as opposed to the hand and forearm. Hinckley et al. compared a similar 3-DOF ball-shaped device to a 3-DOF rectangular-shaped device for rotational tasks, and found no significant differences between the different form factors [90]. Ware and Rose also found no significant effects of form factor for rotational tasks in a similar study [64]. McArthur et al. evaluated four similar form factors for a pointing task, and determined that one form factor was significantly worse than the rest, but contributed this to the device’s spring-loaded button instead of the device’s actual form factor [98]. Based on these results, it appears that form factor does not significantly affect user performance unless the form factor forces users to use different body parts (e.g., Zhai et al. [97]).

2.4.5 Lag

Another aspect of interaction fidelity that has been evaluated is lag. As mentioned, lag is the time it takes to survey input and interpret it [85]. Arthur et al. evaluated lag at 0, 1, 2, 3, and 4 frame intervals, and determined that increases in lag cause decreases in user performance for a tracing a tree of nodes [69]. Ware and Balakrishnan also investigated lag and determined that user performance degraded with increases in lag, particularly if double buffering is used in combination with early sampling [85]. These studies demonstrate that large lag times can result in significantly decreased user performance.

2.4.6 Summary of Interaction Fidelity Effects

In summary, researchers have demonstrated several effects of interaction fidelity on the user experience. Head tracking has been shown to significantly increase user performance when travel techniques are not provided. Real walking appears to be the best general-purpose travel
technique, although task-specific travel techniques can afford better user performance. For manipulation tasks, using input devices that match the number and integration of control dimensions of the task should result in better user performance. It is also important to properly match an input device’s measured properties with an appropriate transfer function, and for positional transfer functions, one-to-one mappings appear to be the most appropriate. Device form factor has not been demonstrated to be an important factor unless the form factor requires the use of different body parts. On the other hand, device lag has been shown to be a significant factor as any lag can significantly decrease user performance.

2.5 Limitations of Prior Fidelity Research

Prior research on the effects of fidelity has been important for demonstrating the potential benefits of increasing fidelity, such as using a high-fidelity VR system instead of desktop computer. Using practical evaluations, researchers have demonstrated that high-fidelity systems can provide better user performance and a greater sense of presence. Through controlled evaluations, most of the components of visual display fidelity have been shown to have significant effects on aspects of the user experience, including stereoscopy, FOV, FOR, display resolution, display size, and frame rate. Similarly, researchers have demonstrated that some high-fidelity interactions (e.g., head tracking, real walking, and virtual hand) improve user performance. Additionally, control dimensions, transfer functions, and lag have all been demonstrated to have significant effects on user performance.

Despite the large amount of prior research on the effects of fidelity, there are a number of limitations. The most obvious limitation has been the lack of research that evaluates both display fidelity and interaction fidelity in a controlled manner (without confounding the two). There have been a number of studies that have evaluated stereoscopy and head tracking (e.g., [28, 59, 68-70]) and a few that have investigated FOR and head tracking (e.g., [36]), but there is a lack of studies investigating display fidelity and interaction fidelity beyond simple view control tasks. Hence, it is important to investigate both for more complex tasks that involve travel and manipulation.

Another limitation of prior research has been the technologies used. Low-resolution HMDs (e.g., [18, 48, 54, 56, 57, 99]) or CAVEs without a full 360-degree FOR (e.g., [22, 23, 36, 49, 61, 79]) have limited some evaluations of display fidelity. Poor tracking accuracies, large lag times, and low frame rates have also potentially impacted prior results on the effects of interaction fidelity [17]. Cumbersome displays (e.g., [48, 54, 56, 99]), restrictive wired devices (e.g., [54, 87, 94, 99]), and unrealistic environments (e.g., [22, 23, 36, 68]) may have decreased the potential effects of fidelity on subjective responses, such as presence.
In order to address these limitations of prior research, we have developed systematic evaluations of both display and interaction fidelity, controlling each independently and combined, while using high-fidelity displays and input technologies.
3 Evaluation of Stereoscopy, FOR, and Interaction Fidelity for a 3D Docking Game

3.1 Goal

The goal of this evaluation was to evaluate the independent and combined effects of stereoscopy, FOR, and interaction fidelity for a 3D docking game (similar to Zhai’s docking task [94]). We wanted to determine, for a particular task, whether the level of display fidelity or interaction fidelity had the greatest effect on user performance. We also wished to explore whether performance might be related to the combination of the level of display fidelity and the level of interaction fidelity.

We chose to evaluate interaction fidelity using three separate 3D interaction techniques—HOMER [100], Go-Go [101], and DO-IT (an interaction technique we designed for use with a keyboard and mouse). We considered HOMER and Go-Go to both be high-fidelity interaction techniques, but chose to evaluate both anyway to determine if there were any significant differences between the two high levels of interaction fidelity. We considered DO-IT to be a low-fidelity interaction technique due to its 2D input and modal controls. Hence, we evaluated high interaction fidelity (two instances) and low interaction fidelity (one instance).

3.2 Task

Since we were investigating the effects of different levels of display fidelity while using different interaction techniques controlled by both 2D and 3D input devices, we designed a system and environment that would support the evaluation of user performance with object selection and manipulation techniques, and in which the components of display fidelity and 3D interaction techniques could be varied.

To support object selection and manipulation tasks, we created a small docking game. The goal of the game was to move twenty 3D objects to corresponding targets and to match both the position and orientation of the objects with those of the targets. We used 3DS MAX and VizX3D to create the geometric models necessary for this game environment. One of these models can be seen in Figure 3.1.
The game environment consisted of twenty simple white letter objects dispersed around the user and four blue targets with the same sizes and shapes as these objects. The objects were modeled after the letters D, J, R, and W. Furthermore, each object was designed to be asymmetrical so that only one orientation of the object would match the target. The blue targets were located to the left, the front, the right, and the back of the user’s position. Five objects were displayed near each target in various initial positions and orientations. Three of these objects corresponded to the nearby target and two corresponded to other targets. A top-down view of the environment can be seen in Figure 3.2.

3.3 Apparatus

We used a 4-screen CAVE in our experiment. The CAVE had three sides and a floor and used projection technology, stereoscopic displays, and head tracking to create an IVE. Unfortunately,
during our project, the floor projector was not working properly and we were only able to use the three walls. The CAVE used an Intersense IS-900 tracking system with a 6-DOF head tracker and a 6-DOF wand device with four buttons and a 2-DOF joystick. The CAVE provided a 270-degree FOR and a 100-degree FOV when viewed through the active stereo glasses. For our desktop interaction technique, we used a standard 101-button keyboard and three-button mouse. These 2D input devices were used in the CAVE in conjunction with a 101.6cm high rolling cart and extra long cords.

We developed our 3D interaction techniques in C++ using DIVERSE [102]. DIVERSE allowed us to create applications that used different input devices and could be executed with or without stereoscopic display.

### 3.4 Experimental Design

Since one of our main goals in our experimental design was to observe the effects of each of the three factors (stereoscopy, FOR, interaction fidelity) independently without introducing any confounding factors, we controlled other factors such as FOV, display resolution, display size, and head tracking. To separate the effects of display fidelity from those of the 3D interaction technique used, we first selected two different components of display fidelity: stereoscopy and FOR.

#### 3.4.1 Independent Variable: Stereoscopy

We controlled stereoscopy at two levels (on and off). We felt that the additional depth cues present in stereoscopic images might improve user performance when making minute rotational and positional adjustments to objects in the environment.

#### 3.4.2 Independent Variable: FOR

We also controlled FOR at two levels (270 degrees and 90 degrees) by varying between using one or three CAVE walls. We felt that a greater FOR might improve subject efficiency when the objects and targets were distributed all around the user spatially.

#### 3.4.3 Independent Variable: Interaction Fidelity

We controlled interaction fidelity at three levels (high, high, and low). We investigated to high-fidelity interaction techniques to determine what kinds of differences might exist between two techniques of a similar level of interaction fidelity.
HOMER

We first implemented the HOMER (Hand-centered Object Manipulation Extending Ray-casting) technique [103]. HOMER uses ray-casting for object selection at a distance and allows the user to manipulate the selected object with a simple, intuitive, hand-centered interaction approach. HOMER is considered a highly usable 3D interaction technique for VE applications [100]. Our implementation of HOMER utilized the wand device for 6-DOF hand input and one of its buttons to select and release an object. The joystick on the wand was used to control the viewpoint orientation; pushing the joystick to the left rotated the scene to the right, and vice-versa.

Go-Go

We also implemented the Go-Go technique [101]. Go-Go uses a non-linear arm extension function allowing the user to reach virtually much farther than she can reach physically. This scaled method is considered usable but has been demonstrated to be not as efficient as the HOMER technique [100]. We set the Go-Go arm extension function such that users could easily reach the entire environment without travel. Our implementation of Go-Go utilized the wand device for tracking the user’s hand and providing selection and release inputs similar to our HOMER implementation. The wand joystick was again used to rotate the scene.

Desktop-Based Technique

After a pilot study and several design iterations, we developed a 3D manipulation technique based on 2D input devices, which we refer to as the Desktop Oriented Interaction Technique, or DO-IT. DO-IT used a window-to-CAVE mouse input mapping (see Figure 3.3) that allows the use of ray-casting. This mapping transformed the point specified in a window by the mouse into a ray-casting-style vector. The position of the mouse within the window was mapped to one of the three CAVE walls. A ray was then created by a vector from the origin of the CAVE to this mapped location (see Figure 3.4). The ray was used to select objects within the environment.

Figure 3.3 Mouse mapping for DO-IT.
Once an object had been selected, DO-IT provided three modes of manipulation: radial movement, depth movement, and virtual sphere rotation. Radial movement (left mouse button) allowed the user to move an object along an imaginary sphere centered about the user by utilizing the window-to-CAVE mapping. Depth movement (middle mouse button) allowed the user to directly manipulate the distance of an object. If the mouse was moved vertically down, the object was brought toward the user. If the mouse was moved vertically up, the object was moved away. The virtual sphere technique [104] is a typical 3D rotation method used in desktop applications. Clicking the right mouse button on an object activated the virtual sphere, whereupon the user could use the ray-casting method just as if the ray were a mouse pointer. The left and right arrow keys on the keyboard were used to control the viewpoint orientation of the user. The keyboard is used in conjunction with DO-IT to control the viewpoint orientation of the user. By pressing the left arrow key the user could rotate her view counterclockwise, and by pressing the right arrow key the user could rotate her view clockwise.

![Figure 3.4 A user using DO-IT in the CAVE.](image)

### 3.4.4 Mixed Experimental Design

We decided to make the two components of display fidelity within-subject factors and the interaction technique a between-subjects factor. Each participant in the experiment performed four trials in the game environment, where their goal was to drop twenty white letters into their corresponding blue letter targets as quickly as possible. Each of the four trials used a different level of display fidelity: non-stereoscopic (mono) with one CAVE wall, non-stereoscopic (mono) with three CAVE walls, stereoscopic with one CAVE wall, or stereoscopic with three CAVE walls. We attempted to control the effect of ordering on performance by giving participants a uniform pre-experiment training time and by staggering the order of conditions.
3.5 Dependent Variables

Our dependent variables were the total time it took a user to complete the game, the individual time it took to manipulate each object, and the number of clutches per object. The total time was measured from the moment a participant picked up the first letter object to the moment the last object was dropped into a target. Individual object time represented the time the participant took to manipulate each object, not counting the time between manipulations. The number of clutches was the number of times the user picked up and dropped each object.

3.6 Procedure

All participants used the CAVE and 6-DOF head-tracked stereo glasses, even for the non-stereoscopic trials. HOMER and Go-Go participants used a 6-DOF wand device while DO-IT participants used a three-button desktop mouse and a keyboard (see Figure 3.4). Participants went through a short training session where they learned how to use their assigned interaction technique, after which they were allowed to practice the technique for five minutes. The subject would then complete a trial through the game for each of the four levels of immersion. The game software contained measurement code to record total run time, individual object manipulation time, and the number of clutches required per object. After the experiment, participants filled out a questionnaire that asked for their opinion on how easy and natural their technique was to use and learn and whether they felt either component of immersion improved the technique.

3.7 Participants

We recruited twelve unpaid participants over the age of 18 (9 male, 3 female) to participate in the experiment. Four additional participants also participated, but due to three cases of technical difficulties and one withdrawal, these participants were not considered in the formal study. Half of the participants had never experienced virtual reality before, but only two participants did not report their computer use as “very often.” Three participants used glasses or contact lenses, but there did not seem to be a correlation between this and their performance or subjective responses.

3.8 Results

3.8.1 Objective Results

We performed a 3-factor ANOVA with a within-subject condition order covariant for total time, and 4-factor ANOVAs for the object time and number of clutches. We could not include within-subject condition order as a fourth fixed factor in the total time ANOVA because this would result in only one data point per factorial combination. In all cases technique was significant:
(F=5.48, p=0.008) for total time, (F=45.22, p<0.0001) for individual object time, and (F=310.81, p<0.0001) for number of clutches per object. FOR and stereoscopy were statistically insignificant for all metrics. The within-subject condition order was significant for individual object manipulation time (F=10.06, p<0.0001) but not for either of the other metrics.

Investigating the cause of the significant effect of technique, we found that DO-IT performed significantly worse than the other two techniques (except in the stereo 1-wall trial) as seen in Figure 3.5. Note also that all of the object time confidence intervals for the different levels of immersion overlap within each technique. In addition, we found that Go-Go and HOMER were not significantly different in object manipulation times, despite HOMER’s better mean times. Figure 3.6 shows the corresponding confidence intervals for clutches, which reveals similar but even stronger results. However, this increase in clutches was expected and even inherent in the DO-IT technique due to the many clicks required for the three different manipulation modes.

Since the number of samples for the total time was so much smaller than that of the previous two metrics (one total time for every twenty objects), we present the technique and display fidelity results separately for total time. Figure 3.7 shows once again that while HOMER’s mean time is smaller than that of Go-Go, they are not significantly different. HOMER does, however, perform significantly better than DO-IT. Figure 3.8 shows that the confidence intervals of the four different levels of display fidelity completely overlap.
Figure 3.6 Mean clutches by stereoscopy, FOR, and technique condition.

Figure 3.7 Mean total trial times by interaction technique.
3.8.2 Subjective Results

In our questionnaire, participants answered questions about their manipulation technique. Answers were on a five-point scale (strongly disagree, disagree, neutral, agree, and strongly agree). For analysis, we assigned each of these levels a numeric score from -2 (strongly disagree) to 2 (strongly agree), with neutral being 0. Figure 3.9 shows the technique-related average scores and Figure 3.10 shows the display-related average scores.
Our results indicate that the 3D interaction technique had a significant effect on object manipulation times and number of clutches whereas the two components of display fidelity did not. These findings seem to show that selecting the appropriate level of interaction fidelity is more important than selecting the appropriate level of display fidelity, at least for strongly manipulation-based applications. This could, however, be the result of using a test environment that did not require as much display fidelity as intended. Despite this, we believe that the difference in significance of the interaction fidelity and the components of display fidelity warrants further experimentation in this area. For some highly interactive VE{s}, a large display with 6-DOF input may be as efficient as a system with much higher display fidelity, at a much lower cost. Of course, this is not true in all cases. The most important lesson to be learned from this result is the importance of carefully choosing the interaction technique and input device in a manipulation-heavy VE.

These results also indicate the performance superiority of high-fidelity 3D interaction techniques based on 6-DOF input devices over low-fidelity techniques based on desktop devices in manipulation-intensive applications. Furthermore, based on the significantly higher number of average clutches per object in the 2D input technique, we find that 6-DOF input techniques can produce substantially less mental workload and much simpler interaction than 2D input techniques. This is due to the direct mapping between 3D input and a 3D environment, which greatly reduces the cognitive requirements on the user.

Interestingly, it appears that participants felt that the increased FOR improved their manipulation technique more than did stereoscopy. The objective data hints at this in places where FOR has a slightly greater effect than stereoscopy, but there is no significant difference. From personal
observations we were not surprised by this subjective neutrality toward stereoscopy, since the most common participant comment during the experiment was “I didn’t notice the difference between mono and stereo.” We attribute this to the fact that most of the objects appeared more than 5m away from the participants in the environment, where stereoscopy does not produce as much of an effect.

We also see that more HOMER participants rated their technique as more natural to use than the other groups in Figure 3.9, with DO-IT participants finding their technique fairly neutral. This is another indication of the natural cognitive mapping of 3D input techniques as compared with 2D input techniques. Two other noteworthy observations from the questionnaire results were that DO-IT participants rated their technique the worst in all three categories, and that Go-Go only exceeded HOMER’s score in the game efficiency category.

The greatest adverse effect of the manipulation technique being a between-subject factor is the increased variance for each condition of display fidelity. Since each condition of display fidelity appeared once in each within-subject ordering position, each measured total time varied more than it might in a completely within-subject experiment.

The largest question left open by these results is whether the input device (mouse versus 6-DOF wand) or the actual 3D interaction technique resulted in the performance differences observed. In our next evaluation, we address this issue by controlling input devices but providing the same integration of control.

### 3.10 Summary

We empirically tested the effects of stereoscopy, FOR, and interaction fidelity for a 3D docking game, and found that the level of interaction fidelity had a significant effect on the performance of manipulating objects, while the two components of display fidelity did not. This implies that object manipulation tasks could be performed with lower-fidelity, less costly displays with no loss of efficiency, and that system designers should pay special attention to the choice of input device and interaction technique when developing highly interactive VEs.

A limitation of these results is that they may not be relevant to interaction tasks other than 3D manipulation. Another limitation is that the CAVE used in the study only provided a 270-degree horizontal FOR, which may not have been enough to find a significant effect of FOR on user performance. Additionally, as discussed, another potential limitation was that the placement of the objects may have countered any potential benefits of stereoscopy.

Because we found no significant effects of FOR or stereoscopy, but did for interaction fidelity, we decided to further investigate the effects of interaction fidelity alone in our next study.
4 EVALUATION OF INTERACTION FIDELITY FOR A RACING GAME

4.1 Goal

In our first evaluation, we determine that the level of interaction fidelity had a significant effect on user performance with two high-fidelity interaction techniques outperforming a low-fidelity technique. Due to multiple differences between the high-fidelity techniques and the low-fidelity technique, we did not know whether to contribute the significant performance of the high-fidelity techniques to the input device used, the integration of DOF, or the underlying transfer function.

Considering the recent trend of higher-fidelity interactions within the gaming industry, we felt it was important to understand more about how high-fidelity interaction techniques affect the player experience, particularly player performance. Player performance influences player enjoyment, which is the single most important goal for a video game, since players will not continue to play a game they do not enjoy [45]. Player performance is additionally important because players will experience anxiety if the challenge of a game proves much greater than their own ability to perform [105].

In order to obtain a better understanding of the effects of interaction fidelity on player performance and other aspects of the player experience, we conducted a study comparing the use of high-fidelity and low-fidelity interaction techniques for Mario Kart Wii, a commercially sold racing game for the Nintendo Wii. We chose Mario Kart Wii for its seemingly balanced design of both high-fidelity and low-fidelity techniques. The Wii Wheel and its accompanying high-fidelity interaction technique (physically turning the wheel to steer) were the marketing focus of this latest version of Mario Kart while the low-fidelity techniques were adopted from previous versions of the racing game released on traditional consoles. Additionally, the devices underlying the techniques provided by Mario Kart Wii used various sensor types and muscle groups, allowing us to learn more about the influence of these factors on player performance.

4.2 Task

Mario Kart Wii features four different game modes. For our experiment, we chose to use the “Time Trial” mode in which a single player races a course alone and completes three laps in an attempt to break existing time records. We chose this game mode due to its lack of dependence on the artificial intelligence (AI) of computer opponents and limitations on in-race items. When a time trial begins, the player has access to three “mushroom” items that provide a short speed boost when used, and the player cannot pick up any other items even after using all three
mushrooms. In other game modes, players have multiple opportunities to pick up items at random, and these random items can create huge variances in the players’ performances.

In addition to selecting a game mode, we also had to decide which courses participants would race on. We wanted to use an easy course and a difficult course to determine if there were any differences within the interaction techniques based on the level of game difficulty. We selected “Luigi Circuit” as the easy course because it is the first course introduced within the game’s “Grand Prix” mode and offers no hazards. For the difficult course, we selected “Wario’s Gold Mine,” which presents many hazards, such as falling off the track and crashing into moving mining carts.

4.3 Apparatus

We used a Nintendo Wii console, a JVC Professional DV/VHS deck, and a Gateway 30-inch widescreen LCD monitor. The console output was set to a screen resolution of 480i and a 16:9 aspect ratio. The output was routed from the console through the deck and to the monitor via standard component cables. This implementation allowed us to record the time trials for verifying collected data and later analysis.

Naturally, we also used a Mario Kart Wii game disc, a Wii Remote, a Wii Wheel accessory, a Wii Classic Controller, and a Nintendo GameCube Controller.

4.4 Experimental Design

The goal of our study was to compare multiple interaction techniques used for steering in Mario Kart Wii for the purpose of understanding the effects of high-fidelity and low-fidelity interaction techniques on the player experience.

4.4.1 Independent Variable: Interaction Fidelity

There are five interaction techniques that players can use to drive a vehicle in Mario Kart Wii. The technique we considered the highest fidelity involved the use of the Wii Wheel accessory (a passive prop) with the Wii Remote to simulate using a steering wheel (see Figure 4.1A). For this high-fidelity technique, players hold and turn the Wii Wheel to steer while using buttons on the Wii Remote to accelerate, brake, drift, and use in-race items. Players can also shake the Wii Wheel to perform speed-boosting tricks on ramps and half-pipes.

By removing the Wii Wheel accessory, a second interaction technique is provided, which we refer to as the Remote technique. This technique works exactly the same as the Wheel technique except that the physical form factors of the underlying devices differ. Instead of holding and
turning a prop shaped like a steering wheel, players hold and turn the box-shaped Wii Remote (see Figure 4.1B). Due to its similarities to the real world action of steering a vehicle, we considered the Remote a high-fidelity interaction technique.

Figure 4.1 A) The Wii Wheel device and B) the Wii Remote device.

Two of the remaining interaction techniques are based on traditional control schemes from prior versions of *Mario Kart* released on older consoles. One of these low-fidelity techniques uses a Wii Classic Controller while the other uses a Nintendo GameCube Controller (see Figure 4.2). For both techniques, steering is achieved by pushing a spring-loaded analog joystick left or right while other game actions are executed by pressing buttons on the controllers. Like the Wheel and Remote techniques, the Classic and GameCube techniques are functionally the same but differ in physical form factors.

Figure 4.2 A) The Wii Classic controller and B) the Nintendo GameCube controller.

The last interaction technique provided by *Mario Kart Wii* is what we refer to as the Nunchuk technique. It uses the Wii Nunchuk connected to the Wii Remote as its underlying input devices. Similar to the Classic and GameCube techniques, the analog joystick on the Wii Nunchuck is used for steering while the buttons on the Wii Remote are used for accelerating, braking, drifting,
and using items. Like the Wheel and Remote techniques, players shake the Wii Remote to perform tricks with the Nunchuk technique.

For our experimental design, we decided to evaluate the Classic, GameCube, Remote, and Wheel techniques, omitting the Nunchuk technique. Obviously, we wanted to compare what we considered at the time to be high-fidelity and low-fidelity techniques to learn more about the effects of interaction fidelity. We chose to evaluate the Wheel and Remote techniques to learn more about the effects of form factors for high-fidelity interaction techniques. For a similar reason, we chose to evaluate the Classic and GameCube techniques. We chose not to evaluate the Nunchuk technique due to its mid-fidelity qualities and to maintain a manageable study.

Table 4.1 Experimental design of Mario Kart Wii study.

<table>
<thead>
<tr>
<th>Form Factor A</th>
<th>Form Factor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Fidelity</td>
<td>Classic</td>
</tr>
<tr>
<td>High Fidelity</td>
<td>Remote</td>
</tr>
</tbody>
</table>

4.4.2 Within-Subjects Experimental Design

To allow for subjective comparisons of the interaction techniques and to reduce variance associated with individual differences, we opted for a within-subjects experimental design. Each participant completed the experiment tasks using each of the four interaction techniques selected for the experiment. To minimize learning and ordering effects, we assigned each participant one of four technique orderings based on a Latin squares design. We chose to group the high-fidelity and low-fidelity techniques within the orderings to avoid confusing participants when switching between techniques. Abbreviating each technique to its first letter, the four orderings were CGRW, WRGC, GCWR, and RWCG.

4.5 Dependent Variables

The dependent variables in the study were time and errors. We decided to consider each of the three time trial laps as individual data points, instead of considering whole time trials. This tripled our number of data points and accounted for performances on individual laps. Our primary metric was lap time, the amount of time required to complete a lap. Fortunately, Mario Kart Wii displays the three lap times at the end of each time trial, eliminating possible inconsistencies in gathering lap times.
The remaining objective metrics were focused on distinct racing errors: directional errors, fall errors, and crash errors. Directional errors (when the player drives in the wrong direction) can occur on any course and are identified by the appearance of the “Lakitu” character holding a U-turn sign above the track. For a fall error, players leave the track and fall into an adjacent pit (only possible on the difficult course). After a few seconds, Lakitu drops the player’s fallen character back onto the track.

Crash errors occur when a player crashes into a mining cart on the difficult course. This is distinct from other collision errors because the player’s vehicle is ejected upwards and comes to a complete stop after landing. Normal collisions only slow a vehicle’s speed and do not require extra time for landing. We decided not to count normal collisions because identifying these errors is subjective, as collisions can vary from scrapes that slightly slow the vehicle to head-on collisions that nearly stop it. It is also important to note we did not count crash errors that transitioned into fall errors, as fall errors require much more time to recover from.

In addition to collecting objective metrics, we surveyed participants after completing the experiment to establish their subjective opinions regarding the interaction techniques. In our survey, we were concerned with four aspects of the participants’ experiences with the interaction techniques: overall preference, perceived ease of use, perceived enjoyment, and perceived performance. We regarded any consistencies between the technique a participant likes best and the other three aspects as an indication of what that participant values in an interaction technique (usability, fun, or performance respectively).

4.6 Procedure

At the beginning of the experiment, each participant filled out a consent form and was assigned a participant ID corresponding to the technique ordering he or she would experience during the experiment. After completing the consent form, a background survey was administered to collect information about each participant’s age, gender, recent games usage, general gaming experiences, and experiences with Mario Kart Wii. Specifically, we asked participants if they had ever played Mario Kart Wii, and, if so, for how many hours and with which interaction techniques.

After finishing the background survey, each participant was given the option to choose an in-game driver from the initial set of twelve Nintendo characters and a “kart” (vehicle) from the initial set of three provided per character. Once chosen, participants were required to use this combination of character and kart for every task. We allowed participants to choose their characters and karts to avoid hindering experienced Mario Kart Wii players with unfamiliar settings. We did prohibit participants from using “bikes” as vehicles due to the additional “wheelie” feature of bikes.
The actual experiment was divided into four segments corresponding to the four interaction techniques. Within each segment, there was a tutorial phase and a data collection phase. During the tutorial phase, each participant was taught how to play the game with the current interaction technique on the easy course. An experimenter would give directions based on a predefined set of instructions to walk each participant through the various game actions, including tricks. Once a participant completed the tutorial, demonstrating the ability to complete the various actions, the participant was allowed to complete a single time trial on the easy course as practice. For the data collection phase, the participant was expected to complete two time trials on the easy course and then two time trials on the difficult course as quickly as possible. For each time trial, an experimenter recorded lap times and directional errors per lap. For the difficult time trials, the experimenter also recorded fall and crash errors per lap.

After completing the experiment, participants filled out the exit survey regarding their impressions of the interaction techniques.

4.7 Participants

We recruited 16 unpaid participants (12 males, 4 females). The age range of the participants was 18 to 29 years old with a mean age of 23. All of the participants had previously played a Nintendo Wii game. Ten of the participants had previously played Mario Kart Wii, ranging from 30 minutes of play to 30 hours. Eight participants reported playing video games at least weekly while the other eight reported playing monthly to yearly.

4.8 Results

In this section, we present analyses of the effects of the interaction techniques on lap times, fall errors, and crash errors (during the experiment there were no directional errors, hence the absence of any analysis of such errors). We also present an analysis of the subjective responses collected from the exit survey at the end of this section.

4.8.1 Lap Times

For the easy course lap times, a two-factor ANOVA (interaction technique and technique order) indicates that interaction technique did not have a significant effect \((F(3,368)=0.9794, p=0.4024)\), although technique order did \((F(3,368)=14.7232, p<0.0001)\). Based on a Tukey post-hoc test, the CGRW and GCWR orderings were significantly slower than the WRGC and RWCG orderings. There was not a significant interaction between interaction technique and technique order \((F(9,368)=0.9143, p=0.5126)\).
Another two-factor ANOVA (interaction technique and technique order) of the eight frequent-gamer participants’ easy course results indicates that interaction technique did have a significant effect for more-experienced gamers (F(3,176)=6.3343, p=0.0004). Their mean lap times (in seconds) were 29.1701 for Classic, 28.9389 for GameCube, 30.2875 for Remote, and 29.9008 for the Wheel. The Remote and Wheel were significantly slower than the GameCube, despite small absolute differences. The Remote was also significantly slower than the Classic. Technique order did not have a significant effect for the frequent-gamers (F(3,176)=1.0906, p=0.3545), and there was not a significant interaction between interaction technique and technique order (F(9,176)=1.5791, p=0.1246).

For the difficult course lap times, another two-factor ANOVA (interaction technique and technique order) indicates that interaction technique had a significant effect for all participants (F(3,368)=13.4382, p<0.0001). The mean lap times were 53.0762 for Classic, 51.5972 for GameCube, 60.4418 for Remote, and 58.8030 for the Wheel. The Remote and Wheel were significantly slower than the Classic and GameCube techniques, with the absolute differences being several seconds. Technique order also had a significant effect on the difficult course lap times (F(3,368)=8.5613, p<0.0001), with the CGRW and GCWR orderings being significantly slower than the WRGC ordering. The CGRW ordering was also significantly slower than the RWCG ordering. There was also a significant interaction between interaction technique and technique order (F(9,368)=2.8007, p=0.0034) (see Figure 4.3). The results of the CGRW and RWCG orderings were similar, as were the results of the WRGC and GCWR orderings. This indicates an apparent learning effect within the high-fidelity techniques, which is likely due to the different form factors of the Remote and Wheel.

![Figure 4.3 Interaction effect between techniques and order for difficult course lap times.](image-url)
4.8.2 Errors

On the difficult course, every participant experienced multiple fall errors, demonstrating the difficulty of the course. A two-factor ANOVA (interaction technique and technique order) of these errors per lap indicates that interaction technique had a significant effect (F(3,368)=11.4477, p<0.0001). The Remote and Wheel resulted in significantly more fall errors (1.0729 and 0.9896, respectively) than the Classic and GameCube techniques (0.4167 and 0.3854, respectively). Technique order also had a significant effect on fall errors (F(3,368)=3.7741, p=0.0109), with the CGRW ordering producing significantly more errors than the WRGC ordering. Again, a similar significant interaction between interaction technique and technique order (F(9,368)=2.9958, p=0.0018), indicates apparent learning effects due to form factor.

A two-factor ANOVA (interaction technique and technique order) of the crash errors per lap shows that interaction technique again had a significant effect (F(3,368)=4.2020, p=0.0061). The Remote and Wheel resulted in significantly more crash errors (0.2500 and 0.2917, respectively) than the GameCube technique (0.0729). Technique order also had a significant effect on crash errors (F(3,368)=6.1682, p=0.0004), but there was not a significant interaction between interaction technique and technique order (F(9,368)=1.1892, p=0.3004).

4.8.3 Subjective Results

Table 4.2 summarizes the primary results of the exit survey in which participants reported their subjective impressions of the four interaction techniques.

Table 4.2 Number of responses indicating each technique for the four preference questions.

<table>
<thead>
<tr>
<th></th>
<th>Most Liked</th>
<th>Easiest to Use</th>
<th>Most Fun</th>
<th>Best Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classic</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>GameCube</td>
<td>8</td>
<td>9</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Remote</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Wheel</td>
<td>5</td>
<td>2</td>
<td>11</td>
<td>0</td>
</tr>
</tbody>
</table>

The most notable detail shown in Table 4.2 is that all of the participants perceived better performance with the low-fidelity interaction techniques. The majority of participants reported a low-fidelity interaction technique as the most liked (9 of 16) and the easiest to use (13 of 16). However, a majority of participants (12 of 16) reported that a high-fidelity interaction technique was the most fun to use, in particular the Wheel (11 of 16).
Table 4.3 shows how consistent participants were in choosing the same technique for each pair of subjective questions.

Table 4.3 Number of consistent responses for each pair of subjective questions.

<table>
<thead>
<tr>
<th></th>
<th>Easiest to Use</th>
<th>Most Fun</th>
<th>Best Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Liked</td>
<td>8</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Easiest to Use</td>
<td>7</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Most Fun</td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 demonstrates that 10 of 16 participants most liked the technique they considered to be the most fun. Meanwhile, only half of the participants most liked the technique they considered to be the easiest to use, and a minority (6 of 16) preferred the technique for which they perceived the best performance. More than half of the participants (9 of 16) thought that the easiest to use technique also resulted in the best performance.

4.9 Discussion

4.9.1 High-fidelity and Low-fidelity Interaction

Overall, we found that the high-fidelity Remote and Wheel techniques performed significantly worse than the low-fidelity Classic and GameCube techniques. The high-fidelity techniques induced more fall and crash errors than the low-fidelity techniques and resulted in significantly slower lap times for the difficult course. The high-fidelity techniques also resulted in significantly slower lap times on the easy course for frequent gamers, and in the absence of errors.

From our observations and our own experience playing the game, we have hypothesized some reasons why the high-fidelity interaction techniques performed significantly worse than the low-fidelity techniques. Our first hypothesis is that the high-fidelity interaction techniques suffered due to their use of large muscle groups. The shoulders, arms, and hands are used to control steering for the Remote and Wheel techniques by design. In contrast, the thumb is used for steering with the Classic and GameCube techniques. Zhai’s prior research suggests that the use of small muscle groups (e.g., thumbs and fingers) should result in faster and more precise performance than the use of large muscle groups (e.g., shoulders and arms) [97].

A second hypothesis for the poor performance of the high-fidelity techniques is that they use sensors that are a mismatch for the game’s steering task. For Mario Kart Wii, the primary task of steering is governed by a rate control transfer function, as opposed to position control. As players steer, they control the rate of turning for their vehicle as opposed to directly controlling the
vehicle’s position. According to Zhai and Milgram [95], rate control works best with isometric sensors or elastic sensors like the spring-loaded analog joysticks used by the low-fidelity techniques. The high-fidelity interaction techniques, on the other hand, use the Wii Remote’s three-axis linear accelerometer, which is an isotonic sensor and is therefore a suboptimal match for rate control techniques.

We also hypothesize that the high-fidelity interaction techniques suffered from latency, the temporal delay between user input and system feedback [47]. For a racing game, such a delay can lead to overcorrections and oversteering, which affect a player’s performance and can lead to in-game errors. The Wii Remote’s three-axis accelerometer, used to measure the direction of gravitational force relative to the Remote, has a 100 Hz update rate, but it may still take some time for the accelerometer readings to stabilize after a quick turning motion. Although we did not measure latency directly, a few participants complained that the high-fidelity interaction techniques seemed slow in responsiveness.

Though we found significant performance differences between high-fidelity and low-fidelity interaction techniques for Mario Kart Wii, we do not conclude that game developers should stop designing high-fidelity interaction techniques. As the subjective results show, high-fidelity techniques can still be perceived as more fun than low-fidelity techniques. However, developers should consider potential limitations such as those described above when designing interaction techniques, especially high-fidelity ones. For example, many high-fidelity interaction techniques can be designed such that a high level of precision is not required (e.g., *Wii Sports*) since the use of large muscle groups may negatively influence performance and precision. Game developers interested in performance should also focus on better matching game controllers and in-game tasks to avoid unsuited sensor types and suboptimal interaction techniques. The *Guitar Hero* series, with its musical props, is a good example of matching controllers and tasks. Finally, game developers should be aware of potential latency issues with new technologies.

### 4.9.2 Physical Form Factor

In our study, it appears that physical form factor only had a significant effect on learning to use the high-fidelity interaction techniques, based on the interaction effect found between technique and technique order. There were no other significant differences between the Remote and Wheel techniques, or between the Classic and GameCube techniques. This result is not surprising considering previous research on physical form factor (e.g.,[64, 90, 98]).

Despite the lack of significant effects in the objective metrics for physical form factor, we did find subjective differences. When asked which technique they liked best, 11 of the 16 participants reported liking the Wheel better than the Remote, and 13 of the 16 participants
reported liking the GameCube better than the Classic. Hence, even when form factor has little significant effect on performance, players may prefer one form factor to another.

4.9.3 Players

The subjective responses from our study demonstrate that players have the ability to discern performance differences of interaction techniques. All of our participants recognized that the low-fidelity interaction techniques produced better performance than the high-fidelity techniques. We assume that participants recognized this distinction based on in-game events, such as fall errors.

The subjective responses also show that most players prefer an interaction technique that they perceive as fun. Meanwhile, it seems that only a minority of players prefer an interaction technique based on performance. These responses suggest that game developers should be concerned with designing fun interaction techniques in addition to usable techniques.

4.10 Summary

Despite the gaming industry’s recent trend for producing realistic experiences through high-fidelity interactions, we have demonstrated that low-fidelity interaction techniques can have significant performance advantages over high-fidelity techniques. Using Mario Kart Wii, we compared two high-fidelity interaction techniques and two low-fidelity techniques. Based on analyses of lap times, fall errors, and crash errors, we found that the high-fidelity techniques result in significantly lower performance. We have hypothesized three potential reasons for this: the influence of large muscle groups (or lack of small muscle groups), the mismatch of isotonic sensors for a steering rate control task, and possible latency issues. We have suggested that game developers should consider these issues when designing interaction techniques, especially high-fidelity ones. Our study also gave us insight into the effects of high-fidelity interaction and form factor on subjective player preferences, finding that players prefer devices with more ergonomic form factors and techniques that are more fun. In this study, high-fidelity interaction techniques were perceived as more fun by a majority of players.

Some potential limitations of this study include the inability to generalize the results beyond racing games or using the Wii Remote as an input device. The results indicating the high-fidelity techniques performed worse than the low-fidelity techniques may not be repeatable for non-racing games, such as a first-person shooter or a fighting game. Additionally, the results may have differed if a higher-quality input device was used for the high-fidelity techniques, as discussed above.
Our understanding of these results has changed slightly since the development of FIFA (discussed in chapter 7). In section 7.4, we present a reinterpretation of the results of this study using FIFA to objectively analyze the level of interaction fidelity encompassed by the Classic, GameCube, Remote, and Wheel techniques. Regardless, at the time of concluding this study, we thought we better understood the effects of interaction fidelity, and therefore decided to return to evaluating the effects of both display fidelity and interaction fidelity in our next study.
5 EVALUATION OF DISPLAY FIDELITY AND INTERACTION FIDELITY FOR A FIRST-PERSON SHOOTER GAME

5.1 Goal

Considering the importance of continuing to explore the effects of increasing fidelity, we designed and conducted a study to independently evaluate both display and interaction fidelity at extremely high and low levels, which yielded four experimental conditions. We used a six-sided CAVE with wireless tracking capabilities to provide the extremely high levels of display and interaction fidelity. For display fidelity, we chose to focus again on stereoscopy and FOR. To gain a better understanding of the effects of fidelity on the user experience, particularly performance, we chose to use a VR first-person shooter (FPS) game as a complex, performance-intensive context for our study. We also evaluated the effects of fidelity on subjective responses, such as presence [20], engagement [32], and perceived usability.

Overall, this study contributes to a better scientific understanding of the effects of display fidelity and interaction fidelity while addressing some practical concerns of choosing appropriate displays and interaction techniques.

5.2 Task

As mentioned, we chose a first-person shooter game for the context of this experiment. Most FPS games require complex interactions, such as maneuvering around obstacles while shooting at enemies. These complex interactions are performance intensive and require high levels of peripheral awareness and spatial understanding to avoid enemies and obstacles. Hence, we expected that our FPS context would provide greater potential for significant differences, especially with regard to the level of interaction fidelity.

After investigating various open-source FPS engines, we eventually used Syzygy’s Quake III Arena map viewer called “cubecake”. In order to maintain experimental control, we developed our own artificial intelligence (AI) routines, designed our own maps, and tracked various player statistics. Since FPS games are often regarded as inherently violent and believed by some to invoke hostility and aggressiveness [106], we decided to use inanimate “androids” as bots (i.e., enemies) and avoided special effects like blood, to reduce the emotional risks of participating. In all conditions, our FPS game ran at an average of 55 frames per second.
To maintain more control during our experiment, we decided to use simple maps with only a single path from start to finish, instead of using sprawling maps with multiple routes to choose from. In particular, we wanted to use these linear layouts to learn more about our components of interest (stereoscopy, FOR, aiming, and locomotion) by designing map sections that would exercise these components individually and in combination. To exercise stereoscopy, we chose to have bots appear (or “teleport”) within three meters of the player since stereoscopy is more effective at close viewing distances [107]. To exercise increased FOR, we decided to have bots teleport around the player’s location in many different directions. For aiming, we had several bots teleport in at once to emphasize the ability to quickly change targets. Finally, for locomotion, we used a retreating AI behavior to force the player to chase the bot by moving.

There were ten total map sections, each with a distinct purpose. In order to maintain the purpose of each section despite player movements and actions, we designed “computer station” game elements that players were required to “hack” (i.e., stand near). These elements allowed us to control player locations when bots appeared. In each section, players were required to eliminate eight bots before the entrance to the next section opened. We also used section entrances as respawn locations if players died within the section. The list below details the purpose of each map section with a brief description.

1. **None**: Bots teleport in one at a time, more than 6m away in a single direction.
2. **Stereoscopy**: Bots teleport in one at a time, within 3m in a single direction.
3. **FOR**: Bots teleport in one at a time, more than 6m away in a surrounding fashion.
4. **Aiming**: All eight bots teleport in at once, more than 6m away in a single direction.
5. **Locomotion**: Bots teleport in one at a time, more than 6m away in a single direction, and retreat when hit.
6. **Stereoscopy + Locomotion**: Bots teleport in one at a time, within 3m in a single direction, and retreat when hit.
7. **FOR + Locomotion**: Bots teleport in one at a time, more than 6m away in a surrounding fashion, and retreat when hit.
8. **Stereoscopy + Aiming**: All eight bots teleport in at once, within 3m in a single direction.
9. **FOR + Aiming**: All eight bots teleport in at once, more than 6m away in a surrounding fashion.
10. **Stereoscopy + FOR + Aiming + Locomotion**: All eight bots teleport in at once, within 3m in a surrounding fashion, and retreat when hit.
5.3 Apparatus

In order to evaluate extremely high and low levels of display fidelity, we used a six-sided CAVE (seen in Figure 5.1), which offered a full 360-degree FOR. This rear-projected, cube-shaped display system measured 3m x 3m x 3m and had a display resolution of 1050 x 1050 pixels on each screen. CrystalEyes technology was used for active stereoscopy. We used Syzygy [108] to control the system’s master/slave framework, which consisted of a master-node computer and six supporting computers (one per screen).

We used the CAVE’s built-in InterSense IS-900 Wireless tracking system with a 6-DOF head tracker and a 6-DOF wand to provide input for high levels of interaction fidelity. We also used a Bluetooth three-button mouse and a Bluetooth standard keyboard for our low level of interaction fidelity. We set both of these atop a 106cm tall podium equipped with a turntable, 46cm in diameter, to afford physical turning with these low-fidelity input devices. We maintained a constant, moderate mouse sensitivity to avoid variability between our participants.

Figure 5.1 We used a six-sided CAVE to evaluate the independent and combined effects of display fidelity and interaction fidelity.

5.4 Experimental Design

We wished to evaluate very high and very low levels of both display and interaction fidelity. To increase experimental control and reduce confounds between the high and low levels, we
adopted a systematic approach that utilizes a CAVE system to control for confounds while investigating specific components of fidelity [4].

5.4.1 Independent Variable: Display Fidelity

We chose to control display fidelity at two levels (high and low). We decided to evaluate the components of stereoscopy and FOR while controlling other components such as FOV, resolution, and frame rate. We chose to evaluate stereoscopy because it has been shown to be a significant factor in prior research [24, 67]. Since we were using a six-sided CAVE for our experiment, we also chose to evaluate FOR, which had not often demonstrated significant effects in VR systems with lower FOR [109, 110]. Hence, our high level of display fidelity used stereoscopic graphics and a full 360-degree FOR (i.e., all six sides of the CAVE). In contrast, our low level of display fidelity involved non-stereoscopic graphics and only a 90-degree FOR (i.e., a single wall of the CAVE).

5.4.2 Independent Variable: Interaction Fidelity

Like display fidelity, we decided to control interaction fidelity at two levels (high and low). For interaction fidelity, we decided to focus on the two most important FPS interactions – aiming and locomotion, removing other interactions such as crouching and picking up objects. For aiming, we chose to compare a traditional FPS mouse technique to natural 3D pointing using the 6-DOF handheld wand with its ergonomic trigger button. For locomotion, we wanted to compare a traditional FPS keyboard technique to a more natural, high-fidelity locomotion technique. We designed and implemented a new technique for this purpose, which we refer to as the human joystick (see below). Therefore, for our high level of interaction fidelity, users would aim and fire with the handheld controller while physically moving to virtually travel. In contrast, for our low level of interaction fidelity, users would use the mouse to turn, aim, and fire while using the keyboard to travel through the virtual world.

The Human Joystick Technique

As mentioned, we wanted to compare a keyboard technique to a more natural, high-fidelity locomotion technique. Unfortunately, real walking [87] – the highest fidelity locomotion technique – was not feasible since users would be limited to the space provided by our CAVE system and our FPS game would involve a much larger virtual space. For similar reasons, redirected walking [111] was not practical to implement for our CAVE-based FPS. We also considered various walking-in-place techniques ranging from head tracking [99] to leg tracking [112] to the new shadow walking technique [113]. But we decided against walking-in-place for our high-fidelity locomotion technique to avoid fatigue and Type I errors (when the system
judges users to be walking in place when they are not [87]) due to the performance-intensive nature of our FPS context.

Thus, we designed a new technique called the *human joystick*. By capturing the 2D horizontal vector from the center of the CAVE to the user’s tracked head position, and utilizing it as a joystick’s 2D vector would be used for locomotion, we essentially turned the user into a giant, human joystick (see Figure 5.2). Since only the user’s head position is used to calculate the vector, the direction the user is facing has no influence on the locomotion, making the human joystick an omni-directional locomotion technique that allows movement in any horizontal direction.

![Figure 5.2](image)

**Figure 5.2** Top-down illustration of the CAVE displaying a large-scale virtual environment. The human joystick technique utilizes the user’s tracked head position from the center of the CAVE for virtual locomotion, as a joystick’s 2D vector would be used.

To avoid constant virtual locomotion due to small distances between the user’s head position and the center of the CAVE, we also included a “neutral zone” with a 20cm radius at the center of the CAVE. While in the neutral zone, one-to-one head tracking provides the user the ability to make minor changes to the viewpoint, such as peering around a corner. Once outside of the neutral zone, the human joystick technique is activated, and the user is virtually translated. The speed of virtual locomotion is linearly related to the user’s distance from the neutral zone with a maximum speed of 5cm per frame near the walls of the CAVE, which is equivalent to our keyboard technique’s maximum speed.

After an informal usability study of the human joystick, we adopted it as our high-fidelity locomotion technique for our experiment. Additionally, we decided to position a small floor mat
in the center of the CAVE to provide a haptic representation of the neutral zone, which would be particularly important in our low-display-fidelity conditions without floor projection.

5.4.3 Within-Subjects Experimental Design

We varied both independent variables – display fidelity and interaction fidelity – at two levels and within subjects for a total of four conditions. The presentation order of the four conditions was counterbalanced between subjects.

5.4.4 Details of Experimental Conditions

In this section, we discuss the details of our four within-subjects conditions and note issues inherent to simultaneously evaluating display and interaction fidelity at high and low levels.

**High-display, high-interaction (HDHI):** This condition was the most straightforward combination of a level of display fidelity with a level of interaction fidelity. Surrounded by six stereoscopic CAVE sides, the user uses the human joystick technique to move virtually through the world while using the 6-DOF wand to point the weapon crosshair into the 3D environment (see Figure 5.3). Due to the 360-degree FOR, the user simply made physical body rotations to turn (i.e., rotate the viewpoint).

![Figure 5.3](image)

*Figure 5.3* In the high-display, high-interaction (HDHI) condition, the user used the human joystick technique for virtual locomotion and a 6-DOF wand to control the crosshair for 3D aiming and firing at all six sides of the CAVE.
**High-display, low-interaction (HDLI):** In most FPS games, the crosshair remains centered on the display screen while the mouse rotates the player’s viewpoint to aim in different directions, including upward and downward. This was not a feasible solution for this condition for two reasons. First, the ability to pitch the VE upward and downward would become disorienting since the user would be physically standing in the space and at times could appear to be levitating parallel to the virtual ground. Second, virtual rotations are known to cause simulator sickness for some people [114], and constant virtual rotations would likely cause many users to become ill. To remedy this, we designed the mouse to control the movement of the crosshair across the surrounding display screens, similar to a cursor on a multi-monitor desktop, except with no boundaries and continuous capability.

A question that arose from this choice was what direction the keyboard locomotion keys would align to. With a single screen, it is intuitive that the up arrow or W key would map to a motion toward the screen, but with surrounding screens, it makes little sense to always map these commands to motion toward the “front” wall of the CAVE, since users are constantly turning to face different screens. Instead, we interpreted keyboard commands relative to the 2D horizontal direction of the crosshair from the center of the CAVE. Hence, if the player positions the crosshair on the right wall of the CAVE, the up arrow and W key now activate motion towards the right side instead of the front. We equipped our podium with the turntable to allow the user to face the crosshair at all times.

*Figure 5.4* In the high-display, low-interaction (HDLI) condition, the user used the keyboard for virtual locomotion and the mouse for aiming and firing at all six sides of the CAVE.
Hence, as depicted in Figure 5.4 of the HDLI condition, the user used the mouse to move the crosshair among the six stereoscopic CAVE sides, presumably physically turning with the turntable at the same time to face the crosshair, while using the arrow or WASD keys to move relative to it.

**Low-display, high-interaction (LDHI):** This condition was very similar to the HDHI condition except that physical body rotations no longer sufficed for turning to see the rest of the environment due to the reduced FOR. Instead, we had to provide a technique for *virtual turning*. In many CAVE applications, the wand’s joystick is used to enable virtual turning, but for this experiment, we did not consider this a suitable technique for two reasons. First, it increased the number of physical actions required by the user to fully interact, hence increasing the cognitive load on the user. Second, the low-display, low-interaction condition would not be using the wand device, and, therefore, virtual turning would be confounded between these two conditions.

With this in mind, we decided to activate virtual turning when the crosshair moves within five degrees of the left and right edges of the single CAVE wall. The activating edge determined the direction of the rotation while the rotation speed was linearly related to the distance between the crosshair and the edge, with a maximum rotation speed of 2.5 degrees once the crosshair was at the edge or off-screen.

![Figure 5.5](image)

*Figure 5.5* In the low-display, high-interaction (LDHI) condition, the user used the human joystick technique for virtual locomotion and a 6-DOF wand for 3D aiming and firing at the front wall of the CAVE.

As seen in Figure 5.5, the user still used the human joystick technique to move through the world in any direction while pointing the wand toward the front CAVE wall. Virtual turning was
provided by pointing the crosshair near or off the edges of the display screen. The graphics were non-stereoscopic, and the projectors for the other CAVE sides were shuttered to create the reduced FOR.

**Low-display, low-interaction (LDLI):** As in the HDLI condition, we designed the mouse in the LDLI condition to control the movement of the crosshair except that, like the LDHI condition, the crosshair also activates virtual turning when near to or past the left and right edges of the front CAVE wall. As depicted in Fig. 6, the user moved the crosshair around on the front CAVE wall with the mouse, virtually turning by moving the crosshair off-screen, and moved relative to the crosshair by using the arrow or WASD keys. For this condition, the graphics were non-stereoscopic, and the other projectors were shuttered.

![Figure 5.6](image)

**Figure 5.6** In the low-display, low-interaction (LDLI) condition, the user used the keyboard for virtual locomotion and the mouse for aiming and firing at the front wall of the CAVE.

### 5.5 Dependent Variables

Concerned with the effects of display and interaction fidelity on the user experience, we decided to gather a broad range of metrics related to user performance, presence, engagement, and perceived usability. For user performance, our FPS game provided several objective metrics per section: completion time, damage taken, accuracy, and number of headshots. We did not track the number of enemy deaths as each section involved eliminating eight bots.

In order to measure perceptions of presence, we administered the Slater-Usoh-Steed (SUS) Presence Questionnaire [20] after each condition. Similarly, to measure engagement, we used a modified Game Engagement Questionnaire (GEQ) [32] after each condition. For perceived
usability and preferences, we developed our own usability questionnaire consisting of seven-point Likert-scale items, which we also administered after each condition.

### 5.6 Procedure

Once recruited, each participant was required to sign an informed consent form and fill out a background survey, which collected data about their gaming and firearm experiences in addition to general demographic information. After the background survey, we administered a spatial orientation test [115] to analyze the spatial abilities of our participants.

In the next phase of the procedure, each participant experienced a high-fidelity VR simulation of a kitchen for five minutes. In prior VR studies involving performance tasks, we had observed participants performing poorly in initial tasks due to being engrossed by the high-fidelity VR. Hence, we hoped this VR exposure would eliminate those “wow-factor” situations.

After the VR exposure phase, participants would proceed through our four experimental conditions, using the order of their assigned permutation. We began each condition with a training session, in which the experimenter would explain how to interact in the given condition and allow the participant to practice with a small five-section map with bots. After the practice session, participants were informed to play through a ten-section map as quickly as possible while avoiding damage and maintaining high accuracy. Afterwards, we gave the participant the presence, engagement, and usability questionnaires. Participation concluded after the fourth condition and normally lasted for approximately 120 minutes, including scheduled breaks.

### 5.7 Participants

To balance ordering effects, we recruited 24 unpaid participants (23 males, 1 female), one for each permutation of the four conditions. The age range of the participants was 18 to 26 years old with a mean age of 20. Using their background survey data, we calculated an FPS-expertise score for each participant by adding the number of hours they played FPS games in the week prior to participation, the average number of hours they played FPS games per week, and the number of FPS games they had ever completed or “beaten”. These calculations yielded expertise scores ranging from 0 to 33, with a mean of 12.69. We used these scores during analysis to determine if FPS expertise had a significant effect on our results.
5.8 Results

5.8.1 Objective Results

For overall completion times, we performed a two-way, repeated-measures ANOVA and determined that neither display fidelity nor interaction fidelity had a significant main effect, but that there was a significant interaction between the two (F(1, 23) = 82.3503, p < 0.0001). Post hoc comparison using the Tukey HSD test indicated that the LDLI and HDHI conditions were significantly faster than the LDHI and HDLI conditions (see Figure 5.7).

![Graph of Completion Time](image)

**Figure 5.7** The LDLI and HDHI conditions were significantly faster than the two “mixed fidelity” conditions for completion time.

For the total damage taken, we performed another two-way, repeated-measures ANOVA and found that the level of interaction fidelity had a significant effect (F(1, 23) = 71.2675, p < 0.0001), with high interaction performing better than low interaction. Display fidelity did not have a significant effect though there was a significant interaction between the two variables (F(1, 23) = 62.0083, p < 0.0001). Based on a Tukey HSD post-hoc test, the HDHI condition was significantly the best and the HDLI condition was significantly the worst, while the two low-display conditions were not significantly different from each other (see Figure 5.8).
Figure 5.8 The HDHI condition was significantly the best for avoiding damage while the HDLI condition was significantly the worst.

For overall accuracy, another two-way, repeated-measures ANOVA indicated that both display fidelity and interaction fidelity had significant effects. For display fidelity (F(1, 23) = 10.0048, p = 0.0043), low display (M = 48.18%) provided significantly better accuracy than high display (M = 45.13%). Similarly, for interaction fidelity (F(1, 23) = 14.3572, p = 0.0009), low interaction (M = 49.60%) was significantly more accurate than high interaction (M = 43.72%). For accuracy, there was no significant interaction between the two aspects of fidelity.

With regard to the total number of headshots, we did not find a significant effect of either display fidelity or interaction fidelity, based on another two-factor ANOVA. Additionally, there was not a significant interaction between the two.

To determine if stereoscopy was likely to have had a significant effect within our experiment, we conducted one-way, repeated-measures ANOVAs (display fidelity) on the objective metrics collected from the map sections (2, 6, 8, and 10) designed to exercise stereoscopy. Display fidelity did not have a significant effect for any of the four metrics. Contrastingly, we conducted one-way, repeated-measures ANOVAs (display fidelity) on the FOR sections (3, 7, 9, and 10) and found that display fidelity had significant effects on completion times (F(1, 23) = 34.3228, p < 0.0001), damage taken (F(1, 23) = 6.5804, p = 0.0173), and accuracy (F(1, 23) = 21.8265, p = 0.0001), with high display performing significantly worse than low display in all cases.

Similarly, we conducted one-way, repeated-measures ANOVAs (interaction fidelity) on the objective metrics collected from the sections designed to exercise aiming (4, 8, 9, and 10) and
found that interaction fidelity had significant effects on completion times \( (F(1, 23) = 4.7341, p = 0.0401) \) and damage taken \( (F(1, 23) = 33.8057, p < 0.0001) \), with high interaction performing significantly better than low interaction in both cases. In the locomotion sections (5, 6, 7, and 10), we determined that interaction fidelity had significant effects on damage taken \( (F(1, 23) = 48.7039, p < 0.0001) \) and accuracy \( (F(1, 23) = 5.8290, p = 0.0241) \), with high interaction performing better for avoiding damage but worse for accurate firing.

To determine if participants’ backgrounds had any significant effects on our results, we computed Pearson correlation coefficients to assess the relationships between our objective metrics and participants’ spatial abilities, FPS expertise, and firearm expertise. We found a positive correlation between spatial ability and the number of headshots \( (r = 0.3750, p = 0.0002) \), but a negative correlation between spatial ability and overall accuracy \( (r = -0.2241, p = 0.0282) \). We also found a positive correlation between firearm expertise and total headshots \( (r = 0.3050, p = 0.0025) \). Interestingly, we did not find any correlations between the FPS expertise of participants and our objective metrics.

### 5.8.2 Subjective Results

For presence, we performed a two-way, repeated-measures ANOVA (display fidelity and interaction fidelity) and determined that both variables had a significant effect on SUS presence scores. For display fidelity \( (F(1, 23) = 27.4669, p < 0.0001) \), high display \( (M = 2.7500) \) provided significantly more presence than low display \( (M = 1.3333) \). Similarly for interaction fidelity \( (F(1, 23) = 41.9552, p < 0.0001) \), the high level of interaction \( (M = 3.0000) \) provided significantly more presence than the low level \( (M = 1.0833) \). There was a significant interaction between our two variables for presence \( (F(1, 23) = 28.2273, p < 0.0001) \). Based on a Tukey HSD post-hoc test, the HDHI condition provided significantly more presence than the other three conditions.

For engagement, we performed another two-way, repeated-measures ANOVA and determined that both display fidelity \( (F(1, 23) = 16.4229, p = 0.0005) \) and interaction fidelity \( (F(1, 23) = 37.8723, p < 0.0001) \) had significant effects on the modified-GEQ scores. High display \( (M = 47.7917) \) engaged the participants significantly more than low display \( (M = 43.3958) \), and the high level of interaction \( (M = 49.7708) \) provided significantly more engagement than the low level \( (M = 41.4167) \). Again, there was a significant interaction between our two variables for engagement \( (F(1, 23) = 9.5299, p = 0.0052) \). Post hoc comparison using the Tukey HSD test indicated that the HDHI condition was perceived as significantly more engaging than the other three conditions.

For perceived usability, another two-way, repeated-measures ANOVA indicated that both display fidelity \( (F(1, 23) = 4.4756, p = 0.0454) \) and interaction fidelity \( (F(1, 23) = 38.0305, p < 0.0001) \)
0.0001) had significant effects on total usability scores. Participants perceived high display (M = 59.5000) as significantly more usable than low display (M = 56.2292), and the high interaction (M = 62.9583) was perceived as significantly more usable than low interaction (M = 52.7708). There was a significant interaction between the two variables (F(1, 23) = 70.3930, p < 0.0001). Post hoc comparison using the Tukey HSD test indicated that the HDHI condition was perceived as significantly more usable than the other three conditions.

5.9 Discussion

Based on the results, our observations, and the comments of participants, we have drawn four inferences from our systematic evaluation of display and interaction fidelity.

5.9.1 Level of Fidelity Impacts Strategy

During our study, we observed that both display fidelity and interaction fidelity seemed to affect the strategies of our participants. Depending on the level of display fidelity, users switched between two strategies for firing at targets. In the high-display conditions, most participants would “spray” gunfire while moving the crosshair towards an enemy (participants were given an unlimited amount of ammunition). In the low-display conditions, however, participants usually lined up the crosshair with the enemy before firing. The significant effect display fidelity had on overall accuracy supports these observations, as low display fidelity was more accurate than high display fidelity. One important consideration about these observed strategies is that in the high-display conditions, participants were able to see their enemies using peripheral vision before moving the crosshair, while in the low-display conditions, participants often would not see their enemies until after virtually turning.

We observed a similar difference in strategies related to interaction fidelity. In the high-interaction conditions, participants tended to move more using the human joystick technique than they moved with the keyboard technique in the low-interaction conditions. This difference in strategies resulted in participants taking less damage and being less accurate with high interaction fidelity while taking more damage and being more accurate with the low level of interaction fidelity. Our analyses concerning damage taken and overall accuracy support both of these observations. One possible explanation for these choices in strategies is that the human joystick technique requires physical movement back to the neutral zone to stop any current virtual movement while the keyboard technique only requires the user to stop pressing the arrow or WASD keys.
5.9.2 Familiarity Improves Performance

A key lesson we took from our systematic evaluation of fidelity is that familiarity improves user performance. Despite being the two extreme combinations of display and interaction fidelity, and despite affording contrasting user strategies, the LDLI and HDHI conditions outperformed the other two “mixed fidelity” conditions with regard to our objective metrics. For completion times, both of these conditions were significantly faster than the LDHI and HDLI conditions. For damage taken, the HDHI condition significantly outperformed the others. Similarly, the LDLI condition provided the best accuracy due to its combination of low display and low interaction, both of which were significantly better than their higher counterparts for accuracy. We saw these results despite the fact that participants were trained on each condition and practiced before completing the actual trials.

Based on our observations and comments from participants, we attribute the excellent performance of the LDLI and HDHI conditions to familiarity. Conceptually, the LDLI condition was very similar to a standard, desktop FPS game with the participants using a mouse and keyboard to interact with a low FOR. Several participants commented that this condition reminded them of playing a desktop FPS. The HDHI condition was similar to interaction in the real world. Participants were expected to hold and point the 6-DOF wand like they would a real weapon, they turned physically to face different directions in the virtual world, and they were afforded some physical locomotion through the use of the human joystick technique. Several participants also commented on how “realistic” the HDHI condition was for them.

In contrast, it is difficult to draw analogies between the two mixed conditions and anything users are familiar with. For instance, the HDLI condition is uncommon because most higher-end display systems come with capabilities to provide higher-fidelity interactions through tracking systems. There might be slight similarities between the LDHI condition and some current motion-controlled video game systems, which would explain why it fared better than the HDLI condition. In particular, the ability to physically point at a target can be found in many newer video games, but the ability to physically move at the same time is less common.

5.9.3 High Fidelity Increases Presence, Engagement, and Perceived Usability

Our study also showed that high levels of either display fidelity or interaction fidelity increased the positive subjective responses of users to the VR system. For presence, engagement, and perceived usability, we found that both display and interaction fidelity had significant positive effects. More importantly, we found that users had the greatest senses of presence, engagement, and usability with the high-display, high-interaction condition. Designers concerned with achieving high levels of presence, engagement, or perceived usability should consider that higher
levels of fidelity appear most suitable. In particular, high levels of both display fidelity and interaction fidelity appear to combine for the best results.

5.9.4 Effects of Fidelity Components Are Nuanced

Despite prior studies demonstrating the significant effects of stereoscopy [24, 67], the results of our evaluation imply that stereoscopy did not have a significant effect on our FPS task. Even though we specifically designed map sections to exercise this display-fidelity component, we found no significant effects of display fidelity on performance in these sections. The most likely reason for this lies in the nature of the FPS aiming task. Regardless of the level of interaction fidelity, a user positions an always-visible crosshair at a human-sized target and then proceeds to fire. Obviously, when the target is far away from the user, stereoscopy is not going to have a significant effect, but even when the target is within 3m, the target appears much larger for the purpose of aiming and stereoscopy is not necessary.

On the other hand, we did find evidence that a component of display fidelity (FOR) and components of interaction fidelity (aiming and locomotion realism) had significant effects on performance. Although we need further evaluation to understand these effects in detail, we can infer that the influences of display and interaction fidelity components are not universal, but have subtle nuances. They are likely to be dependent on the specific application context, tasks, user strategies, and levels of fidelity.

5.10 Summary

We have demonstrated that there is still much to be learned about the effects of increasing a system’s fidelity to the real world. Using a six-sided CAVE and a performance-intensive FPS game, we systematically evaluated extremely high and low levels of display and interaction fidelity to gain a better understanding of their effects on the user experience for a FPS game.

The results of our study show that the levels of display and interaction fidelity are significant factors in determining performance, presence, engagement, and usability. Combined with existing results in the literature, we have contributed to the overall understanding of the effects of fidelity in three important ways. First, we have shown that increased display fidelity can often have positive effects on the user experience, and very rarely has a negative impact (the negative effect of display fidelity on accuracy in this experiment appears to be due to the display’s influence on user strategy). Second, the combination of display fidelity and interaction fidelity can determine the familiarity of the overall system, and it is this familiarity that seems to determine overall performance in many cases. Third, we have also shown that the level of fidelity can influence user strategy. Due to this limitation, we decided to investigate the effects of display fidelity and interaction fidelity on the subtasks of our FPS, absent of user strategies.
6 Evaluation of FOR and Interaction Fidelity for Subtasks of a First-Person Shooter Game

6.1 Goal

In our prior study, with the goal to learn more about the individual effects of display fidelity and interaction fidelity, we used a six-sided CAVE and a performance-intensive first-person shooter (FPS) game to independently evaluate both display and interaction fidelity at extremely high and low levels. The results of that study indicated that both display fidelity and interaction fidelity significantly affected aspects of the user experience, particularly performance. In addition, we observed that both seemed to affect the strategies of our participants, such as whether to maneuver to avoid damage or stand still to improve accuracy.

In order to gain a deeper understanding of our prior results in the absence of user strategy, we designed and conducted two additional studies to reevaluate the effects of display fidelity and interaction fidelity on subtasks of our FPS game. In the first of these two studies, we focused on subtasks of locomotion, specifically long-distance navigation and maneuvering, while comparing the original study’s high-fidelity locomotion technique to a keyboard technique. In the second study, we evaluated the subtasks of targeting enemies—searching, aiming, and firing—while comparing contrasting levels of pointing fidelity. For both studies, we decided to evaluate the total size of the visual field surrounding the user (i.e., field of regard or FOR) at the four levels of 90, 180, 270, and 360 horizontal degrees since our original study indicated that this component of display fidelity had significant effects on user performance.

6.2 Locomotion Tasks

During our original study, we observed two major types of locomotion used by participants while playing our FPS game. After clearing a section of the map, participants would navigate quickly to get to the next section, which was usually more than 15m away. We classified this type of locomotion as long-distance navigation, with the goal of navigating from point A to point B as quickly as possible. At other times, particularly in combat, participants would move short distances and rapidly change direction in an attempt to avoid gunfire. We classified this type of locomotion as maneuvering, with the goal of avoiding gunfire by changing locomotion direction in response to an enemy’s actions.
To investigate the long-distance navigation subtask, we created a large map consisting of ten sequentially connected sections and a single path. The objective of this task was for the user to navigate along the path from the start of the first section to the end of the last section as quickly as possible. Because we were only concerned with the task of locomotion, we indicated the path with a wide red line on the floor of the map to eliminate the need for wayfinding [47].

To investigate the maneuvering subtask, we designed an evasion scenario that consisted of a single room with crates stacked in the center and an enemy “android” patrolling around the crates. The objective of this scenario was for the user to avoid being spotted by the android for 150 seconds by maneuvering around the crates for cover. To emphasize the need for maneuvering, the android would change its circling direction randomly once every 25-second interval. Because we were only concerned with the user’s ability to change locomotion direction in response to an enemy’s actions, we provided the user virtual X-ray vision to see changes in the android’s movement through the crates and without losing cover. We also decided to linearly increase the speed of the android’s movement to increase the difficulty as time passed.

### 6.3 Apparatus for Locomotion Tasks

In order to evaluate contrasting levels of FOR, we used the same six-sided CAVE used in our original study. This rear-projected, cube-shaped display system measured 3m x 3m x 3m and had a display resolution of 1050 x 1050 pixels on each screen. CrystalEyes technology was used for active stereoscopy. We used Syzygy [108] to control the system’s master/slave framework, which consisted of a master-node computer and six supporting computers (one per screen). Our FPS game, based a Syzygy map viewer, ran at an average of 55 frames per second on this system.

Again, we used the CAVE’s Intersense IS-900 Wireless tracking system with a 6-DOF head tracker and 6-DOF wand to provide input for our high levels of interaction fidelity. We used a Bluetooth three-button mouse and a Bluetooth number pad for our low levels of interaction fidelity. For this study, we set the low-fidelity devices within a cardboard carrier with a padded neck strap to allow users to physically move around with these devices (see Figure 6.1). The device carrier weighed 725g and measured 61cm x 41cm x 9cm. We maintained the same constant, moderate mouse sensitivity as our prior study to avoid variability.
6.4 Experimental Design for Locomotion Tasks

6.4.1 Independent Variable: Field of Regard

Because the results of our original study indicated that FOR likely had a significant effect on user performance, we wished to evaluate the display-fidelity component at more levels than the prior study. We chose to evaluate horizontal FOR at 90, 180, 270, and 360 degrees by shuttering combinations of CAVE-wall projectors. For all four levels of FOR, we kept the floor and ceiling projectors on to reduce confounds and to provide a horizontal and vertical 360-degree FOR in the highest level.

As in our original study, physical body rotations were not sufficient to see the entire environment with the lower levels of FOR. Again, we provided users with virtual turning by virtually rotating the environment when the weapon crosshair was within five degrees of the leftmost or rightmost edge of the given FOR. The activating edge determined the direction of the rotation while the rotation speed was linearly related to the distance between the crosshair and the edge. We set a maximum rotation speed of 1.0 degree per frame (or 55 degrees per second on average) after observing several cases of motion sickness during a pilot study.
6.4.2 Independent Variable: Locomotion Fidelity

Since we wished to learn more about the effects of interaction fidelity on locomotion, we decided to evaluate locomotion fidelity at the same high and low levels as our original study by using the more-natural *human joystick* technique and the keyboard technique. In the human joystick technique, the 2D horizontal vector from the center of the CAVE to the user’s tracked head position was used to determine the velocity and direction of virtual locomotion, like a joystick’s 2D vector would be used. To avoid constant virtual locomotion due to small distances between the user’s head position and the center of the CAVE, the human joystick had a *neutral zone* with a 20cm radius at the center of the CAVE. While in the neutral zone, one-to-one head tracking provided the user the ability to make minor changes to the viewpoint, such as peering around a corner. Outside the neutral zone, virtual locomotion was provided at a speed linearly related to the user’s distance from the neutral zone with a maximum speed of 5cm per frame (or 275cm per second on average), which was equivalent to the keyboard technique’s maximum speed.

The keyboard technique was based on traditional FPS keyboard controls with one exception. With surrounding screens, it made little sense to always map the up arrow to motion toward the “front” wall of the CAVE, since users are constantly turning to face different screens. Instead, keyboard commands were interpreted relative to the 2D horizontal direction of the crosshair from the center of the CAVE. Hence, if the player positioned the crosshair on the left wall of the CAVE, the up arrow would activate motion towards the left side instead of the front.

6.4.3 Independent Variable: Pointing Fidelity

Because keyboard locomotion and virtual turning both depended on the ability to position the crosshair, we evaluated pointing fidelity as another independent variable for this study.

In our prior study (see chapter 5), pointing was achieved in the high levels of interaction fidelity by using the 6-DOF wand to directly point the crosshair into the 3D environment. In the low levels of interaction fidelity, the mouse controlled the movement of the crosshair, even across the surrounding display screens, like a cursor on a multi-monitor desktop. For this study, we chose to reinvestigate both the high-fidelity wand technique and the low-fidelity mouse technique.

During our prior study, we observed a few critical failures in which a participant would lose track of the crosshair using the mouse technique in the 360-degree FOR condition. These failures were due to the lack of a frame of reference since the mouse is a relative-positioning device (instead of absolute) and there were more degrees of visual field in which to look for the crosshair.

We developed the *enhanced mouse* (or *e-mouse*) technique to address this issue and to learn more about mid-fidelity interaction techniques. To provide the missing frame of reference, we
decided to use the direction the user’s body was facing (provided by a 6-DOF tracker attached to the device carrier) as a vector pointing to the center of a 90-degree “desktop”. We then restricted the mouse to only controlling the crosshair within this “desktop” space. The user could then physically turn and face another direction to move this frame of reference and the crosshair to another area of the CAVE (see Figure 6.2). Based on a pilot study and to avoid constant movement of the crosshair due to small changes in the user’s heading, we only updated the frame of reference after the heading changed by 2.5 degrees or more from the last update.

![Image of the enhanced mouse](image)

**Figure 6.2** The enhanced mouse (e-mouse) provided users with a frame of reference (shown in blue). A) The user uses the mouse to move the crosshair (shown in red) within the frame. B) The user faces a new direction to move the frame of reference and the crosshair.

### 6.4.4 Mixed Experimental Design

In order to maintain a manageable study and not require excessive participation times, we decided to use a mixed experimental design. Because we were most concerned with the effects of FOR (four levels) and locomotion fidelity (two levels) on our locomotion subtasks (two levels), we decided to keep them within subjects for a total of 16 conditions per participant. We used a Latin square design to determine the orderings of the four FOR levels and alternated the presentation of the locomotion techniques between subjects. We controlled pointing fidelity (three levels) between subjects.

### 6.5 Dependent Variables for Locomotion Tasks

For the long-distance navigation subtask, our application recorded the navigation times for each section and the total time to navigate the entire map. For the maneuvering subtask, our
application recorded how much time passed before the user was spotted by the android, with a maximum of 150 seconds.

6.6 Procedure for Locomotion Tasks

Once recruited, participants were required to sign an informed consent form and fill out a background survey, which collected data about their gaming experiences in addition to general demographic information. After the background survey, we administered a cube-comparison test [115] for later analysis of the spatial abilities of our participants.

In the next phase of the procedure, participants experienced a high-fidelity VR simulation of a kitchen for five minutes. In other VR studies involving performance tasks, we had observed participants performing poorly in initial tasks due to being engrossed by the high-fidelity VR. Hence, like our prior study, we used this VR exposure to reduce those “wow-factor” situations.

After the VR exposure phase, we trained participants how to use their first assigned locomotion techniques. Training involved completing the long-distance navigation subtask in the same FOR level as the first assigned condition. Afterwards, participants completed the long-distance navigation subtask again for all four levels of FOR. Next, participants practiced the maneuvering subtask for 150 seconds. Following this practice session, participants attempted the maneuvering subtask again for all four levels of FOR.

After completing the long-distance navigation and maneuvering subtasks with their first assigned locomotion technique, participants repeated the subtasks, including training, with the second locomotion technique. Finally, we administered an exit questionnaire to survey their opinions of FOR and locomotion techniques. An experimental session normally lasted for approximately 120 minutes, including breaks.

6.7 Participants for Locomotion Tasks

We recruited 12 unpaid participants (ten males, two females), four for each pointing technique. The age range of the participants was 18 to 39 years old with a mean age of 24. Using their background survey data, we calculated an FPS-expertise score for each participant by adding the number of hours they played FPS games in the week prior to participation, the average number of hours they played FPS games per week, and the number of FPS games they had ever completed or “beaten”. These calculations yielded expertise scores ranging from 0 to 25, with a mean of 12.56. We used these scores during analysis to determine if FPS expertise had a significant effect on our results.
6.8 Results for Locomotion Tasks

For overall long-distance navigation times, we performed a three-way ANOVA (FOR, locomotion fidelity, and pointing fidelity) with repeated measures on FOR and locomotion fidelity. We determined that neither FOR nor pointing fidelity had a significant main effect, but locomotion fidelity did ($F(1,9) = 8.9303, p = 0.0152$), with keyboard locomotion ($M = 108.11s$) outperforming the human joystick ($M = 121.61s$). This was likely due to keyboard locomotion requiring less effort to initiate and stop movement (pressing and releasing a key) than the human joystick, which required physically stepping out of and back into the neutral zone. There were no significant interactions among the three factors for long-distance navigation times. For maneuvering times, we performed another three-way ANOVA with repeated measures and found no significant main effects or significant interactions.

To determine if participants’ backgrounds had any significant effects on our results, we computed Pearson correlation coefficients to assess the relationships between our metrics and participants’ spatial abilities and FPS expertise. We found a positive correlation between spatial ability and maneuvering time ($r = 0.2366, p = 0.0203$), indicating a higher spatial ability allows for better maneuvering. Interestingly, we did not find any correlations between FPS expertise and our objective metrics.

6.9 Targeting Tasks

Targeting enemies in our FPS game comprised three major subtasks. The first subtask involved the user looking around or searching for an enemy to target. The second subtask involved moving the crosshair from its current position to the enemy’s position (i.e., aiming). The final subtask was pressing the trigger button or firing.

With the searching subtask, we wanted to learn about how quickly the user could spot an enemy. To facilitate this, we first designed a single room measuring 27m x 27m with a few crates scattered about, which was representative of most of the rooms in the map from our original study. Positioned in the center of the environment and the CAVE, the user started a searching trial by looking towards the “front” wall of the CAVE at a red android, which would disappear when within the central 30 degrees of the user’s FOV. A gray android would then appear in a random location selected from a queue of unobstructed locations (this queue of locations was designed to balance both target distance and direction from the user among all search trials). After spotting the gray android within the 120-degree FOV provided by the CrystalEyes glasses, the user would press the trigger button to end the trial (the user was not required to point at the android with the crosshair). If the gray android was not visible within the 120-degree FOV when the trigger was pressed, an error would be recorded and the trial would be added back to the queue.
In the aiming subtask, we were concerned with how FOR and pointing fidelity would affect how quickly the user could move the crosshair from a prior position to an enemy’s location. Unlike studies of Fitts’ law [116], the target’s location would not always be known before the start of this task due to our lower FOR conditions. We could have indicated where the enemy would be prior to each trial, but that would have increased the mental workload required and may have led to miscommunication issues. Instead, we had the user search for the target before aiming, which was more ecologically valid. We calculated adjusted aiming times by subtracting the participant’s average search subtask time for the same condition.

Again positioned in the center of the environment and the CAVE, the user started an aiming trial by pointing towards the “front” wall of the CAVE at a mid-ranged, red android. After the user pressed the trigger button with the crosshair positioned over the android, the red android would again disappear and a gray android would appear in a random location selected from the same queue of unobstructed locations. After spotting the gray android, the user would use the assigned pointing technique to position the crosshair over the target and then press the trigger button. If the crosshair was not over the gray android when the trigger was pressed, an error would be recorded and the trial would be added back to the queue.

With the firing subtask, we wanted to learn about how quickly the user could repeatedly fire while keeping the crosshair over a target. We were not concerned with the effects of FOR on this subtask, but we were concerned with the differences between stationary and slightly moving targets, in addition to pointing fidelity and target distance. Again, positioned in the center of the single room and the CAVE, the user started a firing trial using the assigned pointing technique to position the crosshair on the “front” CAVE wall over a red android located at a close, mid-ranged, or far distance. When ready, the user would begin repeatedly pressing the trigger button as quickly as possible until successfully hitting the android 20 times. For the series of firing trials, half of the androids would remain stationary while being hit while the other half would move left or right with each hit, remaining within 1m of their original locations.

6.10 Apparatus for Targeting Tasks

We used the same six-sided CAVE as we did in the prior studies. Again, we used the Intersense IS-900 Wireless tracking system to provide input for our high levels of interaction fidelity. We also reused the Bluetooth mouse and Bluetooth number pad with the device carrier for our lower levels of interaction.
6.11 Experimental Design for Targeting Tasks

6.11.1 Independent Variable: Field of Regard

Despite FOR not having a significant effect in the locomotion study, we decided to evaluate the component again at 90, 180, 270, and 360 horizontal degrees because the results of our original study (see chapter 5) indicated that FOR likely had a significant effect on user performance. Again, we provided users with virtual turning by rotating the environment when the crosshair was within five degrees of the leftmost or rightmost edge of the given FOR. We used the same maximum rotation speed of 1.0 degree per frame (or 55 degrees per second on average).

6.11.2 Independent Variable: Pointing Fidelity

Because we were focused on the subtasks of targeting enemies, we decided to evaluate pointing fidelity again, even though it had no significant effect in the locomotion study. We evaluated pointing fidelity at the same three levels: the low-fidelity mouse technique, the mid-fidelity e-mouse technique, and the high-fidelity wand technique.

6.11.3 Independent Variable: Target Distance

In addition to FOR and pointing fidelity, we were also interested in how the distance to the target from the user would affect performance. We were particularly interested in potential interactions between pointing fidelity and target distance. We decided to evaluate target distance at three levels: close (within 3m), mid-range (6m to 9m away), and far (further than 12m).

6.11.4 Mixed Experimental Design

Because we were evaluating three independent variables and focusing on three subtasks, we decided to use another mixed experimental design to avoid excessively long participation times. Since we believed pointing fidelity (three levels) would have a significant effect on the targeting subtasks regardless of the experimental design, we chose to control it between subjects. This also reduced the number of interaction techniques each participant would have to learn from three to one. By evaluating pointing fidelity between subjects, we were able to control FOR (four levels) and target distance (three levels) within subjects. We used a Latin square design to determine the orderings of the four FOR levels. We randomly varied target distance in a balanced manner among the trials of each subtask.
Dependent Variables for Targeting Tasks

For each searching trial, our application recorded the time between the red android disappearing and the trigger button being pressed. In addition to time, the application also tracked the total number of errors during the entire series of searching trials. Our application recorded similar time measurements and errors for the aiming trials. For each firing trial, the application recorded the time between the first trigger press and the 20th successful hit. Additionally, it tracked the total number of trigger presses to calculate the accuracy for each trial.

Procedure for Targeting Tasks

As in the locomotion study, participants were required to sign an informed consent form and fill out a background survey, which collected data about firearm experiences and gaming experience. Afterwards, we administered a cube-comparison test [115]. Then participants were exposed to the high-fidelity VR kitchen to reduce distractions due to “wow-factor” situations.

After the VR exposure phase, we trained participants on how to use their assigned pointing techniques to position the crosshair and activate virtual turning. Following training, participants completed 30 successful searching trials (of which the first six were practice) for all four levels of FOR. Participants then completed 30 successful aiming trials (the first six as practice) for all four levels of FOR. After the aiming trials, participants then completed 18 firing trials with the first six used as practice.

Following the firing trials, we administered an exit questionnaire to survey participants’ opinions of FOR and their assigned pointing technique. Experimental sessions normally lasted for approximately 120 minutes, including scheduled breaks.

Participants for Targeting Tasks

We recruited 12 new, unpaid participants (ten males, two females), four for each pointing technique. The age range of the participants was 18 to 38 years old, with a mean age of 25. Again, using background survey data as described in section 4.7, we calculated FPS-expertise scores for participants and found scores ranging from 1 to 80, with a mean of 25.79. Reported firearm experiences ranged from 0 to more than 100 occasions of using a firearm, with a mean of 20 occasions.

Results for Targeting Tasks

For search times, we performed a three-way ANOVA (FOR, pointing fidelity, and target distance) with repeated measures on FOR and target distance. We determined that neither
pointing fidelity nor target distance had a significant main effect, but FOR did ($F(3, 7) = 31.3959, p = 0.0002$). Based on a Tukey HSD post-hoc test, all four levels of FOR were significantly different (see values in Figure 6.3). As Figure 6.3 shows, these differences were due to trials where virtual turning was required to see the target (e.g., virtual turning was required when the target appeared on the left wall in the 90 and 180-degree conditions, but not in the 270 and 360-degree conditions). There were no significant interactions among the three factors. For search errors, we performed another three-way ANOVA with repeated measures and found no significant main effects or significant interactions.

![Mean Search Times](image)

*Figure 6.3* Increased field of regard afforded faster searching.

Because each aiming trial also involved searching and we were only concerned with the physical act of aiming, we calculated adjusted times for aiming by taking a participant’s average aiming time for a FOR condition and subtracting the participant’s average search time for that same condition. We performed another three-way ANOVA with repeated measures for these adjusted times. We found that both pointing fidelity ($F(2, 9) = 11.0595, p = 0.0038$) and target distance ($F(2, 8) = 6.1317, p = 0.0243$) had significant effects while FOR did not. Based on a Tukey HSD post-hoc test, the mouse and e-mouse pointing techniques were significantly slower than the wand technique (see Figure 6.4). We conjecture this was due to the ability to leverage proprioceptive senses with the absolute positioning of the wand, as opposed to the relative positioning of the mouse. Another Tukey HSD post-hoc test indicated that far targets ($M = 0.6916s$) required significantly more time to aim at than mid-range ($M = 0.4719s$) or close ($M = 0.4762s$) targets, which is an intuitive result since distant targets are smaller. There were no significant interactions among the three factors for aiming times.
Figure 6.4 Mean adjusted aiming times with standard error bars. The high-fidelity wand technique was faster for aiming than the mouse and e-mouse techniques.

For aiming errors, another three-way ANOVA with repeated measures indicated that neither FOR nor pointing fidelity had a significant main effect, but target distance did (F(2, 8) = 9.9957, p = 0.0067), with far targets (M = 1.1667) inducing significantly more errors than close targets (M = 0.3125). There were no significant interactions for aiming errors.

For firing times, we performed a three-way ANOVA (pointing fidelity, target distance, and target movement) with repeated measures on target distance and target movement. We determined that pointing fidelity (F(2, 9) = 5.4981, p = 0.0275), target distance (F(2, 8) = 18.2845, p = 0.0010), and target movement (F(1, 9) = 116.2463, p < 0.0001) all had significant main effects. A Tukey HSD post-hoc test revealed that the e-mouse performed significantly worse than the mouse and wand techniques (see Figure 6.5). Another Tukey HSD post-hoc test showed it took significantly longer to repeatedly fire at far targets (M = 6.2421s) than close targets (M = 5.2322s). A Student’s t-test revealed moving targets (M = 7.8891s) took significantly longer to repeatedly fire at than stationary targets (M = 3.6876s). Among the three factors, there was a single significant interaction between pointing fidelity and movement type (F(2, 9) = 5.5514, p = 0.0269). A Tukey HSD test revealed that using the e-mouse (M = 9.5586s) on moving targets was significantly worse than using the mouse (M = 7.5222s) or wand (M = 6.5864s) on moving targets while there was no significant differences among the techniques on stationary targets. This was likely due to difficulty controlling the crosshair with both the mouse and physical turning.
The e-mouse technique was significantly slower for firing than the mouse and wand techniques.

For firing accuracy, we performed another three-way ANOVA with repeated measures on target distance and target movement. We determined that target distance (F(2, 8) = 10.5237, p = 0.0058) and target movement (F(1, 9) = 275.0244, p < 0.0001) both had significant main effects while pointing fidelity did not. For target distance, a Tukey HSD post-hoc test indicated that close targets (M = 81.90%) were significantly easier to hit than mid-range (M = 76.06%) and far (M = 76.26%) targets. A Student’s t-test revealed that stationary targets (M = 97.25%) were significantly easier to hit than moving targets (M = 58.90%). There were no significant interactions among the three factors.

We computed Pearson correlation coefficients to assess the relationships between our metrics and participants’ spatial abilities, FPS expertise, and firearm experiences. For search times and search errors, we did not find any correlations. For adjusted aiming times, we found significant correlations for spatial ability (r = -0.2216, p = 0.0076), FPS expertise (r = -0.1793, p = 0.0315), and firearm experiences (r = -0.4478, p < 0.0001), indicating that these abilities and experiences afford faster aiming. We did not find any correlations for aiming errors or firing times/accuracy.

**6.16 Discussion**

Based on the results of our original FPS study and the results of the two subtask studies presented here, we have drawn two primary inferences from our systematic evaluations of the effects of display fidelity and interaction fidelity.
6.16.1 Extremely High Interaction Fidelity Provides Better User Performance

The first inference is that extremely high interaction fidelity provides significantly better user performance. In the case of the pointing techniques we evaluated, our results have indicated that the wand technique, which provided the extremely high-fidelity capability to directly point at targets, was significantly faster for aiming than the low-fidelity mouse technique and the mid-fidelity e-mouse technique. We conjecture that this was due to the ability to leverage proprioceptive senses for aiming with the wand technique. Additionally, despite being faster for aiming, the wand technique was apparently as accurate as the mouse and e-mouse techniques, based on the lack of significant effects for aiming errors and firing accuracy.

In addition to pointing, our studies have also indicated that extremely high-fidelity physical turning is faster than low-fidelity virtual turning. Consider our results that indicated increasing FOR affords faster searching. The fastest (and highest) level of FOR was 360 degrees, in which virtual turning was not required and only physical turning was necessary to view the entire virtual environment. Contrastingly, each lower level of FOR was increasingly slower, provided less physical turning, and required more virtual turning. For instance, with the lowest level of 90 degrees, virtual turning was constantly required and physical turning was not useful. Hence, our results favored extremely high-fidelity physical turning to low-fidelity virtual turning.

6.16.2 Moderate Interaction Fidelity Does Not Improve User Performance

The second inference is that moderately increasing interaction fidelity does not necessarily improve user performance and can actually decrease performance in some cases. Consider again the pointing techniques we have evaluated. Our results for aiming times and firing times have indicated that the e-mouse technique performed significantly worse than the high-fidelity wand technique and, in particular, the low-fidelity mouse technique. Interestingly, we designed the e-mouse technique as an enhanced version of the basic mouse technique by providing a frame of reference in increased levels of FOR. Despite the good intentions behind the design of this technique, we believe that the e-mouse induced more mental workload than the mouse because users had to choose between two methods for controlling the crosshair (moving the mouse and physically turning).

Our results for the human joystick technique also provide evidence for this inference. The human joystick was significantly worse for long-distance navigation than the low-fidelity keyboard technique. We designed the human joystick to be a more-natural, higher-fidelity locomotion technique, but it was a compromise since real walking [87] (the highest-fidelity locomotion technique) was not feasible, due to the limited space provided by the CAVE system and the large
virtual space required by our FPS game. Even though the human joystick provided the ability to physically step to initiate virtual locomotion, nuances of the technique, such as the requirement to step back into the neutral zone to stop moving, decreased its overall fidelity.

6.17 Summary

Although a technological revolution has brought more-realistic experiences into the homes of consumers in recent years, we have demonstrated that there is still much to be learned about the effects of increasing a system’s fidelity. Using a six-sided CAVE and a first-person shooter game, we conducted two studies that systematically evaluated FOR and interaction fidelity for locomotion and targeting subtasks, in order to better understand their effects on user performance.

The results of our studies show that the levels of FOR and interaction fidelity are significant factors in determining performance for tasks related to a FPS. Combined with the results of our original study, we have contributed to the overall understanding of the effects of fidelity in two important ways. First, we have shown that extremely high levels of interaction fidelity (and FOR, which affords high-fidelity physical turning) can provide better user performance than lower levels. Second, we have shown that moderately increasing the level of interaction fidelity does not necessarily improve user performance and, in some cases, actually decreases performance compared to low-fidelity interactions. It is important to note that these results may be caveats of using a FPS game for the context of the research though we expect them to be useful when considering display fidelity and interaction fidelity in other application contexts.
7 A FRAMEWORK FOR ANALYZING LEVELS OF INTERACTION FIDELITY

7.1 Motivation

As discussed in Chapter 1, practical evaluations of fidelity are useful for determining if a high-fidelity system is better than a low-fidelity system for a particular task. Nonetheless, the results of practical evaluations are limited in multiple ways. First, the results of practical evaluations are not generalizable due to the high number of confounds between the systems. Second, again due to comparing such different systems, practical evaluations cannot indicate whether moderate levels of fidelity would provide the same significant benefits as the high-fidelity VR systems. Third, because some practical evaluations involve complex applications and interdependent tasks, it is difficult to generalize the results of these evaluations for other applications or tasks.

Due to these limitations of practical evaluations, researchers have begun exploring the effects of fidelity by conducting controlled evaluations, which control one or more components of fidelity to determine their effects and possible interactions. For display fidelity, many controlled evaluations have investigated the effects of visual components such as stereoscopy, FOV, FOR, display resolution, display size, and frame rate (see Chapter 2 for more details). Based on these prior studies, we developed a framework for determining how visual characteristics of display fidelity contribute to the overall level of fidelity in other work [4]. Using this framework to distinguish levels of display fidelity, our research group has successfully conducted more than a dozen controlled evaluations on the effects of display fidelity (e.g., [28, 36, 72, 73]).

A number of controlled evaluations have similarly investigated the effects of interaction fidelity, but these studies have been limited in several ways. Like practical evaluations of VR systems, many controlled evaluations of interaction fidelity are not generalizable due to numerous confounds between different interaction techniques. For instance, consider the study by Hinckley et al. [90]. A number of differences (e.g., 3-DOF vs. 2-DOF input, absolute positioning vs. relative positioning, fully integrated control vs. modal control) could have contributed to users performing better with the high-fidelity techniques. Hence, it is not possible to conclude that the higher DOF caused better user performance because the true cause may have been the subtle integration of control.

Another limitation of controlled evaluations of interaction fidelity is that moderate levels of interaction fidelity are difficult to identify and evaluate. It is easy to identify a high-fidelity interaction technique that will be similar to a real world action. It is also easy to identify a low-fidelity technique that will be drastically different from the real-world action. However, it is
difficult to identify a moderate or mid-fidelity technique, as there is currently no methodology for objectively determining degrees of interaction fidelity. Instead, researchers must make subjective decisions on what aspects of interaction constitute moderate levels of interaction fidelity, and of course, researchers may disagree on whether a “mid-fidelity” interaction technique is truly mid-fidelity.

A similar limitation is that interaction techniques with similar levels of interaction fidelity cannot be compared to effectively determine the effects of interaction fidelity. Consider a hypothetical evaluation demonstrating that boxing in *Wii Sports*, which requires a Wii Remote and Wii Nunchuk, afforded more user enjoyment than boxing in *Kinect Sports*, which relies on controller-less interactions. One researcher may claim that the Wii Remote technique had a higher level of interaction fidelity because it closely approximated the force required of the user, and conclude that increasing interaction fidelity resulted in better user satisfaction. On the other hand, another researcher may argue that the Kinect technique had a higher level of fidelity due to a more accurate replication of movements, and conclude that increasing interaction fidelity did not increase user enjoyment.

Considering the limitations of controlled evaluations of interaction fidelity, the key issue is how to objectively describe the level of fidelity based on the components and aspects of the techniques involved. Currently, there is no taxonomy or framework that defines how these components and aspects contribute to the overall interaction fidelity of a technique. This issue is further complicated by the lack of an objective method that can determine how a particular component or aspect correlates to the level of interaction fidelity for the multitude of interaction techniques that exist.

To address the inability to objectively analyze the level of interaction fidelity provided by an interaction technique, we decided to design a framework for describing the fidelity of specific aspects of interaction, similar to our prior display fidelity framework [4]. By reviewing prior interaction fidelity studies (see Chapter 2) and utilizing our own evaluations of the effects of interaction fidelity (see Chapters 3, 4, 5, and 6), we have developed the Framework for Interaction Fidelity Analysis (FIFA) for objectively analyzing levels of interaction fidelity.

In this chapter, we present the three broad concepts of FIFA—biomechanical symmetry, control symmetry, and system appropriateness—and discuss how each can be analytically evaluated. We then present a series of case studies where we use FIFA to objectively analyze the level of interaction fidelity for some well-known interaction techniques and the techniques used in our own studies. Finally, we discuss how FIFA can be used to analyze levels of interaction fidelity, to provide a method for developing new interaction techniques, and to design controlled experiments for determining the effects of interaction fidelity.
7.2 The Framework for Interaction Fidelity Analysis

As mentioned, we have categorized the aspects of interaction fidelity into three broad concepts: biomechanical symmetry, control symmetry, and system appropriateness. In this section, we define each concept while presenting measures and methods for objectively determining levels of interaction fidelity.

7.2.1 Biomechanical Symmetry

When considering the recent advances of interaction fidelity in videogames and mobile devices, the prevalent use of gestures is the most distinct development. Instead of using joysticks or buttons, gestures allow users to interact with natural postures and body movements. A gesture that greatly corresponds to a real-world action for a particular task provides a high level of interaction fidelity. For example, swinging a PlayStation Move controller to hit a virtual baseball, which has a high correspondence to swinging a real baseball bat, is a high-fidelity gesture. Gestures with lesser degrees of correspondence to real actions, such as jogging in place to indicate the act of running, still afford moderately realistic interactions that we consider mid-fidelity. Finally, a gesture might not correspond to a specific real world action in any regard, which results in a low level of interaction fidelity. Shaking a Wii Remote to stand up after being knocked down in *Wii Sports* boxing is an example of a low-fidelity gesture.

For describing the level of correspondence between an interaction and the action that would be used to accomplish a represented real-world task, we use the term biomechanical symmetry. We define *biomechanical symmetry* as the objective degree of exactness with which real world body movements for a task can be reproduced through interaction to successfully complete the task. Essentially, the level of biomechanical symmetry is the amount of correspondence between body movements made during an interaction and the body movements that would be made for the same task in the real world. Hence, the high-fidelity PlayStation Move gesture mentioned above has a high level of biomechanical symmetry to swinging a baseball bat.

In the field of biomechanics, a substantial amount of work has focused on how to properly describe, measure, analyze, and assess human movements. In the book *Biomechanics and Motor Control of Human Movement* [117], David Winter categorized the variables that are used in the description and analysis of body movements as kinematics, kinetics, anthropometry, muscle mechanics, and electromyography. Kinematic, kinetic, and anthropometric variables are used to describe and analyze body movements, their causing forces, and the body parts involved in those movements, respectively. On the other hand, muscle mechanics and electromyography are concerned with the mechanical characteristics of muscles and the neurological signals used to control the muscles. For FIFA and our concept of biomechanical symmetry, we are mainly
interested with body movements and not individual muscles. Therefore, we only focus on kinematics, kinetics, and anthropometry.

**Kinematic Symmetry**

Kinematics is concerned with the details of body motion, but not with the forces that cause the motion [117]. We use the term *kinematic symmetry* to refer to the objective degree of exactness with which a real-world body motion for a task (regardless of its causing forces) can be reproduced through interaction to successfully complete the task. Returning to our prior example, swinging the Move controller has a high level of kinematic symmetry to swinging the baseball bat because the motions of the torso, arms, and hands in the swing are very similar to the motions of those body segments when swinging a bat in the real world.

Leveraging prior work in biomechanics, kinematic symmetry can be objectively evaluated in a number of ways. The complete kinematics of a body segment, such as a forearm, can be described with a number of spatial-temporal characteristics [117], which include

- the position \((x, y, z)\) of the segment,
- the linear velocity \((x', y', z')\) of the segment,
- the linear acceleration \((x'', y'', z'')\) of the segment,
- the angle \((\theta_{xy}, \theta_{yz})\) of the segment in two planes,
- the angular velocity \((\omega_{xy}, \omega_{yz})\) of the segment, and
- the angular acceleration \((\alpha_{xy}, \alpha_{yz})\) of the segment.

By analyzing such characteristics, researchers in biomechanics have been able to identify kinematic differences in the movements of people. For instance, Grieve and Gear found differences in stride lengths, step frequencies, swing times, and walking speeds among children and adults [118]. Using a similar approach, we can objectively compare the kinematics of a real-world body motion to the kinematics of a successful interaction by analyzing the variances of the spatial-temporal characteristics involved, which is how we analytically determined that swinging the Move controller has a high level of kinematic symmetry to swinging the baseball bat.

Using an analytic approach, we can also compare the kinematic symmetries of differing interaction techniques. Consider the real-world action of positioning and rotating a handheld object in 3D space, similar to Zhai’s 6-DOF “docking” task [94]. The 6-DOF glove technique that Zhai developed allowed users to make gestures with their arms, hands, and fingers that had nearly the same kinematics as those body segments in the real-world action. Now consider using a standard Bluetooth mouse to complete the same 6-DOF task. A user could hold the wireless mouse and make the same gestures that Zhai’s glove afforded, but those gestures would not accomplish the task since the mouse would not provide the 6-DOF required by the task. To successfully accomplish the 6-DOF task with the mouse technique would involve various 2-DOF
mouse movements and button presses, which are very different, kinematically, than the real-world motions. Hence, we have analytically demonstrated that Zhai’s glove technique provided a higher kinematic symmetry to the real-world action than using a standard mouse technique.

In some cases, an analytical comparison of interaction techniques is not sufficient to determine if one technique has a higher kinematic symmetry. For example, analytically comparing the Move controller to a Kinect-based technique for swinging a virtual baseball bat would be extremely subjective and speculative. Instead, a more ecologically valid comparison must be made. A plausible approach would be to use a VICON system to capture kinematic data of many users successfully using the Move controller, the Kinect-based technique, and a real baseball bat to hit a (virtual or real) baseball, then analyzing the captured data to determine any significant differences in the motion of the involved body segments. The technique with the fewest differences from the real baseball bat swing would have the higher kinematic symmetry.

Kinetic Symmetry

Kinetics refers to the forces that cause and influence body movements [117]. According to Meriam and Kraige [119], forces are classified as either body forces (those “generated by virtue of the position of a body within a force field such as a gravitational, electric, or magnetic field”) or contact forces (those “produced by direct physical contact”). Winter further categorizes contact forces as either external (e.g., ground reaction forces contacting the foot when taking a step) or internal (e.g., muscle forces causing an elbow to bend) [117].

We define kinetic symmetry as the objective degree of exactness with which a force involved in a real-world movement can be reproduced through interaction to successfully complete the task. For example, in Wii Sports boxing, throwing a punch with the Wii Remote reproduces a muscle force that is very similar to throwing a real punch, and therefore, has a high kinetic symmetry. Similarly, the Wii Fit snowboard technique has a high kinetic symmetry to snowboarding by measuring gravitational forces with the Wii Balance Board. On the other hand, the Wii Fit running interaction, which consists of jogging in place with a Wii Remote, only has a moderate level of kinetic symmetry to actual running because its associated shear forces (those parallel to the ground) are smaller in magnitude than the shear forces associated with true running.

Like kinematic symmetry, we can objectively compare the kinetics of a real-world action to the kinetics of a successful interaction by analyzing the variances in the external and internal contact forces involved, which is how we analytically determined the kinetic symmetries of the examples just mentioned. We can also compare the kinetic symmetries of differing interactions using an analytic approach similar to the one used for kinematic symmetry.

As with kinematic symmetry, an analytical comparison of interaction techniques is not sufficient to determine differences in kinetic symmetry for some cases. For example, we are unable to
analytically compare the kinetic symmetries of throwing a punch in *Wii Sports* and throwing a punch in *Kinect Sports* without subjective speculation. Hence, a more ecologically valid comparison must be made, by capturing kinetic data with a force transducer [117], and determining which interaction has the fewest kinetic differences from a real-world punch.

**Anthropometric Symmetry**

Anthropometry is the branch of biomechanics concerned with the physical measurements of the human body, in order to determine differences among individuals or groups [117]. The most basic measurement is the length of one of the major body segments: feet, legs, thighs, trunk, head, upper arms, forearms, and hands [117]. Other anthropometric measurements include determining the densities, masses, and centers of mass (COM) of body segments or the body as a whole [117].

We use the term *anthropometric symmetry* to refer to the objective degree of exactness with which the body segments involved in a real-world action can be matched by the body segments involved in an interaction that successfully completes the task. By measuring the lengths, densities, and masses of body segments, we can objectively determine the anthropometric symmetry an interaction has to a real-world action. Most gestures have a high anthropometric symmetry to their real-world actions because they involve the same body segments, which obviously will have the same lengths, densities, and masses. For example, swinging a Move controller involves the trunk, upper arms, forearms, and hands, just as swinging a real baseball bat does. In contrast, some gestures involve body segments that are different from the represented real-world action. For instance, the cycling interaction in *Wii Sports Resort* uses the upper arms, forearms, and hands to simulate pedaling a bicycle as opposed to the thighs, legs, and feet. Despite involving different body segments, this cycling gesture has a higher level of anthropometric symmetry than a pedaling gesture involving the index and middle fingers considering that the fingers are much shorter than the arms, whereas the arms are nearly as long as the legs.

As we have shown, kinematic symmetry, kinetic symmetry, and anthropometric symmetry can all be objectively evaluated with analytic approaches or methods already used to analyze human movements in biomechanics. These analysis methods also provide the ability to determine if one interaction technique affords a higher level of symmetry to a real-world action, in terms of kinematics, kinetics, or anthropometry, than another interaction technique. Together, these methods allow us to objectively describe the level of biomechanical symmetry that an interaction provides.
7.2.2 Control Symmetry

As high-fidelity gestures have become prevalent in consumer technologies, the ability to control more aspects of interaction has as well. Instead of completing an entire action by pressing a button, consumers are now able to specify aspects of particular actions through increased control. For example, consider playing basketball in *Wii Sports Resort*. Using a gesture with high biomechanical symmetry to shooting an actual basketball, players are able to control the direction, arc, and force of the virtual ball’s trajectory, instead of pressing a button and allowing the computer to determine how the basketball is shot. By providing users with greater control and influence over aspects of virtual actions, techniques like the Wii basketball gesture afford a higher level of interaction fidelity than traditional interaction techniques.

We use the term *control symmetry* to refer to the objective degree of exactness with which control in a real-world task is provided through interaction. Basically, the level of control symmetry is the amount of correspondence between the control provided by an interaction technique and the control possible in the real world. Therefore, the Wii basketball gesture can be described as having a high level of control symmetry to shooting an actual basketball because it provides the ability to influence many of the aspects of the ball’s trajectory that are controllable in the real world.

Within the human-computer interaction (HCI) community, a considerable amount of research has been conducted on how to effectively increase control through various aspects of interaction. Because we are mainly interested in how to increase control to match real-world control, we focus on three aspects of the research that we consider the most relevant: control dimensions, transfer functions, and stopping interaction.

**Dimensional Symmetry**

Two characteristics of control that are key in interaction tasks, particularly manipulation tasks, are the *number of control dimensions* (how many domains of output can be controlled) and the *integration* of those dimensions (which domains can be controlled simultaneously with a single movement) [47]. In their input device taxonomy, Card et al. identified several control dimensions by distinguishing the physical properties (position, movement, force, and delta force) of the linear axes (x, y, z) and the physical properties (angle, delta angle, torque, and delta torque) of the rotary axes (rX, rY, rZ) [30]. They also discussed “merge composition,” which is the combination of multiple domains to yield a cross-product domain. We refer to this combining of domains as “integration,” a term adopted from Bowman et al. [47].

We define the term *dimensional symmetry* as the objective degree of exactness with which control dimensions in a real-world task are provided through interaction. For example, in the real world, a table tennis player has control over the position (x, y, z) and orientation (rX, rY, rZ) of
the tennis paddle at any given instant of time. When playing table tennis in *Sports Champions*, the PlayStation Move offers the same six control dimensions (x, y, z, rX, rY, rZ) and therefore has a high level of dimensional symmetry to manipulating an actual table tennis paddle. On the other hand, only three control dimensions (rX, rY, rZ) are offered when playing table tennis in *Wii Sports Resort*, with the other three dimensions (x, y, z) controlled by the game, resulting in a lower level of dimensional symmetry.

Just as providing too few control dimensions can decrease an interaction’s dimensional symmetry, providing too many control dimensions can also result in a lower level of symmetry. As Hinckley et al. discuss, it makes little sense to allow a user to control the position of an object if the presented task should only involve orienting the object, especially considering that extraneous dimensions could make the task more difficult [90]. Consider the real-world task of steering a car, which involves rotating a steering wheel in a single dimension (rY). A 1-DOF (rY) technique would constrain the user to controlling the single dimension, resulting in a high level of dimensional symmetry to true steering. Contrastingly, a 4-DOF (x, y, z, rY) technique would allow the user to move the virtual steering wheel to another position, which is not realistic and results in a low dimensional symmetry.

In the real world, most tasks involve the ability to control multiple dimensions at once, hence the integration of control dimensions is as important to dimensional symmetry as the total number of dimensions. The research by Hinckley et al. supports this claim by demonstrating that two fully integrated 3-DOF techniques outperformed two partially integrated 3-DOF techniques for rotating objects in three dimensions (rX, rY, rZ) [90]. Similarly, Balakrishnan et al. demonstrated that a fully integrated 3-DOF technique outperformed a partially integrated 3-DOF technique for positioning objects in three dimensions (x, y, z) [91]. Despite these studies demonstrating the benefits of fully integrating control dimensions, dimensional symmetry is still dependent on the represented task. As Jacob and Sibert demonstrated, user performance is significantly improved when the task and interaction technique are both integral (i.e., the control dimensions are perceived as a single attribute) or both separable (i.e., the control dimensions are perceived as distinct attributes) [120].

**Transfer Function Symmetry**

A transfer function is a function that interprets input data and transforms it into an output effect [31]. Many transfer functions preserve the physical properties of input data by creating output data with the same physical properties. For example, the position-to-position transfer function behind the virtual hand technique [47] uses position data from a 6-DOF input device to determine the position of the grabbed virtual object with a one-to-one mapping. This one-to-one, position-to-position mapping is an exact match to the real-world control of moving a handheld object. Hence, we consider the virtual hand technique to have a high level of *transfer function*...
symmetry, which we define as the objective degree of exactness with which a real-world transfer function is reproduced through interaction.

Some transfer functions interpret one type of physical property and generate another type [121]. For instance, consider the transfer function that governs the speed of a car. As the driver presses the gas pedal (effectively changing its position), the speed of the car (its movement) increases, which makes this a position-to-movement transfer function. Therefore, using an isotonic lever to control the speed of a virtual car, which also uses a position-to-movement function, has higher transfer function symmetry to real driving (at least in terms of physical properties) than using an isometric device, which uses a force-to-movement function.

In addition to interpreting physical properties as other types of properties, transfer functions can also interpret input data at different resolutions [30], which some researchers refer to as a control-to-display ratio [121]. Reconsidering our driving example, if the gas pedal provides an input range of \([0, 120]\) and the car’s top speed is 120mph \([0, 120]\) then the governing transfer function would have a ratio of \(120:120\) or one-to-one. In the example of the isotonic lever, if it only provides an input range of \([0, 10]\), its transfer function would have a ratio of \(10:120\) or one-to-twelve. On the other hand, if the isotonic lever provided a higher resolution range of \([0, 30]\), the transfer function would have a ratio of \(30:120\) or one-to-four, which has much higher transfer function symmetry to the gas pedal.

**Termination Symmetry**

Another important aspect of control symmetry is how an interaction is stopped or terminated in the real world. For example, consider the walking-in-place technique [99]. Like the real-world task of walking, when the user desires to stop (virtual) locomotion, the user stops making the alternating step gestures that initiated and continued the interaction. Hence, we consider walking-in-place to have a high level of termination symmetry, which we define as the objective degree of exactness with which the termination of a real-world interaction is reproduced through interaction.

Some interaction techniques require additional input from the user to stop interaction, which results in lower levels of termination symmetry. This is particularly evident for interactions that rely on position-to-movement transfer functions. For example, consider the Virtual Motion Controller (VMC) device that allowed users to initiate virtual locomotion by stepping away from the center of the platform of sensors [122] (very similar to the human joystick technique). With the VMC, users were required to step back to the center of the platform to terminate virtual locomotion, which is an additional action compared to terminating real walking. Hence, the VMC provided a low level of termination symmetry. Some techniques based on position-to-movement transfer functions still manage to maintain a high level of termination symmetry. For
instance, Zhai’s isotonic rate control interaction was terminated with an open-hand gesture [94], which mimics the real-world action of releasing a held object.

Aside from requiring additional actions to terminate interaction, some techniques have lower levels of termination symmetry due to not providing any method of manually stopping interaction. For example, many target-based travel techniques, such as the ZoomBack technique [123], continue locomotion until the designated location is reached. Hence, once virtual locomotion is initiated, the user has no control to stop the locomotion, which results in a very low level of termination symmetry.

As discussed, dimensional symmetry, transfer function symmetry, and termination symmetry objectively describe how interactions provide control. Dimensional symmetry is concerned with the number of control dimensions afforded and how those dimensions can be simultaneously changed. Transfer function symmetry is concerned with the interpretation of physical properties and the resolution of that interpretation. Termination symmetry regards how the user controls the termination of an interaction. Together, these three types of symmetry allow us to objectively define the level of control symmetry that an interaction.

7.2.3 System Appropriateness

Aside from biomechanical symmetry and control symmetry, there are numerous factors than can influence the overall fidelity of an interaction. Most of these factors characterize how suitable the system is for implementing a particular aspect of interaction. Therefore, we consider these factors as components of system appropriateness, which constitutes part of the overall interaction fidelity of a particular implementation of an interaction technique. We have developed four categories of system appropriateness factors: input accuracy, input precision, latency, and form factor.

Input Accuracy

The accuracy of an input device is how close its readings are to the “true” values it measures [124]. How accurately input is measured can significantly affect user performance, as inaccurate input can result in uncontrollable, unwanted effects. For example, Ware and Rose evaluated accuracy by investigating the virtual hand technique with an offset of 60cm and no offset [64]. They determined that the more accurate technique afforded faster rotations than the less accurate version. In a similar study, Mine et al. compared the virtual hand technique to several offset versions (ranging from 10cm to 60cm), and also determined than any decrease in accuracy caused a decrease in user performance for 6-DOF manipulations [93]. Hence, we consider any negative effect of input accuracy to decrease a technique’s level of interaction fidelity.
**Input Precision**

The precision of an input device, also called repeatability, is the degree to which repeated measurements in static conditions yield the same results [124]. Like accuracy, the precision of an input device can significantly affect user performance, as low precision can also result in uncontrollable, unwanted effects. For instance, Ragan et al. demonstrated that decreasing precision (by increasing jitter) causes significantly worse user performance for a 3D object manipulation task [125]. Like accuracy, we consider any negative effect of input precision to decrease a technique’s level of interaction fidelity.

**Latency**

Latency is the temporal delay between user input and feedback generated by the system in response to it [47]. Like poor accuracy or precision, a high latency can result in poor user performance and undesired effects [121], which decrease the interaction fidelity of the technique. Latency can further be defined in terms of a report rate and an update rate. The report rate is the speed at which an input device sends data to a system [85]. The update rate is the speed at which the system processes input data and creates a feedback [69].

**Form Factor**

Form factor is the “shape and size” of the input device used [96]. Zhai et al. evaluated form factor by comparing a 6-DOF ball-shaped device to a glove with a 6-DOF tracker located in the palm [97]. They determined that the ball-shaped device afforded faster object manipulations than the glove, and concluded this was due to the ability to use the fingers as opposed to the hand and forearm. Hence, we believe the form factor of an input device can affect the overall fidelity of an interaction. For instance, consider using the Wii Wheel accessory (a passive prop) to steer in *Mario Kart Wii*. Though the Wii Wheel technique actually depends on the masked Wii Remote, we consider this interaction technique to be higher-fidelity than just using the Wii Remote without the passive prop.

While biomechanical symmetry and control symmetry are concerned with obvious differences in interaction fidelity due to body movements and control, system appropriateness refers to a number of subtle factors that can significantly impact user performance and decrease the overall level of fidelity for an interaction technique. While more work is needed to further understand how system appropriateness affects interaction fidelity, we have tentatively categorized those factors as input accuracy, input precision, latency, and form factor issues.
7.3 How To Use FIFA

As mentioned in the motivation of the framework, we designed FIFA as a tool that would provide an objective analysis of the level of interaction fidelity provided by an interaction technique when compared to a real-world action. In this section, we demonstrate how FIFA can be used to objectively analyze the interaction fidelity provided by some well-known travel techniques by comparing them to the real-world action of walking.

Travel is the “motor component of navigation” [47], which involves moving from one location within a VE to a different location. Multitudes of differing travel techniques have been researched, including physical locomotion, steering, route planning, targeting, manual manipulation, travel-by-scaling, viewpoint orientation, and velocity specification [47]. Bowman et al. provided a taxonomy of travel techniques based on the subtasks of direction or target selection, velocity/acceleration selection, and conditions of input [89].

The highest fidelity travel technique is real walking, the action of physically walking through a 3D world. This technique is natural, provides vestibular cues, and promotes spatial understanding [47]. However, because of technological and space limitations, real walking is not always practical or feasible. For instance, real walking only works when the size of the VE is less than the range of the tracking system.

An alternative to real walking that has been investigated is walking in place, where users move their feet to simulate walking without actually translating their bodies [99]. This physical locomotion technique overcomes the requirement for a large physical space. One approach to implementing walking in place has been to use a head tracker and a neural network to determine when users are walking in place and base the direction of locomotion on the direction of gaze reported by the head tracker (e.g., [87, 99]).

Another solution to overcoming the spatial requirements of real walking has been to scale physical steps to equal several virtual steps. One example of this is the “seven league boots” technique, which involves determining a user’s intended direction of travel from a head tracker and then augmenting only the component of virtual motion that is aligned with that direction [126].

Yet another alternative to real walking has been to use omnidirectional treadmills, which use two sets of rollers that move orthogonally to one another to allow walking (or even running) in any direction [127]. In order to keep the user from walking off the edge of the device, an active control is used to continually move the surface in order to recenter the user on the treadmill. However, when turning or sidestepping, the recentering motion has been known to cause users to lose their balance [47].
Using FIFA, we objectively analyzed the interaction fidelity of these travel techniques by comparing their biomechanical symmetry, control symmetry, and system appropriateness to real walking (see Table 7.1). From this analysis, we can see that seven league boots has a high biomechanical symmetry to walking. The omnidirectional treadmill also has a relatively high biomechanical symmetry but has a lower kinetic symmetry than seven league boots. Walking in place has the lowest biomechanical symmetry, which is still moderate with a high anthropometric symmetry.

In terms of control symmetry, the omnidirectional treadmill has the highest fidelity with a high dimensional symmetry, transfer symmetry, and termination symmetry to real walking. Both walking in place and seven league boots have relatively high control symmetry to real walking but both differ in terms of transfer function symmetry. For walking in place, the transfer function interprets a stepping motion as a positional change in the VE while the transfer function of seven league boots interprets the user’s positional changes but scales them in the intended direction of travel.

All three of the travel techniques have a moderate level of system appropriateness due to requiring a head tracker. Walking in place has slightly lower system appropriateness than seven league boots due to any latency caused by the neural network. The omnidirectional treadmill has the lowest system appropriateness with the latency and form factor of its belts and the requirement of a harness to maintain balance.

Overall, it appears that seven league boots has the highest level of interaction fidelity based on this analysis (although we do not suggest that the levels of each component can be added in any way to determine a quantitative overall level of interaction fidelity). It has the highest biomechanical symmetry, a moderate control symmetry, and decent system appropriateness. While lower than seven league boots, walking in place and the omnidirectional treadmill have moderately high interaction fidelity. Walking in place has higher system appropriateness than the omnidirectional treadmill, but the treadmill has higher control symmetry and slightly higher biomechanical symmetry.
**Table 7.1 Interaction Fidelity Analysis of Walking in Place, Seven League Boots, and Omnidirectional Treadmill Using FIFA.**

<table>
<thead>
<tr>
<th></th>
<th>Walking</th>
<th>Walking In Place</th>
<th>Seven League Boots</th>
<th>Omnidirectional Treadmill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomechanical Symmetry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic Symmetry</td>
<td>Move thighs, legs, and</td>
<td>Move thighs, legs, and</td>
<td>Move thighs, legs, and</td>
<td>Move thighs, legs, and</td>
</tr>
<tr>
<td></td>
<td>feet to translate entire</td>
<td>feet to step in place</td>
<td>feet to translate entire</td>
<td>feet to translate entire</td>
</tr>
<tr>
<td></td>
<td>body</td>
<td></td>
<td>body</td>
<td>body</td>
</tr>
<tr>
<td>Kinetic Symmetry</td>
<td>Large vertical and shear</td>
<td>Large vertical ground</td>
<td>Large vertical and shear</td>
<td>Large vertical and shear</td>
</tr>
<tr>
<td></td>
<td>ground forces</td>
<td>ground forces</td>
<td>ground forces</td>
<td>ground forces; Belt forces</td>
</tr>
<tr>
<td>Anthropometric Symmetry</td>
<td>Thighs, legs, and feet</td>
<td>Thighs, legs, and feet</td>
<td>Thighs, legs, and feet</td>
<td>Thighs, legs, and feet</td>
</tr>
<tr>
<td>Control Symmetry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensional Symmetry</td>
<td>$x + y$</td>
<td>$x + y$</td>
<td>$x + y$</td>
<td>$x + y$</td>
</tr>
<tr>
<td>Transfer Function Symmetry</td>
<td>1:1 position-to-position</td>
<td>1:1 movement-to-position</td>
<td>1:1 position-to-position</td>
<td>1:1 position-to-position</td>
</tr>
<tr>
<td>Termination Symmetry</td>
<td>Stop taking steps</td>
<td>Stop taking steps</td>
<td>Stop taking steps</td>
<td>Stop taking steps</td>
</tr>
<tr>
<td>System Appropriateness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Accuracy</td>
<td>N/A</td>
<td>Head tracker</td>
<td>Head tracker</td>
<td>Head tracker</td>
</tr>
<tr>
<td>Input Precision</td>
<td>N/A</td>
<td>Head tracker</td>
<td>Head tracker</td>
<td>Head tracker</td>
</tr>
<tr>
<td>Latency</td>
<td>N/A</td>
<td>Head tracker and neural</td>
<td>Head tracker</td>
<td>Head tracker and belts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form Factor</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Belts and balance harness</td>
</tr>
</tbody>
</table>

Low Fidelity  High Fidelity
7.4 Reanalyzing Prior Studies Using FIFA

Using FIFA, we have reanalyzed the results of our prior studies to learn more about the effects of the components of interaction fidelity. In this section, we discuss the results of each study in the context of using FIFA to objectively determine the levels of interaction fidelity evaluated as opposed to the prior levels assumed based on subjective observations and classifications.

7.4.1 Reanalysis of 3D Docking Game Results

In our first study (see chapter 3), we compared HOMER, Go-Go, and our DO-IT technique for playing a simple object manipulation game. We originally considered both HOMER and Go-Go to provide higher interaction fidelity than our DO-IT technique because of their ability to control all six DOFs at once. Using FIFA, we have objectively analyzed the interaction fidelity of these techniques for manipulating an object in 3D. Table 7.2 shows our analysis of the techniques for the manipulation task.

For the manipulation task, we have shown that both HOMER and Go-Go have high biomechanical symmetry to manipulating an object in 3D space. Contrastingly, DO-IT has a much lower biomechanical symmetry due to using the mouse. For control symmetry, HOMER and Go-Go have moderately high symmetry but differ from the real-world action due to the 1:N position-to-position aspects of their transfer functions. Again, DO-IT has a much lower symmetry due the modal control required of using the mouse. HOMER and Go-Go had lower levels of system appropriateness than the DO-IT technique due to the accuracy, precision, and latency involved with using the IS-900 wand compared to the mouse.

Reconsidering the results of our first study, which indicated that HOMER and Go-Go were significantly better for manipulating objects than the DO-IT technique, it appears that their higher levels of biomechanical symmetry and control symmetry contributed to their success despite having a slightly lower level of system appropriateness. In particular, it appears that the much lower dimensional symmetry and transfer function symmetry of DO-IT caused the mouse-based technique to perform significantly worse than the two 6-DOF techniques.
Table 7.2 Interaction Fidelity Analysis of HOMER, Go-Go, and DO-IT for Manipulation Using FIFA.

<table>
<thead>
<tr>
<th>Biomechanical Symmetry</th>
<th>Manipulating an object</th>
<th>HOMER</th>
<th>Go-Go</th>
<th>DO-IT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic Symmetry</strong></td>
<td>Move and twist upper arm, forearm, and hand to manipulate object</td>
<td>Move and twist upper arm, forearm, and hand to manipulate object</td>
<td>Move and twist upper arm, forearm, and hand to manipulate object</td>
<td>Move forearm and hand to move object or rotate object</td>
</tr>
<tr>
<td><strong>Kinetic Symmetry</strong></td>
<td>Moderate muscle forces</td>
<td>Moderate muscle forces</td>
<td>Moderate muscle forces</td>
<td>Small muscle forces</td>
</tr>
<tr>
<td><strong>Anthropometric Symmetry</strong></td>
<td>Upper arm, forearm, and hand</td>
<td>Upper arm, forearm, and hand</td>
<td>Upper arm, forearm, and hand</td>
<td>Forearm and hand</td>
</tr>
<tr>
<td><strong>Control Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dimensional Symmetry</strong></td>
<td>$x + y + z + rX + rY + rZ$</td>
<td>$x + y + z + rX + rY + rZ$</td>
<td>$x + y + z + rX + rY + rZ$</td>
<td>$x + y + z; rX + rY + rZ$</td>
</tr>
<tr>
<td><strong>Termination Symmetry</strong></td>
<td>Release object</td>
<td>Release selection button</td>
<td>Release selection button</td>
<td>Release selection button</td>
</tr>
<tr>
<td><strong>System Appropriateness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Input Accuracy</strong></td>
<td>N/A</td>
<td>Hand tracker</td>
<td>Hand tracker</td>
<td>Mouse</td>
</tr>
<tr>
<td><strong>Input Precision</strong></td>
<td>N/A</td>
<td>Hand tracker</td>
<td>Hand tracker</td>
<td>Mouse</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>N/A</td>
<td>Hand tracker</td>
<td>Hand tracker</td>
<td>Mouse</td>
</tr>
<tr>
<td><strong>Form Factor</strong></td>
<td>N/A</td>
<td>Hand tracker</td>
<td>Hand tracker</td>
<td>Mouse</td>
</tr>
</tbody>
</table>
7.4.2 Reanalysis of Racing Game Results

In our second study (see chapter 4), we compared the Classic, GameCube, Remote, and Wheel techniques for steering in *Mario Kart Wii*. We considered both the Remote and Wheel techniques to be high-fidelity interaction techniques due to their 3D interaction aspects. On the other hand, we considered the Classic and GameCube techniques (both based on using a spring-loaded joystick) to be low-fidelity techniques. Using FIFA, we have objectively analyzed the interaction fidelity of these techniques for turning the racing vehicle. Table 7.3 shows our analysis of these techniques for the steering task. (Note: We combined the Classic and GameCube techniques together in the table due to space limitations.)

Based on our analysis, we have confirmed that both the Remote and Wheel techniques had a moderately high biomechanical symmetry to steering a car while the Classic and GameCube techniques had extremely low biomechanical symmetry. Considering control symmetry, all four of the steering techniques differed from the real-world action in terms of their transfer functions, but most importantly the Remote and Wheel techniques had much lower levels of termination symmetry due to requiring a recentering action to stop the vehicle from turning. We did determine that the Classic and GameCube controllers had a higher level of system appropriateness than the Remote and Wheel techniques due to negligible errors in accuracy, precision, and latency. On the other hand, the Wheel was more appropriate in terms of form factor.

Reconsidering the results of our second study, which indicated the Remote and Wheel techniques performed significantly worse than the Classic and GameCube techniques, it appears that control symmetry, particularly termination symmetry, has a greater effect on user performance than biomechanical symmetry. It is also feasible that the lower levels of system appropriateness provided by the Remote and Wheel techniques, due to input issues with the Wii Remote, also contributed to the poor performance of the techniques we originally considered as high fidelity.
**Table 7.3 Interaction Fidelity Analysis of Classic, GameCube, Remote, and Wheel for Steering Using FIFA.**

<table>
<thead>
<tr>
<th></th>
<th>Turning a vehicle</th>
<th>Classic / GameCube</th>
<th>Remote</th>
<th>Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomechanical Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic Symmetry</td>
<td>Move upper arms, forearms, and hands to turn the steering wheel</td>
<td>Move thumb to move joystick</td>
<td>Move upper arms, forearms, and hands to turn the Wii Remote</td>
<td>Move upper arms, forearms, and hands to turn the Wii Wheel</td>
</tr>
<tr>
<td>Kinetic Symmetry</td>
<td>Moderate muscle forces</td>
<td>Extremely small muscle forces</td>
<td>Moderately high muscle forces (due to holding Remote)</td>
<td>Moderately high muscle forces (due to holding Wheel)</td>
</tr>
<tr>
<td>Anthropometric Symmetry</td>
<td>Upper arm, forearm, and hand</td>
<td>Thumb</td>
<td>Upper arm, forearm, and hand</td>
<td>Upper arm, forearm, and hand</td>
</tr>
<tr>
<td><strong>Control Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensional Symmetry</td>
<td>$rZ$</td>
<td>$rZ$</td>
<td>$rZ$</td>
<td>$rZ$</td>
</tr>
<tr>
<td>Termination Symmetry</td>
<td>Release steering wheel</td>
<td>Release joystick</td>
<td>Recenter steering wheel</td>
<td>Recenter steering wheel</td>
</tr>
<tr>
<td><strong>System Appropriateness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Accuracy</td>
<td>N/A</td>
<td>Classic / GameCube</td>
<td>Wii Remote</td>
<td>Wii Remote</td>
</tr>
<tr>
<td>Input Precision</td>
<td>N/A</td>
<td>Classic / GameCube</td>
<td>Wii Remote</td>
<td>Wii Remote</td>
</tr>
<tr>
<td>Latency</td>
<td>N/A</td>
<td>Classic / GameCube</td>
<td>Wii Remote</td>
<td>Wii Remote</td>
</tr>
<tr>
<td>Form Factor</td>
<td>Steering wheel</td>
<td>Classic / GameCube</td>
<td>Wii Remote</td>
<td>Wii Wheel</td>
</tr>
</tbody>
</table>
7.4.3 Reanalysis of First-Person Shooter Game Results

In our third study (see chapter 5), we evaluated interaction fidelity at two subjectively determined levels (high and low). For the high level of interaction fidelity, users aimed and fired at enemies with the handheld wand while physically moving with the human joystick technique to virtually travel. In contrast, for the low level of interaction fidelity, users used the mouse to aim and fire while using the keyboard to travel through the virtual world. Using FIFA, we have objectively analyzed the separate aspects of aiming and locomotion for both the high and low levels of interaction fidelity evaluated. In Table 7.4, we show our analysis of the two levels of aiming compared to aiming with a real-world weapon. In Table 7.5, we show our analysis of the two levels of locomotion compared to real walking.

Based on the analysis of the two levels for aiming, we see that the wand technique (3D pointing) had a high level of biomechanical symmetry to pointing a real weapon while the mouse technique had an obviously low biomechanical symmetry. The wand technique also had the highest control symmetry to aiming while the mouse technique greatly differed from real aiming in terms of its transfer function. For system appropriateness, the mouse technique was higher in terms of accuracy, precision, and latency while the wand technique was extremely high due to the gun-like form factor of the IS-900 wand used.

Based on the analysis of the two levels for locomotion, we see that the human joystick had a high level of biomechanical symmetry to real walking while the keyboard technique had an extremely low level. For control symmetry, both the human joystick and the keyboard technique had moderate levels of transfer function symmetry, which mapped positions (either body or key) to the velocity of travel, but the human joystick had a low level of termination symmetry due to requiring the user to return to the neutral zone to stop virtual locomotion. For system appropriateness, we determined that the human joystick had a moderate level of fidelity due to potential accuracy, precision, and latency issues. On the other hand, the keyboard technique did not suffer from those issues, but did introduce a form factor issue.

Reconsidering the results of our third study, which indicated the high level of interaction fidelity was better for avoiding damage but worse for accurately firing at enemies, we are unable to definitively determine which components of interaction fidelity contributed to the results because of the differences within the same component of fidelity due to the two different tasks (aiming and locomotion). Based on the analysis of the sections designed to exercise locomotion (found in chapter 5), we do hypothesize the poor accuracy of the high level of interaction fidelity was caused by the low level of termination symmetry provided by the human joystick.
### Table 7.4 Interaction Fidelity Analysis of Mouse and Wand Techniques for Aiming Using FIFA.

<table>
<thead>
<tr>
<th></th>
<th>Aiming a weapon</th>
<th>Mouse</th>
<th>Wand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomechanical Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic Symmetry</td>
<td>Move trunk, upper arm, forearm, and hand to point weapon</td>
<td>Move forearm and hand to orient crosshair of weapon</td>
<td>Move trunk, upper arm, forearm, and hand to point weapon</td>
</tr>
<tr>
<td>Kinetic Symmetry</td>
<td>Moderate muscle forces</td>
<td>Small muscle forces</td>
<td>Moderate muscle forces</td>
</tr>
<tr>
<td>Anthropometric Symmetry</td>
<td>Trunk, upper arm, forearm, and hand</td>
<td>Forearm and hand</td>
<td>Trunk, upper arm, forearm, and hand</td>
</tr>
<tr>
<td><strong>Control Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensional Symmetry</td>
<td>$x + y + z$</td>
<td>$x + y + z$</td>
<td>$x + y + z$</td>
</tr>
<tr>
<td>Termination Symmetry</td>
<td>Press trigger</td>
<td>Press button</td>
<td>Press button</td>
</tr>
<tr>
<td><strong>System Appropriateness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Accuracy</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Wand</td>
</tr>
<tr>
<td>Input Precision</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Wand</td>
</tr>
<tr>
<td>Latency</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Wand</td>
</tr>
<tr>
<td>Form Factor</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Wand</td>
</tr>
</tbody>
</table>
Table 7.5 Interaction Fidelity Analysis of Keyboard and Human Joystick Techniques for Locomotion Using FIFA.

<table>
<thead>
<tr>
<th></th>
<th>Walking</th>
<th>Keyboard Technique</th>
<th>Human Joystick</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomechanical Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic Symmetry</td>
<td>Move thighs, legs, and feet to translate entire body</td>
<td>Move fingers to press keys</td>
<td>Move thighs, legs, and feet to translate entire body</td>
</tr>
<tr>
<td>Kinetic Symmetry</td>
<td>Large vertical and shear ground forces</td>
<td>Extremely small muscle forces</td>
<td>Large vertical and shear ground forces</td>
</tr>
<tr>
<td>Anthropometric Symmetry</td>
<td>Thighs, legs, and feet</td>
<td>Fingers</td>
<td>Thighs, legs, and feet</td>
</tr>
<tr>
<td><strong>Control Symmetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensional Symmetry</td>
<td>$x + y$</td>
<td>$x + y$</td>
<td>$x + y$</td>
</tr>
<tr>
<td>Transfer Function Symmetry</td>
<td>1:1 position-to-position</td>
<td>1:N position-to-movement</td>
<td>1:N position-to-movement</td>
</tr>
<tr>
<td>Termination Symmetry</td>
<td>Stop taking steps</td>
<td>Stop pressing keys</td>
<td>Step back to neutral zone</td>
</tr>
<tr>
<td><strong>System Appropriateness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Accuracy</td>
<td>N/A</td>
<td>Keyboard</td>
<td>Head tracker</td>
</tr>
<tr>
<td>Input Precision</td>
<td>N/A</td>
<td>Keyboard</td>
<td>Head tracker</td>
</tr>
<tr>
<td>Latency</td>
<td>N/A</td>
<td>Keyboard</td>
<td>Head tracker</td>
</tr>
<tr>
<td>Form Factor</td>
<td>N/A</td>
<td>Keyboard</td>
<td>N/A</td>
</tr>
</tbody>
</table>
7.4.4 Reanalysis of FPS Locomotion Subtask Results

In our fourth study (see chapter 6), we evaluated locomotion fidelity at two levels (high and low). For the high level of interaction fidelity, we used the human joystick technique because it involved using the legs to initiate virtual locomotion. For the low level of interaction fidelity, we used the keyboard technique from the third study. As shown in Table 7.5, we have already used FIFA to objectively analyze the level of interaction fidelity for both the human joystick and the keyboard technique.

As mentioned above, based on the analysis of the human joystick and the keyboard technique compared to real walking, the human joystick technique had a high level of biomechanical symmetry, a low level of control symmetry (primarily due to a low level of termination symmetry), and a moderate level of system appropriateness due to potential accuracy, precision, and latency issues with the IS-900 head tracker. On the other hand, the keyboard technique had a very low level of biomechanical symmetry, a moderate level of control symmetry, and a moderate level of system appropriateness.

Reconsidering the results of our fourth study, which indicated that the keyboard technique afforded better virtual locomotion than the human joystick, it appears that termination symmetry once again had the greatest effect on user performance. It is also feasible that the lower levels of system appropriateness provided by the human joystick (due to potential accuracy, precision, and latency issues), might have also contributed to the poor performance of the technique we originally considered to be higher fidelity than the keyboard technique.

7.4.5 Reanalysis of FPS Targeting Subtask Results

In our fifth study (see chapter 6), we evaluated pointing fidelity at three levels (high, middle, and low). For the high level of interaction fidelity, we used the wand technique for pointing. For the low level of interaction fidelity, we used the standard mouse technique. For the middle level of interaction fidelity, we created the new e-mouse technique that provided a frame of reference for not losing the crosshair, which was controlled by the user’s torso. Using FIFA, we have objectively analyzed the interaction fidelity of these techniques for pointing at targets. Table 7.6 shows our analysis of these techniques for the targeting task.
**Table 7.6 Interaction Fidelity Analysis of Mouse, E-mouse, and Wand Techniques for Aiming Using FIFA.**

<table>
<thead>
<tr>
<th>Biomechanical Symmetry</th>
<th>Aiming a weapon</th>
<th>Mouse</th>
<th>E-mouse</th>
<th>Wand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Symmetry</td>
<td>Move trunk, upper arm, forearm, and hand to point weapon</td>
<td>Move forearm and hand to orient crosshair of weapon</td>
<td>Move trunk, or forearm and hand to orient crosshair of weapon</td>
<td>Move trunk, upper arm, forearm, and hand to point weapon</td>
</tr>
<tr>
<td>Kinetic Symmetry</td>
<td>Moderate muscle forces</td>
<td>Small muscle forces</td>
<td>Moderate and small muscle forces</td>
<td>Moderate muscle forces</td>
</tr>
<tr>
<td>Anthropometric Symmetry</td>
<td>Trunk, upper arm, forearm, and hand</td>
<td>Forearm and hand</td>
<td>Trunk, forearm, and hand</td>
<td>Trunk, upper arm, forearm, and hand</td>
</tr>
</tbody>
</table>

### Control Symmetry

<table>
<thead>
<tr>
<th>Dimensional Symmetry</th>
<th>(x + y + z)</th>
<th>(x + y + z)</th>
<th>(x + y + z)</th>
<th>(x + y + z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Termination Symmetry</td>
<td>Press trigger</td>
<td>Press button</td>
<td>Press button</td>
<td>Press button</td>
</tr>
</tbody>
</table>

### System Appropriateness

<table>
<thead>
<tr>
<th>Input Accuracy</th>
<th>Weapon</th>
<th>Mouse</th>
<th>Mouse and torso tracker</th>
<th>Wand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Precision</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Mouse and torso tracker</td>
<td>Wand</td>
</tr>
<tr>
<td>Latency</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Mouse and torso tracker</td>
<td>Wand</td>
</tr>
<tr>
<td>Form Factor</td>
<td>Weapon</td>
<td>Mouse</td>
<td>Mouse and device carrier</td>
<td>Wand</td>
</tr>
</tbody>
</table>
Based on this analysis, we see that the wand technique had a high level of biomechanical symmetry to pointing a real weapon. The e-mouse technique had a clearly moderate biomechanical symmetry while the mouse technique had an obviously low biomechanical symmetry. The wand technique also had the highest control symmetry to aiming while the mouse technique had a more control symmetry than the e-mouse technique. The mouse had the best system appropriateness in terms of accuracy, precision, and latency while the wand had the most appropriate form factor. Due to the combination of input devices, the e-mouse had the worst system appropriateness for all four aspects.

Reconsidering the results of our fifth study, which indicated the wand technique was the fastest technique for aiming while the e-mouse was the worst for firing, it appears that control symmetry, specifically transfer function symmetry probably had a significant role in the results. It is also probably that biomechanical symmetry also played a role since the superior wand technique also had the highest level of biomechanical symmetry.

7.4.6 Summary of Reanalyzing Prior Studies Using FIFA

Based on the re-analyses of the prior studies and their results using FIFA, we have provided evidence that the level of control symmetry appears to be the most significant factor considering the techniques that offered the best performance in each study had the highest levels of control symmetry. Termination symmetry, how the user stops an interaction, appears to have been a major factor for the steering techniques in the second study and the locomotion techniques in the third and fourth studies. Similarly, transfer function symmetry was likely to have been a major factor for the manipulation techniques in the first study and the aiming techniques in the third and fifth studies.

In addition to control symmetry, it appears that there may have also been some issues with the system appropriateness of input devices used in the studies, particularly in the second study involving the Wii Remote. How significant these issues were is not clear as differences in control symmetry were additionally confounded with the differences in system appropriateness. Similarly, we are unable to extrapolate any conclusions on the effect of biomechanical symmetry other than it is likely to be less significant than control symmetry due to biomechanical symmetry being confounded by varying levels of control symmetry in all of the studies.

7.5 Interrelationships of FIFA Components

From our studies of using FIFA to determine the interaction fidelity of various interaction techniques, we have discovered several interrelationships among the components of FIFA, which we discuss below.
7.5.1 Biomechanical Symmetry and Control Symmetry

In our studies, we found that biomechanical symmetry had no effect on control symmetry, but in some cases we found that control symmetry could influence the kinematics, kinetics, and even the anthropometry of users’ movements. Specifically, we observed that transfer symmetry could affect the length of movements, the forces behind those movements, and the body parts involved in those movements. For example, consider the Go-Go technique [101]. Though the technique has an extremely high biomechanical symmetry to the real-world action of manipulating an object, most users will not perform movements with the same kinematics and kinetics as the real action because the transfer function scales the position of the virtual object relative to the position of the hand. For another example, consider the human joystick technique. Like Go-Go, the human joystick provides a high biomechanical symmetry, but during our studies, we observed users leaning to activate virtual locomotion instead of stepping, which changed the anthropometrics of their actions, in order to constrain the movement generated by the human joystick’s transfer function.

7.5.2 Biomechanical Symmetry and System Appropriateness

Like the interrelationship between biomechanical symmetry and control symmetry, we found that biomechanical symmetry had no effect on system appropriateness, but that system appropriateness could affect the biomechanics of a user’s interactions. As several studies have demonstrated (e.g., [64, 69, 85, 93, 125]), input accuracy, precision, and latency all can significantly affect user performance. A major reason for this is that users will attempt to compensate for low accuracy, poor precision, and high latency by modifying their interactions and (more relevantly) movements. In addition to potential impacts that accuracy, precision, and latency have on kinematics and kinetics, we have determined that form factor can affect biomechanics. Consider the research by Zhai et al. comparing their 6-DOF glove technique to a ball-shaped 6-DOF tracker [97]. The researchers determined that the ball-shaped device allowed users to use their fingers instead of using their hands and forearms, which is an obvious change in kinematics and kinetics.

7.5.3 Control Symmetry and System Appropriateness

Though we did not observe an interrelationship between control symmetry and system appropriateness in our case studies, we claim that system appropriateness could affect control symmetry. Consider two theoretical form factors for manipulating a 6-DOF tracker. The first form factor is the tracker encased within a ball-shaped housing. The second form factor is the tracker encased within a gun-shaped housing, at the tip of the barrel. While both devices will afford 6-DOF tracking and the ability to control the linear (x, y, z) and rotary (rX, rY, rZ) dimensions of an object, the ball-shaped housing will allow users to manipulate the rotary
dimensions without majorly affecting the linear dimensions. On the other hand, the gun-shaped housing will present a linear offset, which means that users will majorly affect the linear dimensions of the controlled object when manipulating the rotary dimensions. Hence, system appropriateness can affect control symmetry.

7.6 Potential Uses of FIFA

In this chapter, we have demonstrated that FIFA can be used to objectively analyze and describe the interaction fidelity of a technique, guided by the concepts of biomechanical symmetry, control symmetry, and system appropriateness. In addition to analyzing levels of interaction fidelity, our new framework can also be used to guide experimental design for evaluations of interaction fidelity.

In the studies presented in this dissertation, we had to subjectively choose or design techniques that we considered to have high and low levels of interaction fidelity because there was no methodology for defining levels of interaction fidelity. Now, researchers can use FIFA to design experiments that evaluate interaction fidelity with more control, as it is possible to determine how two techniques differ in terms of interaction fidelity. Similarly, FIFA can also be used to identify the components of interaction fidelity that have not been evaluated in controlled experiments.

Another potential use of FIFA is as a design space for new interaction techniques. By focusing on specific concepts, researchers can devise and explore new interaction metaphors with different levels of interaction fidelity than existing techniques. Considering the fidelity limitations of techniques like walking in place, seven league boots, and the omnidirectional treadmill (section 7.3), researchers might ask if it was possible to develop travel techniques that are more similar to real walking. For example, some redirected walking techniques [111] might have been designed by starting with seven league boots and looking for ways to increase the transfer function fidelity, leading to techniques that use a 1-to-1 transfer function most of the time but use a 1-to-N function for rotations when necessary to redirect users away from the boundaries of the tracked area.

7.7 Conclusions

After reconsidering prior research on the effects of interaction fidelity and conducting our own evaluations of its effects, we have developed the Framework for Interaction Fidelity Analysis (FIFA), which provides a method for objectively analyzing levels of interaction fidelity. FIFA categorizes the aspects of interaction fidelity into three broad concepts—biomechanical symmetry, control symmetry, and system appropriateness. Biomechanical symmetry is further characterized into the concepts of kinematic symmetry, kinetic symmetry, and anthropometric
symmetry. Likewise, control symmetry is divided into the categories of dimensional symmetry, transfer symmetry, and termination symmetry. Aspects of system appropriateness include input accuracy, input precision, latency, and form factor. Based on the re-analyses of our studies, we have also hypothesized that control symmetry, particularly transfer function symmetry and termination symmetry, had the greatest effect on the results of our studies, with higher levels of control symmetry resulting in better user performance.
8 CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

The goal of this dissertation was to provide a better understanding of the effects of display fidelity and interaction fidelity for the domain of videogames. Through five systematic evaluations of fidelity, this research has contributed to our knowledge about the effects of display fidelity, the effects of interaction fidelity, and the interaction effects between display and interaction fidelity. Overall, the broader contributions of this research include the Framework for Interaction Fidelity Analysis (FIFA) and understanding how display fidelity, interaction fidelity, and familiarity correlate to user performance.

8.1.1 Effects of Display Fidelity

For our research, we chose to focus on two components of visual display fidelity—stereoscopy and FOR. In the studies in which we controlled stereoscopy, we found no significant effects of the display fidelity component. Considering the contexts of those studies, we have attributed this finding to those games not requiring interactions close to the body. Additionally, neither game required a keen spatial understanding ability to be successful, which prior benefits of stereoscopy has been linked to (e.g., [24, 28, 67-69]). It is probable that stereoscopy may have a greater effect in contexts different from our 3D docking game and our FPS game.

In contrast to stereoscopy, we did find significant effects of FOR in two of the four studies in which we controlled FOR. In our FPS game, we found indications that FOR had significant effects on completion times, damage taken, and firing accuracy, with high FOR providing better user performance than low FOR in all cases. In our FPS subtask studies, we determined that increasing FOR afforded faster visual searching, which agrees with prior research that suggests FOR is most useful for tasks that benefit from high bandwidths of information (e.g., [36, 49]). Though FOR may not be useful for all tasks that would benefit from high bandwidths of information, as we only evaluated the single application context of a FPS game.

In addition to the effects of display fidelity on user performance, our third study demonstrated that a high level of display fidelity can induce greater positive responses from users. We found that display fidelity had significant positive effects on presence, engagement, and perceived usability. These results correlate to prior findings about the effects of display fidelity on presence and other subjective responses (e.g., [33, 70, 71, 80, 82]). These results may have also been due to the intensive nature of the FPS context used in the research.
Another effect of display fidelity that we observed was that it seemed to affect the strategies of the participants in our third study. Depending on the level of display fidelity, users switched between two strategies for firing at targets. In the high-display conditions, most participants would “spray” gunfire while moving the crosshair toward an enemy. However, in the low-display conditions, participants usually lined up the crosshair with the enemy before firing. An important consideration about these observed strategies is that the high-display conditions allowed participants to see their enemies using peripheral vision before moving the crosshair, while the low-display conditions usually required virtual turning before enemies would be seen. The influence of the level of display fidelity on user strategy may have been due to the complex nature of the FPS game involved.

8.1.2 Effects of Interaction Fidelity

In our first three studies, we chose to evaluate “high-fidelity” and “low-fidelity” interaction techniques, and in our last two studies, we decided to also evaluate a “mid-fidelity” technique. From these evaluations, we have provided evidence that extremely high levels of interaction fidelity provide better user performance than lower levels. In our first study, we showed that two techniques with high biomechanical and control symmetries (HOMER and Go-Go) outperformed a technique that had a low biomechanical symmetry and low control symmetry (DO-IT). Similarly, in our fifth study, we showed that 3D pointing, which has a high biomechanical symmetry and high control symmetry, when compared to aiming a firearm, outperformed two techniques with lower biomechanical and control symmetries (a standard mouse technique and our new enhanced mouse technique). In other contexts, extremely high levels of interaction fidelity might not provide the same benefits.

We have also provided evidence that moderate levels of interaction fidelity do not improve user performance and can actually cause decreases in user performance. In our second study, we found that two low-fidelity techniques with low biomechanical symmetries and moderate control symmetries (Classic and GameCube controls) outperformed two “high-fidelity” techniques that had high biomechanical symmetries, but lower control symmetries (Remote and Wheel controls). In our fourth study, we determined that our “high-fidelity” locomotion technique (the human joystick), which had a moderately high biomechanical symmetry and low control symmetry, performed worse than our low-fidelity keyboard technique, which had a low biomechanical symmetry and higher control symmetry. In the fifth study, we also found that our mid-fidelity enhanced mouse technique performed worse than the low-fidelity mouse technique. For contexts beyond games, it is feasible that mid-fidelity techniques may provide some benefits.

Based on the re-analyses of our studies using FIFA, we have also provided evidence that maintaining a high level of control symmetry (particularly transfer function symmetry and termination symmetry) is likely the most significant factor on user performance. In all five
studies, based on the results yielded by FIFA, we found that the techniques with the highest level of control symmetry afforded the best user performance. In the first, third, and fifth studies, the best techniques had a higher level of control symmetry due to a higher level of transfer function symmetry. In the second, third, and fourth studies, we found the best techniques had a higher level of control symmetry due to a higher level of termination symmetry. Hence, we believe both transfer function symmetry and termination symmetry to be key factors in predicting the user performance yielded by an interaction technique.

In addition to user performance, we found that interaction fidelity had significant effects on subjective responses in the third study. We found that the high-interaction conditions resulted in higher presence, engagement, and perceived usability. Again, these results may have been due to the intensive nature of the FPS game involved.

Like display fidelity, we have observed that the level of interaction fidelity can affect user strategy. In our third study, participants tended to move more using the human joystick technique than they moved with the keyboard technique. This difference in user strategy resulted in participants taking less damage and being less accurate with high interaction fidelity while taking more damage and being more accurate with the low level of interaction fidelity. The probable cause of this difference was the human joystick required physical movement back to the neutral zone to stop any current virtual movement while the keyboard technique only required the user to stop pressing a key. The influence of the level of interaction fidelity on user strategy may have been due to the complex interactions involved with the FPS game.

Another finding we had about interaction fidelity was that form factor had no significant effects on user performance in our second study other than potential learning effects. We evaluated form factor for two different levels of interaction fidelity. For low-fidelity interaction, we compared the Classic and GameCube controllers, and found no significant differences between the two form factors. Similarly, for higher-fidelity interaction, we compared the Remote and Wheel controllers, and found only one significant difference between the two form factors with regard to technique ordering. These results agree with prior research that has found form factor to not be significant unless it involves different body parts (e.g., [64, 90, 98]). Of course, these results may also be limited by the nature of the racing game involved.

### 8.1.3 Interaction Effects Between Display and Interaction Fidelity

In our third study, we determined that matching levels of display and interaction fidelity provide better user performance than mixing levels. Despite being the two extreme combinations of display and interaction fidelity, the low-display, low-interaction and high-display, high-interaction conditions outperformed the other two mixed conditions for completion times, damage taken, and firing accuracy. Based on our observations and comments from participants,
we attribute the excellent performance of these matched conditions to familiarity. Conceptually, the low-display, low-interaction condition was very similar to a standard, desktop FPS game while the high-display, high-interaction condition was very similar to the real world. For less intensive contexts, these results may not be generalizable.

Our third study also showed that users had the greatest senses of presence, engagement, and usability with the high-display, high-interaction condition. We have commented that designers concerned with achieving high levels of presence, engagement, or perceived usability should consider that higher levels of fidelity appear most suitable. In particular, high levels of both display and interaction fidelity appear to combine for the best results. Again, the intensive nature of the FPS game involved may have increased these subjective results, and therefore, these results might not be generalizable beyond FPS games.

Another interaction between display fidelity and interaction fidelity that we have observed is that increasing FOR affords more physical turning, thereby increasing interaction fidelity. In our fifth study, the 360-degree FOR condition, in which virtual turning was not required and only physical turning was necessary to view the entire virtual environment, afforded the fastest searching. Contrastingly, each lower level of FOR was increasingly slower, provided less physical turning, and required more virtual turning. For instance, with the 90-degree FOR condition, virtual turning was constantly required and physical turning was not useful.

### 8.1.4 Broader Contributions

After reconsidering prior research on the effects of interaction fidelity and conducting our own evaluations of its effects, we developed the Framework for Interaction Fidelity Analysis (FIFA), which provides a method for objectively analyzing levels of interaction fidelity. FIFA categorizes the aspects of interaction fidelity into three broad concepts—biomechanical symmetry, control symmetry, and system appropriateness. Biomechanical symmetry is further characterized into the concepts of kinematic symmetry, kinetic symmetry, and anthropometric symmetry. Likewise, control symmetry is divided into the categories of dimensional symmetry, transfer symmetry, and termination symmetry. Aspects of system appropriateness include input accuracy, input precision, input lag, and form factor.

Based on our own evaluations and prior studies of display fidelity, we have demonstrated that the level of display fidelity tends to have positive effects on user performance. Though not in our studies, stereoscopy has been shown to positively affect user performance for tasks that rely heavily on spatial understanding (e.g., [24, 28, 67-69]). In our evaluations and prior research (e.g., [36, 49]), FOR has been demonstrated to positively affect user performance for tasks that benefit from a large bandwidth of information, like searching. Like FOR, FOV (e.g., [72, 74-76]) and display resolution (e.g., [72, 81]) have been shown in prior research to improve user
performance for large information bandwidth tasks. Other research studies have demonstrated that larger display sizes (with the same FOV, display resolution, color brightness, and contrast) improve user performance for spatial orientation tasks (e.g., [82]) and navigation (e.g., [83]). Finally, low frame rates have been shown to result in poor user performance (e.g., [16, 69, 85]).

Given the results of our studies and the re-analyses of those results using FIFA, another contribution of this research is evidence that the level of control symmetry appears to have a positive, linear effect on user performance. In all five of our studies, we have determined that interaction techniques with the highest levels of control symmetry provide the best user performance. For the manipulation techniques and aiming techniques we evaluated, we found that transfer function symmetry was a significant indicator to user performance. For the steering and locomotion techniques we evaluated, we found that termination symmetry was likely a significant factor on user performance.

As mentioned, in our third study, we attributed the excellent performance of the low-display, low-interaction and high-display, high-interaction conditions to familiarity. We contended that the low-display, low-interaction condition was very similar to a standard, desktop FPS game, which would make the condition familiar for any regular FPS gamers. We also observed that the high-display, high-interaction condition was very similar to the real world, with many participants commenting how “realistic” the condition was for them, which should make the condition familiar to everyone. Similarly, in our fifth study, we found that our new enhanced mouse technique, which was designed to enhance user performance with a mouse by providing a frame of reference, performed worse than the normal mouse technique and the realistic 3D pointing technique. Overall, these results indicate that the level of familiarity often has a positive effect on user performance.

8.2 Future Work

The research presented in this dissertation opens a wide range of future research on the effects of fidelity.

As mentioned, the goal of this dissertation was to address a limitation of prior fidelity research by evaluating the effects of display fidelity and interaction fidelity independently and combined. Demonstrated by our studies, significant interaction effects between display and interaction fidelity do exist, at least for videogame contexts. Considering this, it would be beneficial to continue researching the effects of display fidelity and interaction fidelity in the same systematic manner for contexts other than virtual reality games. It is plausible that additional interaction effects may present themselves in other contexts.

In addition to evaluating the effects of fidelity on objective in-session metrics and subjective post-session responses, we believe it would be truly useful to the research community to evaluate
the effects of fidelity on post-session experiences. In particular, studying the effects of fidelity on training transfer and learning could finally objectively validate the importance of high-fidelity VR systems, or at least provide indication to what levels of display fidelity and interaction fidelity are necessary to benefit training and learning. In addition to training transfer and learning, we are interested to see what the post-session effects of fidelity would be after repeated, long-term exposures to a VR system.

Another line of future research that has been opened by this research is the exploration of how the primary aspects of interaction fidelity—biomechanical symmetry, control symmetry, and system appropriateness—as defined by our new framework, interact with one another and if control symmetry is the dominant factor in determining user performance for most interaction techniques.
REFERENCES


APPENDIX A: EXPERIMENT DOCUMENTS FOR EVALUATION OF STEREOSCOPY, FOR, AND INTERACTION FIDELITY FOR A 3D DOCKING GAME
DATE: March 28, 2006

MEMORANDUM

TO: Doug A. Bowman
    Douglas Gorton
    Joseph Gresock

FROM: David M. Moore

SUBJECT: IRB Expedited Approval: “Separating the Benefits of Immersion and 3D Manipulation Techniques”, IRB # 06-207

Approval date: 3/24/2006
Continuing Review Due Date: 3/9/2007
Expiration Date: 3/23/2007

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective March 24, 2006.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.

2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

3. Report promptly to the IRB of the study’s closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher’s responsibility to obtained re-approval from the IRB before the study’s expiration date.

4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

Important:
If you are conducting federally funded non-exempt research, this approval letter must state that the IRB has compared the OSP grant application and IRB application and found the documents to be consistent. Otherwise, this approval letter is invalid for OSP to release funds. Visit our website at http://www.irb.vt.edu/pages/newstudy.htm#OSP for further information.

cc: File
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: Separating the Benefits of Immersion and 3D Manipulation Techniques

Investigators: Doug Gorton, Joseph Gresock, William McConnell, Ryan P. McMahan, Doug A. Bowman

I. PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study of interaction in virtual environments. This research studies the performance of people using different manipulation techniques under various levels of immersion. This study involves experimentation for the purpose of separating and quantifying the benefits of immersion and 3D manipulation techniques. Eighteen subjects of 18 years or older will participate in the experiment using three different manipulation techniques under four various levels of immersion.

II. PROCEDURES

You will be asked to perform a set of tasks using a virtual environment system. These tasks consist of manipulating virtual 3D objects. You will use the CAVE™. Your role in these tests is that of evaluator of the software. We are not evaluating you or your performance in any way; you are helping us to evaluate our manipulation techniques. All information that you help us attain will remain anonymous. The time you take to do each task and other aspects of your interaction with the system will be measured and recorded. You will be asked questions after the usage of our system, in order to clarify our understanding of your evaluation.

You will also be asked to fill out a questionnaire relating to your background with such systems.

The session will last about one hour. The tasks are not very tiring, but you are welcome to take rest breaks as needed. One scheduled rest break will be given to you about half-way through the experiment. You may also terminate your participation at any time, for any reason.

You will be given full instructions before every task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests of performance using standard virtual environments displays, trackers, and input devices. Participation involves standing (while using the CAVE) and performing simple tasks. The physical components of these tasks are not stressful, and include head and body turning and pointing. All light and sound intensities are well within normal ranges. The only foreseeable physical risks are slight eye strain, dizziness, or mild nausea. There are minimal mental risks.

If you experience any eye strain, dizziness, or nausea during a session, then between tasks please step away from the CAVE and take a rest break. The experimenter will explain when you can take such rest breaks. If you are having trouble with any task, please tell us. If dizziness or nausea becomes uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS

Your participation in this project will provide information that may be used to improve the design of virtual environments hardware and/or software. No guarantee of benefits has been made to encourage you to participate.

You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

VT IRB - This document is valid from 24 March 2006 to 23 March 2007

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The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

VI. COMPENSATION

Your participation is voluntary and unpaid.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason.

VIII. APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, and by the Department of Computer Science.

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

________________________  ________________
Signature                                                      Date

Name (please print)

Should I have any pertinent questions about this research or its conduct, and research subjects’ rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Doug Gorton  Investigator  Email: dogorton@vt.edu
Joseph Gresock  Investigator  Email: jgresock@vt.edu
William McConnell  Investigator  Email: wmcconn@vt.edu
Ryan P. McMahan  Investigator  Email: ryrcm@vt.edu
Doug A. Bowman  Faculty Advisor  Email: bowman@vt.edu  Phone: (540) 231-2058
David M. Moore  Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects  Email: moored@vt.edu
Office of Research Compliance
1880 Pratt Drive, Suite 2006 (0497)  Blacksburg, VA 24061

VT IRB - This document is valid from 24 March 2006 to 23 March 2007
Background Survey

Please help us to categorize our user population by answering the following questions.

1. What is your gender?
   () Male     () Female

2. How old are you?

3. Are you wearing glasses or contact lenses during the experiment?
   () Glasses   () Contact Lenses   () No

4. Are you left or right handed?
   () Left     () Right

5. What is your occupation? (If you’re a student, indicate graduate or undergraduate)

6. If you indicated you’re a student in question 5, what is your major?

7. You are familiar with computers.
   () Strongly Disagree   () Disagree   () Neutral   () Agree   () Strongly Agree

8. How often do you use computers?

9. Please briefly describe your experience with virtual reality or gesture input devices, if any.
APPENDIX B: EXPERIMENT DOCUMENTS FOR EVALUATION OF INTERACTION FIDELITY FOR A RACING GAME
DATE: December 8, 2008

MEMORANDUM

TO: Doug A. Bowman
    Ryan McMahan
    Mara Silva

FROM: David M. Moore

SUBJECT: IRB Exempt Approval: “Comparison Evaluation of 2D and 3D Interaction Styles for Mario Kart Wii”, IRB # 08-754

I have reviewed your request to the IRB for exemption for the above referenced project. The research falls within the exempt status. Approval is granted effective as of December 8, 2008.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in the research protocol. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.

2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

cc: File
Title: Comparison evaluation of 2D and 3D interaction styles for Mario Kart Wii

Investigators: Dr. Doug A. Bowman, Ryan P. McMahan, Mara Silva, David Machaj, Alexander Joel D. Alon, Vineeth Tuluri, Shaimaa Lazem, Bobby Beaton, Michael Schaefer

I. Purpose of this Research

The purpose of this research is to use Mario Kart Wii, which utilizes both 3D interaction through Wii Remote technology and 2D interaction with Classic and GameCube controllers, to determine the effects of high-fidelity interaction. By studying how users perform and enjoy the game while using contrasting controls, this research will provide information and insight on the differences between 3D and 2D interaction. A total of 32 participants will be involved with the research, and each participant must be 18 years of age or older.

II. Procedures

This research will take place at the Center for Human-Computer Interaction’s Black Lab facility in Knowledge Works II or at Lab Room 106 in McBryde during a 90-minute session. You will sit in a chair and will be playing Nintendo’s Mario Kart Wii using four interaction styles: the Wii Wheel, Wii Remote, Wii Classic Controller, and GameCube Controller. You will first fill out a background survey to gather information about your experiences with video games. You will then play Mario Kart Wii, a racing game, using the Time Trials feature, where you will race around tracks following a computer-driven racer. For each of the four interaction styles, you will practice the style on an easy track, complete two Time Trials on the same track, and then complete two Time Trials on a more difficult track. You are to complete the Time Trials as quickly as possible as we will be counting the number of errors you make and noting your lap times. After playing Mario Kart Wii, you will finally fill out an exit survey to give your impressions of each of the interaction styles.

III. Risks

The only foreseeable physical risk is slight eye strain. There is a rest break scheduled approximately half way through the study procedure to reduce this risk. There are minimal emotional and social risks involved.

IV. Benefits

Your participation in the study will provide information that may be used to better understand 2D and 3D interaction styles. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis of this research when it is completed.

V. Extent of Anonymity

Your anonymity will be kept as data collected from your participation will be associated with a participant ID instead of any of your identifying information such as your name.
VI. Compensation

There is no compensation for participating. Your participation is voluntary and unpaid.

VII. Freedom to Withdraw

You are free to withdraw from the study at any time for any reason.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:
You are requested to refrain from discussing the evaluation with other people who might be in
the candidate pool from which other participants might be drawn.

IX. Subject's Permission

I have read the Consent Form and conditions of this project. I have had all my questions answered.
I hereby acknowledge the above and give my voluntary consent:

_______________________________________________________________________________  Date________
Participant signature

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Investigators:  Dr. Doug A. Bowman
Phone: 540-231-2058   Email: dbowman@vt.edu
Associate Professor, Computer Science Department

Ryan P. McMahan, Mara Silva, David Machaj, Alexander Joel D. Alon,
Vineeth Tuluri, Shaima Lazem, Bobby Beaton, Michael Schaefer
Email: rymcmaha@vt.edu, mara@vt.edu, dmachaj@vt.edu, alon@vt.edu,
vineeth@vt.edu, shlazem@vt.edu, rbeaton@vt.edu, mschaefer@vt.edu
Graduate/Undergraduate Students, Computer Science Department

David M. Moore
Phone: 540-231-4991   Email: moored@vt.edu
Chair, Virginia Tech Institutional Review
Board for the Protection of Human Subjects
Office of Research Compliance
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, VA 24060
Mario Kart Wii Study - Background Survey

What's your participant ID? (Ask your experimenter)

What is your age?

What is your gender?
○ Male
○ Female

Which is your dominant hand? (Which do you use for the majority of your actions?)
○ Left Hand
○ Right Hand

Will you be wearing glasses or contact lenses during the study? Choose one.
○ No
○ Glasses
○ Contact Lenses

How often do you play video games?
○ Daily
○ Weekly
○ Monthly
○ Bi-monthly
○ Semi-yearly
○ Yearly
○ Never

How many hours have you played video games in the past week?

How many hours have you played video games in the past month?

Please list all of the video games that you have played in the past month and on what platforms. (For example, NFL 2k9 - Nintendo Wii or Halo 3 - Xbox 360 or 501 Darts - iPhone)
Of the previous list of games, which did you play the most often in the past week?

Of the previous list of games, which did you play the most often in the past month?

Have you ever played Mario Kart Wii?
- Yes
- No

If yes, how many total hours have you played?

If yes, which controller configuration have you used the most?
- Wii Wheel
- Wii Remote
- Wii Remote with Nunchuk
- Wii Classic Controller
- GameCube Controller

If yes, which controller configurations have you EVER used? Mark all that apply:
- Wii Wheel
- Wii Remote
- Wii Remote with Nunchuk
- Wii Classic Controller
- GameCube Controller

Have you ever played any Nintendo Wii game?
- Yes
- No

Have you ever played any racing game?
- Yes
- No

What is the primary reason you play video games?
- To win
- To have fun
- To waste time
- To socialize
- To: 

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Please rate your level of gaming expertise.

- Professional gamer
- Expert gamer
- Experienced gamer
- Recreational gamer
- Occasional gamer
- Non-gamer

Submit
Mario Kart Wii Study - Exit Survey

What's your participant ID? (Ask your experimenter)

Overall
Of the four controller configurations, which did you like best?
○ Wii Wheel
○ Wii Remote
○ Wii Classic Controller
○ GameCube Controller

Of the four controller configurations, which did you find easiest to use?
○ Wii Wheel
○ Wii Remote
○ Wii Classic Controller
○ GameCube Controller

Of the four controller configurations, which did you find the most fun to use?
○ Wii Wheel
○ Wii Remote
○ Wii Classic Controller
○ GameCube Controller

Of the four controller configurations, which did you perform the best with?
○ Wii Wheel
○ Wii Remote
○ Wii Classic Controller
○ GameCube Controller

Please explain your reasonings for the previous four questions.

What part of driving (if any) did you find the Wii Wheel was best for?

What part of driving (if any) did you find the Wii Remote was best for?
What part of driving (if any) did you find the Wii Classic Controller was best for?

What part of driving (if any) did you find the GameCube Controller was best for?

Did the difficulty of the track (Luigi Circuit vs. Wario’s Gold Mine) affect which controller configuration you like best? If so, please explain how.

2D vs. 3D
Between 2D and 3D interaction, which did you like best?
- 2D (Wii Classic Controller and GameCube Controller)
- 3D (Wii Wheel and Wii Remote)
Between 2D and 3D interaction, which did you find easiest to use?
- 2D (Wii Classic Controller and GameCube Controller)
- 3D (Wii Wheel and Wii Remote)
Between 2D and 3D interaction, which did you find the most fun to use?
- 2D (Wii Classic Controller and GameCube Controller)
- 3D (Wii Wheel and Wii Remote)
Between 2D and 3D interaction, which did you perform the best with?
- 2D (Wii Classic Controller and GameCube Controller)
- 3D (Wii Wheel and Wii Remote)
Please explain your reasonings for the previous four questions.

2D Form Factor
For 2D interaction, which did you like best?
- Wii Classic Controller
- GameCube Controller
For 2D interaction, which did you find easiest to use?
- Wii Classic Controller
- GameCube Controller
For 2D interaction, which did you find the most fun to use?
- Wii Classic Controller
- GameCube Controller
For 2D interaction, which did you perform the best with?
Wii Classic Controller
GameCube Controller

Please explain your reasonings for the previous four questions.

3D Form Factor
For 3D interaction, which did you like best?
- Wii Wheel
- Wii Remote
For 3D interaction, which did you find easiest to use?
- Wii Wheel
- Wii Remote
For 3D interaction, which did you find the most fun to use?
- Wii Wheel
- Wii Remote
For 3D interaction, which did you perform the best with?
- Wii Wheel
- Wii Remote

Please explain your reasonings for the previous four questions.

If you have any comments about the interaction styles not covered by the previous questions, please type those comments here.
APPENDIX C: EXPERIMENT DOCUMENTS FOR EVALUATION OF DISPLAY FIDELITY AND INTERACTION FIDELITY FOR A FIRST-PERSON SHOOTER GAME

Name of Institution or Organization Providing IRB Review (Institution/Organization A):
Duke University

IRB Registration #: 00000560 FWA #: 00000265

Name of Institution Relying on the Designated IRB (Institution B):
Virginia Tech FWA #: 00000572

The Officials signing below agree that Virginian tech may rely on the designated IRB for review and continuing oversight of its human subjects research described below: (check one)

( ) This agreement applies to all human subjects research covered by Institution B’s FWA.

(X) This agreement is limited to the following specific protocol(s):

Name of Research Project: Exploring the Effects of Display Fidelity and Interaction Fidelity for Serious Virtual Reality Games
Name of Principal Investigator: Duke: Rachel Brady Virginia Tech: Ryan McMahan
Sponsor or Funding Agency: University of California, Santa Barbara
Award Number, if any: ____________

( ) Other (describe): ____________________________

The review performed by the designated IRB will meet the human subject protection requirements of Institution B’s OHRP-approved FWA. The IRB at Institution/Organization A will follow written procedures for reporting its findings and actions to appropriate officials at Institution B. Relevant minutes of IRB meetings will be made available to Institution B upon request. Institution B remains responsible for ensuring compliance with the IRB’s determinations and with the Terms of its OHRP-approved FWA. This document must be kept on file by both parties and provided to OHRP upon request.

Signature of Signatory Official (Institution/Organization A):
________________________________________ Date: 10/1/10

Print Full Name: James N. Siedow
Institutional Title: Vice Provost for Research

Signature of Signatory Official (Institution B):
________________________________________ Date: ____________

Print Full Name: Robert W. Walters
Institutional Title: Vice President for Research
December 13, 2011

Re:  

Exploring the Effects of Display Fidelity and Interaction Fidelity for Serious Virtual Reality Games
IRB Approval Number A0263
Researchers: Ryan McMahen (VPISU) and Rachel Brady (Duke University)

To Whom It May Concern;

The purpose of this correspondence is to confirm that the above-referenced protocol was approved on July 22, 2010 by the Duke University Institutional Review Board for the Protection of Human Subjects in Non-medical Research. The protocol was approved under the auspices of an Institutional Authorization Agreement in which Duke agreed to be the IRB of record because the research took place at Duke.

Please contact me if you need additional information. I can be reached at lorna.hicks@duke.edu

Sincerely yours,

[Signature]

Lorna Hicks, Director
Program for the Protection of Human Subjects in Non-Medical Research
INFORMED CONSENT FORM

Directions: Read this consent form carefully and ask any questions you may have. If you decide to continue with participation in this research study, please sign on the designated line in the final section and return this copy to the experimenter.

Title: Exploring the Effects of Display Fidelity and Interaction Fidelity for Serious Virtual Reality Games

Investigators: Ryan P. McMahan, Doug A. Bowman, Rachael Brady

I. Purpose of this Research

The purpose of this research is to explore the effects of display fidelity (e.g., 3D graphics) and interaction fidelity (e.g., 3D interaction) on a serious virtual reality game. The game developed for this research is a first-person shooter that takes place on a space ship and involves eliminating androids that have malfunctioned and are attacking the ship’s crew. The game can be played with a keyboard and mouse or with a 3D-input device and 3D head tracker. By studying how people perform and experience the game while using contrasting controls and in contrasting display conditions, this research will provide information and insight on the effects of display fidelity and interaction fidelity.

II. Study Procedures

This research will take place in DiVE Room 1617A, CIEMAS on Duke University’s west campus. The study will last approximately 120 minutes. You will first fill out a background survey to gather information about your experiences with video games. You will then take a spatial ability test to quantify your ability to understand spatial relations. After this, you will wear 3D glasses and a head tracker while using a 3D-input device to experience a virtual kitchen inside the DiVE virtual reality system. In this virtual environment, you can open virtual cabinets and grab virtual objects by pressing a button on the input device. This experience will last approximately five minutes.

After you have experienced the virtual kitchen, you will play the serious first-person shooter game in four separate conditions: keyboard and mouse with only one DiVE wall, keyboard and mouse with all six DiVE walls and stereoscopy, 3D-input device and head tracker with only one DiVE wall, and 3D-input device and head tracker with all six DiVE walls and stereoscopy. For each condition, you will receive training from the experimenter on how to play the game with the given interaction fidelity and display fidelity. After approximately five minutes of training, you will then play a complete level of the game, in which you must eliminate all of the androids you encounter and reach the end of the level. During this level, the game software will log statistics on how you perform (e.g., firing accuracy, number of respawns, time taken). After completing the level, you will then take a presence questionnaire, an engagement questionnaire, and a usability questionnaire to help quantify your experience playing the game in the condition. After each of the first three conditions, you will be given a break to relax and use the restroom. After the final condition, you will be given comparative versions of the prior questionnaires to determine how you compare the four conditions in terms of presence, engagement, and usability.

III. Risks

The only foreseeable physical risks are slight eyestrain, dizziness, and mild nausea. We have scheduled multiple breaks during the study procedure to reduce these risks. The emotional and social risks involved are considered minimal as you will be firing at non-living androids and there are no emotion-invoking special effects included within the serious game.
IV. Benefits

Your participation in the study will provide information that may be used to better understand the effects of display fidelity and interaction fidelity. No guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity

Your anonymity will be kept, as data collected from your participation will be associated with a study ID instead of any of your personal identifying information such as your name.

VI. Freedom to Withdraw

Participation in this research study is voluntary. You are free to withdraw from the study at any time without reason.

VII. Compensation

There is no compensation for participating in this research study. Participation is voluntary and unpaid.

VIII. Further Information

Should you have any questions about this research now, please ask the experimenter. Should you have any questions about this research later, please contact one of the investigators:

Ryan P. McMahan  Doug A. Bowman  Rachael Brady
rymemaha@vt.edu  dbowman@vt.edu  rbrady@duke.edu
(540) 230-6634    (540) 231-2058    (919) 660-0185

Should you have any questions about your rights as a research subject, please contact:

Duke University Campus Institutional Review Board
(919) 684-3030

IX. Acknowledgment

I have carefully read this consent form and the conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent to participate in this research study:

__________________________________________________________________________
Participant Signature

__________________________________________________________________________
Date
DiVE: Background Survey

What is your study ID? (ask the experimenter)

General

What is your gender?
☐ Male  ☐ Female

What is your age?

What is your height?

Which is your dominant hand? (Which do you use to hold a spoon?)
☐ Left  ☐ Right

Will you be wearing glasses or contacts during the study?
☐ No  ☐ Glasses  ☐ Contact

Video Games

How many hours have you played video games in the past week?

On average, how many hours per day do you play video games?

On average, how many days per week do you play video games?

List the five video games you have played the most in the past month and specify the platforms (e.g., StarCraft II – PC):

List the five video games you have played the most in the past year and specify the platforms (e.g., Halo 3 – Xbox 360):
First- and Third-Person Shooters

How many hours have you played first- and third-person shooters in the past week?

On average, how many hours per day do you play first- and third-person shooters?

On average, how many days per week do you play first- and third-person shooters?

List the five first- and third-person shooters that you have played the most in the past month and specify the platforms (e.g., Gears of War 2 – Xbox 360):

List the five first- and third-person shooters that you have played the most in the past year and specify the platforms (e.g., Left 4 Dead 2 – PC):

List all the first- and third-person shooters that you have “beaten” or finished and specify the platform (e.g., GoldenEye 007 – N64):

Firearm Experience

How many occasions have you fired a firearm in the past week?

How many occasions have you fired a firearm in the past year?

How many occasions have you fired a firearm in your life?
DiVE: Presence Questionnaire

What is your study ID?

1. Please rate your sense of being on the space ship, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.
   
   I had a sense of "being there" on the space ship...
   ○1 Not at all  ○2 ○3 ○4 ○5 ○6 ○7 Very much

2. To what extent were there times during the experience when the space ship was the reality for you?
   
   There were times during the experience when the space ship was the reality for me...
   ○1 At no time  ○2 ○3 ○4 ○5 ○6 ○7 Almost all the time

3. When you think back about your experience, do you think of the space ship more as images that you saw, or more as somewhere that you visited?
   
   The space ship seems to me to be more like...
   ○1 Images that I saw  ○2 ○3 ○4 ○5 ○6 ○7 Somewhere that I visited

4. During the time of the experience, which was strongest on the whole, your sense of being on the space ship, or of being elsewhere?
   
   I had a stronger sense of...
   ○1 Being elsewhere  ○2 ○3 ○4 ○5 ○6 ○7 Being on the space ship

5. Consider your memory of being in the space ship. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the space ship, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.
   
   I think of the space ship as a place in a way similar to other places that I've been today...
   ○1 Not at all  ○2 ○3 ○4 ○5 ○6 ○7 Very much so

6. During the time of the experience, did you often think to yourself that you were actually on the space ship?
   
   During the experience I often thought that I was really standing on the space ship...
   ○1 Not very often  ○2 ○3 ○4 ○5 ○6 ○7 Very much so
DiVE: Engagement Questionnaire

What is your study ID? 

Directions: For each of the following, please rate your experience of the sensation while playing the game, on the following scale from 1 (did not experience) to 5 (definitely experienced).

1. I lost track of time.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

2. Things seemed to happen automatically.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

3. I felt different.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

4. I felt scared.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

5. The game felt real.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

6. I felt tense.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

7. Time seemed to stand still or stop.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

8. I felt unaware of my surroundings.
   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

   ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

10. My thoughts were fast.
    ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced

11. I forgot I was in a virtual environment.
    ○1 Did not experience   ○2   ○3   ○4   ○5 Definitely experienced
12. I played without thinking about how to play.

13. Playing made me feel calm.

14. I really got involved with the game.

15. I did not want to stop playing.
DiVE: Usability Questionnaire

What is your study ID?

1. Please rate how easy it was for you to look for the androids, on the following scale from 1 (extremely difficult) to 7 (extremely easy).
   - 1 Extremely difficult
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely easy

2. Please rate how easy it was for you to fire and hit the androids.
   - 1 Extremely difficult
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely easy

3. Please rate how easy it was for you to move around the space ship.
   - 1 Extremely difficult
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely easy

4. Please rate how easy it was for you to distinguish close objects from far objects.
   - 1 Extremely difficult
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely easy

5. Please rate how easy it was for you to play the game in general.
   - 1 Extremely difficult
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely easy

6. Please rate how natural it was for you to look for the androids, on the following scale from 1 (extremely unnatural) to 7 (extremely natural).
   - 1 Extremely unnatural
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely natural

7. Please rate how natural it was for you to fire and hit the androids.
   - 1 Extremely unnatural
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely natural

8. Please rate how natural it was for you to move around the space ship.
   - 1 Extremely unnatural
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely natural

9. Please rate how natural it was for you to distinguish close objects from far objects.
   - 1 Extremely unnatural
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7 Extremely natural

10. Please rate how natural it was for you to play the game in general.
    - 1 Extremely unnatural
    - 2
    - 3
    - 4
    - 5
    - 6
    - 7 Extremely natural

11. Please rate how much fun you had playing the game, on the following scale from 1 (extremely frustrating) to 7 (extremely fun).
    - 1 Extremely frustrating
    - 2
    - 3
    - 4
    - 5
    - 6
    - 7 Extremely fun

12. Please rate how tiring it was for you playing the game, on the following scale from 1 (extremely exhausting) to 7 (not tiring at all).
    - 1 Extremely exhausting
    - 2
    - 3
    - 4
    - 5
    - 6
    - 7 Not tiring at all

13. Please give any additional comments you may have.
APPENDIX D: EXPERIMENT DOCUMENTS FOR EVALUATION OF FOR AND INTERACTION FIDELITY FOR SUBTASKS OF A FIRST-PERSON SHOOTER GAME
Memorandum

To: Ryan McMahan

From: Lorna Hicks

Re: Amendment to Protocol No. A0263, Exploring the Effects of Display Fidelity and Interaction Fidelity for Serious Virtual Reality Games

Date: May 16, 2011

This purpose of this memo is to inform you that the above-referenced amendment was approved, effective today.

The IRB Database is being moved to an OIT server and we cannot access it at this time.

You will receive another notice generated by the database later in the week. That notice will provide additional information about managing your protocol.
INFORMED CONSENT FORM

Directions: Read this consent form carefully and ask any questions you may have. If you decide to continue with participation in this research study, please sign on the designated line in the final section and return this copy to the experimenter.

Title: Exploring the Effects of Display Fidelity and Interaction Fidelity for Serious Virtual Reality Games

Investigators: Ryan P. McMahan, Doug A. Bowman, Rachael Brady

I. Purpose of this Research

The purpose of this research is to explore the effects of interaction fidelity (e.g., 3D interaction) and field of regard (i.e., number of displays) on a serious virtual reality game. The game developed for this research is a first-person shooter that takes place on a space ship and involves eliminating androids that have malfunctioned and are attacking the ship’s crew. The game is played with a keyboard and mouse, a 3D-input device, and a 3D head tracker. By studying how people perform and experience the game while using contrasting controls in contrasting display conditions, this research will provide information and insight on the effects of interaction fidelity and field of regard.

II. Study Procedures

This research will take place in DiVE Room 1617A, CIEMAS on Duke University’s west campus. The study will last approximately 120 minutes. You will first fill out a background survey to gather information about your experiences with video games. You will then take a spatial ability test to quantify your ability to understand spatial relations. After this, you will wear 3D glasses and a head tracker while using a 3D-input device to experience a virtual kitchen inside the DiVE virtual reality system. In this virtual environment, you can open virtual cabinets and grab virtual objects by pressing a button on the input device. This experience will last approximately five minutes.

After you have experienced the virtual kitchen, you will play the serious first-person shooter game in multiple experimental conditions. For each condition, you will receive training from the experimenter on how to complete the designated game task with the given interaction fidelity and field of regard. After training, you will then complete the same game task across multiple trials with the same levels of interaction fidelity and field of regard. During these trials, the game software will log statistics on how you perform (e.g., firing accuracy or time taken). After completing the trials, you will then take a series of subjective questionnaires to help quantify your experience playing the game in the experimental condition. After each of the conditions, you will be given a break to relax and use the restroom.

III. Risks

The only foreseeable physical risks are slight eyestrain, dizziness, mild nausea, and fatigue. We have scheduled multiple breaks during the study procedure to reduce these risks. The emotional and social risks involved are considered minimal as you will be firing at non-living androids and there are no emotion-invoking special effects included within the serious game.

IV. Benefits

Your participation in the study will provide information that may be used to better understand the effects of display fidelity and interaction fidelity. No guarantee of benefits has been made to encourage you to participate.
V. Extent of Anonymity

Your anonymity will be kept, as data collected from your participation will be associated with a study ID instead of any of your personal identifying information such as your name.

VI. Freedom to Withdraw

Participation in this research study is voluntary. You are free to withdraw from the study at any time without reason.

VII. Compensation

There is no compensation for participating in this research study. Participation is voluntary and unpaid.

VIII. Further Information

Should you have any questions about this research now, please ask the experimenter. Should you have any questions about this research later, please contact one of the investigators:

Ryan P. McMahan          Doug A. Bowman          Rachael Brady
  rymcmaha@vt.edu          dbowman@vt.edu          rbrady@duke.edu
(540) 230-6634            (540) 231-2058            (919) 660-0185

Should you have any questions about your rights as a research subject, please contact:

Duke University Campus Institutional Review Board
(919) 684-3030

IX. Acknowledgment

I have carefully read this consent form and the conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent to participate in this research study:

__________________________________________________________________________  __________
Participant Signature                                                      Date
DiVE: Background Survey

What is your study ID? (ask the experimenter)

General

What is your gender?
  ○ Male  ○ Female

What is your age?

What is your height?

Which is your dominant hand? (Which do you use to hold a spoon?)
  ○ Left  ○ Right

Will you be wearing glasses or contacts during the study?
  ○ No  ○ Glasses  ○ Contact

Video Games

How many hours have you played video games in the past week?

On average, how many hours per day do you play video games?

On average, how many days per week do you play video games?

List the five video games you have played the most in the past month and specify the platforms (e.g., StarCraft II – PC):

List the five video games you have played the most in the past year and specify the platforms (e.g., Halo 3 – Xbox 360):
First- and Third-Person Shooters

How many hours have you played first- and third-person shooters in the past week?

On average, how many hours per day do you play first- and third-person shooters?

On average, how many days per week do you play first- and third-person shooters?

List the five first- and third-person shooters that you have played the most in the past month and specify the platforms (e.g., Gears of War 2 – Xbox 360):

List the five first- and third-person shooters that you have played the most in the past year and specify the platforms (e.g., Left 4 Dead 2 – PC):

List all the first- and third-person shooters that you have “beaten” or finished and specify the platform (e.g., GoldenEye 007 – N64):

Firearm Experience

How many occasions have you fired a firearm in the past week?

How many occasions have you fired a firearm in the past year?

How many occasions have you fired a firearm in your life?