3D Travel Comparison Study Between Multi-Touch and GamePad

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Abstract

This study explored interactions between users and a 3D virtual world by means of a multi-touch display, and sought to identify advantages of this form of interaction. An experiment was conducted with 28 subjects, who were classified into two groups: experienced gamers and casual gamers. The experiment involved a pseudo-universe, where users were required to find five objects using the multi-touch display, and five objects using a game controller (GamePad). Overall, the multi-touch was slightly faster than the GamePad in the search for objects. Experienced users performed significantly better when using the GamePad, compared to casual gamers. When casual gamers were analyzed separately, their performance was better (at a statistically significant level) with the multi-touch display, compared to the GamePad. Finally, users had a significantly higher error rate when switching from the GamePad to the keyboard.

Keywords: Device Comparison, 3D travel, travel, 3DUI, game controller, GamePad, 3D navigation, multi-touch, keyboard, homing

1. Introduction

With the introduction of new input devices such as multi-touch surface displays, the Nintendo WiiMote, the Microsoft Kinect, and the Leap Motion sensor, among others, the field of human computer interaction (HCI) finds

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B	Regular PC user. No video game console experience. iPad user	3
C	Game developer and experienced game player	2
D	Regular iPhone and MAC user. Little experience with video game console	2
E	Multi-touch user. iPad and iPhone User. Experienced game user.	6

Table 1: Pre-Trial Users.

itself at an important crossroads that requires solving new challenges. With the amount of 3-dimensional (3D) data available today, 3D navigation is a necessary function of 3D User Interfaces (3DUI). 3D navigation is divided into travel, the engine of navigation (which allows the system to move), and way-finding (the cognitive understanding of navigation) (Bowman et al. 2004, Ortega et al. 2016). We have focused on the travel part of navigation. However, it is important to note that from the user's perspective it is hard to break apart travel from the way-finding. We were interested in finding out whether multi-touch is useful for 3D travel in exploring 3D virtual environments. Specifically, we aimed to answer how multi-touch compares to a game controller (GamePad) when used in a 6-degrees of freedom (DOF) 3D travel environment. In addition, we wanted to investigate the implications of intermittently using a keyboard in this type of scenario. There are several examples where multi-touch with a physical keyboard could be used. For example, 3D modeling in software, like Blender, 3DS Max, or even the popular Unity Game Engine, provide opportunities where multi-touch can can be of use.

1.1. Pilot Studies

We performed several pilot studies to determine the best device for comparison against multi-touch and to decide on the type of gestures used. We recruited five users for iterative design purposes (see Table 3). During the pilot-studies, users were asked to try alternative input devices and gestures. Each visit lasted between 30 and 60 minutes. The information provided was used to design the experiment. The GamePad was the preferred method by these users.

During the pilot studies, we tested the GamePad against a WiiMote and a 3dconnexion. The WiiMote returned noisy data (because of the gyroscope add-on) and was thus not chosen for this experiment. The 3dconnexion was disliked by participants. The is anecdotal evidence that artists will use 2 of them to overcome the limited range of inputs that they provide. At the time of this study the Oculus and HTC Vive controllers were not available.

The same participants (see Table 3 were asked to complete the 3D travel experiment using multi-touch and GamePad. This helped us gain insight into the problem and areas of interest before the final experiments. Using a smaller set of the pilot participants (those willing to come more than twice), we finalized the gestures to be used for the multi-touch interaction and determine the best GamePad configuration. The most important outcome of this pilot-study is that it determined the set of gestures used. Wobbrock and colleagues (and later Morris et. al) have suggested that while a large set of users may be ideal to create a set of gestures, the second-best approach is to create a set among experts and/or a smaller set of users (Wobbrock et al. 2009, Morris et al. 2010).

The experimenter designed an initial set of gestures that was then modified based on the experience and recommendations of the participants in the pilot studies; all gestures were either modified or replaced, with the exception of the "Hold-and-Roll" gesture for the translation on z-axis, which received positive feedback during the pilot study. This work led to the development of a set of hypotheses (H) that were investigated in the final user study, shown in Table 2. Note that this study is not aimed at investigating the effects of arm fatigue but rather the effect of task and input switching. We hypothesized that the act of placing a controller to the side, thus breaking eye contact with the keyboard, and breaking concentration, would cause increased error rates with the GamePad (H_z).

1.2. Contributions

The primary contribution of this paper is a better understanding of multi-touch displays as a means of 3D travel for users as compared to the GamePad. It also provides a gesture set constructed from the inputs of a small set of people with different backgrounds (from the pilot-studies), and it also looks at how users switch from multi-touch to keyboard as opposed to GamePad to keyboard. Users may be required to type while traversing complex data. For example, an astronomy researcher may need to add annotations to a 3d rendering of their data. We wanted to understand, which of the two input devices compared in this study (multi-touch versus GamePad) would make a difference in such a situation. While a digital keyboard may be available, some users prefer a physical keyboard.

2. Related Work

Six-DOF as input devices and how participants deal with them have been studied in full detail by Zhai (Zhai 1995). The study (Zhai 1995) is of great relevance to our experiment because it established that the muscle groups involved in a 6-DOF action vary depending on the device used, which helped us design a better interface. His study also talks about transfer functions (see (Hinckley 2012))that have to be compatible with the characteristics of the actual device, which was corroborated by Bowman et al. (Bowman et al. 2004, Chapter 5), in their guidelines: "match the interaction technique to the device" (Bowman et al. 2004, p. 179). This provided a guideline for our work. Another guideline that was considered for our study was the one suggested by Poupyrev, where he mentioned that non-isomorphic rotations should be prioritized(Poupyrev et al. 2000). This meant that our design was required to have rotations that were not mapped directly to the gesture (a 1:1 mapping), or as LaViola Jr. and Katzourin wrote in their comparison study, that "non-isomorphic mappings let users interact with virtual world objects at an amplified scale, in contrast to isomorphic mappings" (LaViola and Katzourin 2007). It is important to note that this notion of non-isomorphic rotations has been supported in different studies, including (LaViola and Katzourin 2007), where the results showed that non-isomorphic rotations with an amplification factor of 3 provided a 15.0% faster interaction for the users (LaViola and Katzourin 2007). We suggest reviewing additional guidelines in (Hancock et al. 2007, Jacob et al. 2008, Bowman et al. 1999; 2006, Hinckley 2012, Bowman et al. 2004). A last reason that we didn't use isomorphic gestures is because both input devices were not 6DOF, therefore, it provided more flexibility to travel in 3D by using non-isomorphic gestures.

One study that influenced our gesture design was "Separability of Spatial Manipulations in Multi-touch Interfaces" by Nacenta et al., which analyzed different aspects rotations, translations, and scaling gestures separate or combined (Nacenta et al. 2009). In particular, they concluded that "it becomes difficult to control one of the dimensions (e.g. orientation) without slightly affecting other (e.g. size)" (Nacenta et al. 2009). While this may apply more to interaction than travel, we kept this principle in mind when choosing our gestures. For example, translations in X and Y were allowed to be performed together. Note that while their study was slightly different from ours, their results remain meaningful in terms of their design and objectives. An additional area of concern for us was learning whether bi-manual gestures would be necessary. Based on studies, such as (Kin et al. 2009, Moscovich and Hughes 2008) and the results from our pilot studies, we decided to keep the Hold-and-Roll as the only bi-manual gesture. Some studies have concluded that one-hand techniques are better suited for integral tasks (e.g., rotations), while two-hand techniques are better suited for separable tasks (Kin et al. 2009, Moscovich and Hughes 2008).

Search is a common task for 3D navigation in virtual environments. Bowman describes two types of search: naive and primed (Bowman et al. 1997). This was first studied for large virtual worlds by Darken and Sibert (Darken and Sibert 1996). They concluded that if no visual cues or directional guides are given, users have a tendency to become disoriented (Darken and Sibert 1996). This study, along with (Bowman et al. 1999), influenced our decision to include visual cues for the participants. Bowman et al. attached a pole with a flag on each object, with numbers 1-4. In addition, the target was marked with a painted circle consisting of a 10-meter (large), or a 5-meter (small) radius. For the naive search, the gaze-directed technique (Bowman et al. 1999) was the fastest out of the seven techniques tested.

Santos et al. studied the difference between 3D navigation with a non-stereo desktop display, versus a head mounted display (HMD) [2] (Sousa Santos et al. 2008). In this comparison study, the subjects were divided into two groups, non-experienced, and experienced gamers; and three subgroups, based on their stereoscopic usage - none, moderate, and experienced. The

[2] HMD are stereo.

participants from the "experienced" group were shown to have significantly different performance with respect to the number of objects caught in the game using the desktop display (Sousa Santos et al. 2008). This indicated that previous skill could influence how subjects perform tasks due to their familiarity with similar environments. No statistical difference for the groups was found when they used the HMD. Santos et al. found that users preferred the desktop display (Sousa Santos et al. 2008). This study provided a first indication that we needed to consider groupings based on experience. In addition, Kulshereshth and LaViola Jr. (Kulshreshth et al. 2013) evaluated performance benefits when using a head-tracking device. The games tested were Arma II, Dirt2, Microsoft Flight, and Wings of Prey (Kulshreshth et al. 2013) using a Personal Computer (PC) and an Xbox 360 controller. The subjects where divided into two groups: casual and experienced gamers. Their analysis found that experienced gamers may benefit from using a head-tracking device in certain scenarios, such as First-Person Shooter (FPS) and air combat games (Kulshreshth et al. 2013). Based on their study, we adapted our questionnaire to differentiate between experienced and non-experienced gamers.

The closest study to ours was conducted by Yu et al., who studied 3D navigation using a touch screen. The technique used in (Yu et al. 2010) allowed users to travel in 3D. The virtual world was a representation of scientific data. Users navigated using single-touch gestures or the mouse (this is a major difference, since we are using multi-touch and a GamePad). The objective was to test a 7-DOF that included X, Y, Z translations; yaw, pitch, and roll rotations; and scaling (the 7th degree) to zoom in or out of the screen. For our particular case, we decided to test only 6-DOF since we were concerned with the primary part of the travel engine, rotations and translations. As already stated, their approach (Yu et al. 2010) limited touch to single finger interactions in most instances and provided the use for an additional touch to create specific constraints to aid the movement (similar to a widget in the edges of the display). Their study showed that the mouse yielded a shorter time for translation and rotation, but only the improvement in rotations was statistically significant. The scale case (zoom in/out) showed a significant difference between both input devices, with the mouse having a faster action time (Yu et al. 2010). Additional studies with 6+ DOF include (Stannus et al. 2014, Feng et al. 2015, Cho and Wartell 2015).

3. Methods

3.1. Rate-Control vs Position-Control

The first impression is that the comparison between GamePad and multi-touch is incompatible due to one having rate-control and the other one having position-control. However, the multi-touch device was used as a rate-control device.

3.2. Hold-and-Roll Gesture

While this publication concentrates on the experiment as the main contribution, it is important to mention that the gesture we created called **Hold-and-Roll** was inspired by similar approaches, such as the ARCBALL (Arvo 1994) and the rolling ball (Glassner 1993).

Hold-and-Roll is intended to be a bi-manual multi-touch interaction. With this said, it is possible to try to perform this gesture with one hand, as will be clear when the gesture is explained. The gesture designed allowed for a different gesture to move forward and back (Z direction). The scale gesture was disabled from the experiment because it is reserved for zoom in or out or adjusting the camera's view angle. It is important to consider that moving forward and back, is not the same as zooming in or out of the virtual world. This gesture performed as follows: (1) The gesture uses two stationary fingers with the non-dominant hand and a rolling movement with the finger of the dominant hand; (2) The finger from the dominant hand rolls vertically, either up and down. (3) The rolling finger can be assigned a momentum value, which will decay over time.

We observed a few users try to perform a pinch during the experiment. While we did not test 7-DOF travel (which would had included zoom), the experimenter made users aware of the difference between zoom-in and out versus translation on the z-axis. It was explained to the users before the experiment and they were allowed to use all the gestures available during training. Using an alternative method has been considered before. For example, Feng et al. studied several techniques for 3D Travel (Feng et al. 2015). Spindle+Wheel – a variant of the Grab-and-Scale method – and One-Hand+Scale. The results showed that the techniques perform equivalently whenever no scale adjustments are needed. When scaling was needed, the Spindle+Wheel and Grab-and-Scale performed better and were faster than the One-Hand+Scale (Feng et al. 2015). The Hold-and-Roll gesture is similar to Spindle+Wheel technique.

3.3. Keyboard

In a typical study of keyboard, the words-per-minute (WPM) of each of the users is critical. However, in this experiment, the users performed the same sentences with bboth devices (GamePad and multi-touch). The time used for 3D travel represents only the time using the primary devices, not the keyboard. Therefore, it does not affect the timing of 3D travel when using multi-touch or GamePad. At most, it may affect the comparison of the keyboard time and their error rate. Another important consideration is homing. The homing time between putting down the GamePad and using the keyboard is not a factor in this study, as we understand that placing the GamePad down may require more time than removing the hands from the multi-touch display.

3.4. Experiment Environment

The equipment used for the experiment consisted of a few pieces of hardware. They included a Dell Precision T3500 PC with 12 gigabit (GB) random-access memory (RAM) and Intel Xeon four-core central processing unit (CPU) W3530 2.8 giga Hertz (GHz), 3M M2256PW multi-touch display, keyboard, experimenter controller, Xbox 360 GamePad (Figure 1b), AMD ATI FirePro V7800 graphics processing unit (GPU), and stereo speakers.

The software utilized for the experiment included commercial platforms and solutions developed by us. This included Microsoft Windows 7 64-bit, Microsoft Visual Studio 2012, Object-Oriented Graphics Rendering Engine (OGRE) (version 1.9), OpenGL 4.1, MyGui Application Programming Interface (API) (version 3.2), Gesture Works Core (GWC) 1.0, and OpenAL (audio library). All the software was developed using C++.

In addition to the development of the 3D travel environment, one key component was added. A custom gesture filter to detect the gestures used in this experiment and to detect their decay. The initial layer provided by GWC 1.0 only yielded a set of features for each gesture but it failed to consistently recognize gestures. Without having a reliable gesture detection, an additional layer was implemented to recognize the gesture. In addition to recognizing a given gesture, the level of decay of the gesture (power of specific features) allowed us to recognize a new gesture without requiring the users to have to lift their hands from the multi-touch if desired. While this part is not considered a major contribution for this paper, it provides smooth interaction from the user's perspective. We customized the gesture recognition of the Windows API and the GWC. At the time of the experiment, the

H_t	The proposed real-time multi-touch interaction for 3D navigation will take less time to find the objects in a primed search in comparison to the GamePad.	**F**
H_u	Given the multi-touch input, there will be a significant difference between casual and experienced gamers.	**F**
H_v	Given the GamePad input, there will be a significance difference between casual and experienced gamers.	**T**
H_y	It will take less time to complete the sentences when switching from the multi-touch than when switching from the GamePad.	**F**
H_z	There will be a higher error rate when switching from the GamePad than when switching from the multi-touch.	**T**

Table 2: Hypotheses and Final Results

Windows API or the GWC did not provided accurate recognition for the gestures we were using. GWC, while claiming to recognized gestures, it never did. Therefore, using the raw-data from Windows in addition to GWC, we customized the gesture recognition used in this experiment.

3.5. Experiment Design

The primary objective of the study was to learn whether there are any significant differences between multi-touch display and a GamePad for 3D navigation (with 6-DOF). Additionally, we needed to learn what if any co-factors influence the results for these two devices. This led to the hypotheses in Table 2.

Before the experiment started, a training video and a training scenario (with one target to find per device) were presented to the user. In the experiment, a subject would use the multi-touch device or the GamePad to navigate and reach five objects (targets). The order of the devices used was randomized. Prior to starting the experiment, upon reaching each object a pop-up window would appear showing a target sentence, and the subject would be asked to use a keyboard to type the sentence in the space provided within the pop-up window, and hit enter. If the target sentence was properly typed, the pop-up window would disappear (with an audio cue of success), allowing the subject to continue navigating. Otherwise, the window would persist and indicate an error.

ID	Type of User	Visits
A	Regular iPhone and iPad User. Little experience with video game console	5
B	Regular PC user. No video game console experience. iPad user	3
C	Game developer and experienced game player	2
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E	Multi-touch user. iPad and iPhone User. Experienced game user.	6

Table 3: Pre-Trial Users

Before proceeding with the experiment, we asked a few subjects with different skills to test a preliminary version of the experimental protocol. There were five pre-trial users, as shown in Table 3, which describes each user (identified by a letter). The choice of multi-touch gestures, multi-touch and GamePad mappings, visual cues, and the reset button, among others, were derived from pre-trial feedback.

3.6. Device Selection and Apparatus

The GamePad controller was selected as the device to compare to the multi-touch display, for the 3D navigation tasks. The primary reason for this is that the GamePad has been in the market for more than 30 years (Loguidice and Barton 2014) and can provide 6DOF via the thumb-sticks and trigger buttons. Finally, it is important to note that selection with GamePad (Natapov et al. 2009) in combination with game controllers and tablets for TV interaction (Cox et al. 2012) has been studied.

3.7. Gesture Mapping

Morris et al. showed that a gesture dataset created by a group of users is preferred and that a group of users/designers would also show an improvement over the selection of a single user/designer (Morris et al. 2010) (see also (Wobbrock et al. 2009)) – this is the approach we took. This yielded the gestures shown in Table 4. In order to create a fair comparison and based on the results from our pilot studies, some constraints were established: first, diagonal translations were enabled for the X and Y axes; this was possible

(a) 3M Multi-Touch Display

(b) XBox 360 GamePad

Figure 1: Comparison Devices

because the swipe gesture allowed the user to move diagonally (e.g., increasing X axis while decreasing Y axis, among other options). This was the only gesture that allowed two combined movements with a single gesture (by swiping diagonally). All other gestures were independent (one gesture to one action). For the z-axis, the **Hold-and-Roll** performed as follows: (1) The gesture uses two stationary fingers with the non-dominant hand and a rolling movement with the finger of the dominant hand; (2) The finger from the dominant hand rolls vertically, either up or down. (3) The rolling finger can be assigned a momentum value, which will decay over time (see Section 3.2 for further details explaining where these gestures were derived from). The rotate gesture provided the roll rotation. In the case of the pitch and yaw rotations, there was a possibility to provide dual rotation, since it used a two-finger swipe gesture. However, during the pre-trials, this created confusion for the users (disorientation). This was because the environment being traveled in (the pseudo-universe) did not mirror our universe, nor did it have any landmarks or reference points. In the pilot study when users preformed both rotations at once they often did not know which direction they were facing afterwards in relation to their previous direction. Therefore, it was disabled. To overcome the possibility of the user creating a small diagonal when they meant to do a horizontal or vertical swipe in a rotation action, the system provided a way to adjust the swipe to the closest match (either vertical or horizontal). The same constraints were applied to the GamePad.

Fingers	Gesture	Action
1	Swipe horizontal	Translate X
1	Swipe vertical	Translate Y
3	Hold-and-Roll bi-manual	Translate Z
1	Swipe diagonal	Translate X & Y.
2	Swipe horizontal	Yaw
2	Swipe vertical	Pitch
2	Rotate	Roll
2	Swipe diagonal	Disabled
n	Scale gesture	Disabled

Table 4: Gesture Mappings

3.8. GamePad Design

The GamePad design was also tested during pre-trials. Specifically, one of the pre-trial users is a game developer, leader of the Miami Game Developer Guild[3], and an experienced game player. He, along with the other users, helped to test the GamePad implementation for 3D navigation. This aided the decision making in regards to the experiment design.

The Xbox 360 controller comes with two thumb-sticks. A thumb-stick is a small joystick that is designed for the use of a thumb. By providing two analog thumb-sticks (this has been the standard, since the introduction of the Sony Dual Analog Controller and Dual-Shock (Loguidice and Barton 2014)), this type of dual-thumb-stick GamePad can provide a more accurate movement with 4-DOF[4]. In gaming, it is customary to prevent the character from looking up or down past a given angle (Zechner and Green 2011, pp. 561–572)[5]. In some domain-specific scenarios, having less than 6-DOF is very suitable (Sultanum et al. 2013). In our case, 6-DOF were needed. Therefore, additional mapping was required, as shown in Table 5. The constraint of having one rotation per mapping was added to the GamePad as it was with the Multi-Touch display. The only 2:1 mapping was the translation on the X and Y axes (same as multi-touch).

[3] See `http://www.gamedevelopersguild.com`.

[4] Using the additional buttons, is possible to have 6-DOF navigation.

[5] See also (Luna 2011, Chapter 14) and (Mukundan 2012, pp. 47–49).

Control	Direction	Action	Analog
Left thumb-stick	Up/down	Translate y axis	Yes
Left thumb-stick	Left/right	Translate X axis	Yes
Left thumb-stick	Diagonal	Translate Y axis	Yes
Left/Right upper trigger	-	Translate Z axis	Yes
Right thumb-stick	Up/down	Pitch	Yes
Right thumb-stick	Left/right	Yaw	Yes
Left/Right lower trigger	-	Roll	No

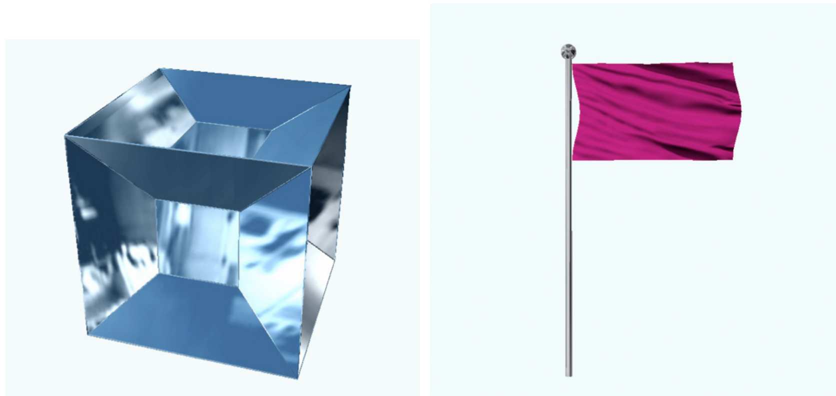
Table 5: Controller Mappings

3.9. Naive Search

We used a **Search** task for this experiment, as described in (Bowman et al. 2004). We measured the time taken with each device to find the targets. This would have proven difficult with the exploration technique. Once the search technique was selected, the options of using **naive** and **primed** searches were evaluated. We showed images (on a piece of paper) to the users of the targets that they were searching for but not their locations (as it would be in a primed search). Therefore, the search performed was naive (with the slight modification of showing images of their targets). In order to reduce a possible frustration factor, two objects were always very easy to spot, one less easy to spot, and two were difficult to find. During the training that preceded the timed navigation experiment, the user did not see the actual objects, but was presented with a hypercube, as shown in Figure 2a.

3.10. Visual Cues

The visual cues provided were minimal. First, the subjects were told that the universe was surrounded by a big sphere, called the inner sphere. They were told that all the objects would be found inside the inner sphere. It was also explained to them that an outer sphere surrounded the inner sphere. Exiting the inner sphere would be allowed, given that there was a space between both spheres. However, if the users found themselves too close to the outer sphere, the environment would trap them, forcing them to press the reset button. Pressing the reset button would produce a large penalty in distance traversed. It is important to note that while all the objects were inside the inner sphere, the user could not see them right away. This incentivized the users to try to stay within the boundaries of the inner sphere.



(a) Hyper Cube for Training (b) Search Object Marker (Flag)

Figure 2: Training and Flag Objects

The decision to let them out of the traversal space (in the inner sphere) was done to keep navigation smooth, while users were in the boundaries.

The users were also told that the targets would have a flag, as shown in Figure 2b. This flag would indicate that the object next to it was a target, as there were other objects in the virtual world that were not targets. Once a target was reached, its flag would disappear. For each treatment, all the search objects would start with their flags showing, and as the subject reached them, the flag would disappear. In addition to the flag, in the top right corner of the screen, the name of the targets would appear, written in red, once they were reached.

3.11. Device Switching

The device switching, also known as user's access time (English et al. 1967), is the measurement of time for a user to go from device A to device B. For example, this could mean that someone using a GamePad to navigate may be required to put down this device before using the keyboard. This was tested by English et al. (English et al. 1967). In the case of our experiment, the objective was to see if there was any difference when subjects performed the switch from either of the two devices tested (GamePad and multi-touch), to the keyboard. This meant the time the user took between the target collision and the successful typing of a sentence using the keyboard. Similar situations involving switching between two devices have been studied (Song et al. 2011). The users' access time is called homing, when working with the

Keystroke-Level Model (KLM) (Card et al. 1980). The KLM is related to Goals, Operators, Methods, and Selection (GOMS) (Dix et al. 2004) because it attempts to break down complex tasks. For further information about homing and related topics, see (Card et al. 1983; 1980, Mackenzie 2012, Hinckley 2012). It is important to note that the search time was not affected by the keyboard time, as this time was subtracted.

3.12. Gamers' Experience

Before the experiment started, there was a valid concern that some users may have extensive experience with the GamePad when navigating in 3D games. The entry questionnaire shown in Table 7 provided a way to classify users in this regard. Similar methods for gamers classification have been used before in (Kulshreshth et al. 2013). Equation 1 shows the game experience calculation, which is the weighted sum of some questions divided by the maximum score (13.25), providing a normalized value from 0 to 1 (0% to 100%). This formula contains Q_n, where Q stands for the question and the index n stands for the question number, a weight for each question (reflecting its importance), and the constant of 13.25 to normalize the results into L, which is the game-level experience. The answers to the questions (Q) were valued between 0 and 1 by the researcher based on the depth of the responses provided. Additional information in how the criteria was formulated is found in (Ortega 2014). Experienced gamers were selected where L was greater or equal to 0.7. The limit for the categorizations was validated using the post-interviews conducted with those participants who were available for the follow-up. Experienced users were the ones that were accustomed to using a GamePad with high frequency in complex games. Otherwise, they were classified as non-experienced gamers. It was important to make a difference between people that played casual games or played games that require very little use of a controller.

$$L = \frac{(3Q_1 + 6Q_2 + 0.25Q_5 + 1.5Q_6 + 1.5Q_7 + 0.5Q_8 + 0.5Q_9)}{13.25} \tag{1}$$

Studies have looked at finding measurements for game levels (see (Terlecki and Newcombe 2005, Jennett et al. 2008)). In this particular approach, based on aforementioned studies, Equation 1 was validated with the extended interviews conducted with participants who were available for a follow-up. The second validation was provided by the additional questions given to the subjects chosen at random. By no means is this a general model, and

Symbol	Choices
¶	6 months; 1 year; 2-4 years; 4-6 years; 5-10 years; 10 or more years
§	Never; Rarely; Daily; Weekly; Once a month; Once every 3 months; Once in 6 months; Once a Year.
†	5:Extremely well skilled; 4: Very good; 3: Good; 2: Not very skilled; 1: Not skilled at all.
‡	Choose either for GamePad or multi-touch, each of the following operations: Rotation: Yaw, Roll, Pitch Translations: Up/Down, Left/Right, Forward/Back

Table 6: Multiple Choice Legend

further examination is needed to determine a general approach to game-level classification. Nevertheless, specifically in this study the described approach gave correct results and provided a way to define a game-level factor for the experiment.

3.13. Questionnaires and Measurements

Participants were given entry and exit questionnaires. Some surveys had to be sent more than once because the participant did not complete all questions. The legend that accompanied the survey is shown in Table 6.

The entry survey, shown in Table 7, provided a way to classify the subject's game expertise level (casual or experienced). This measured a ranking for the 3D navigation using a GamePad controller. An additional questionnaire was given to a number of participants selected at random. This helped validate the previous question's objective, which was to determine the expertise of the subjects in relation to game playing.

The exit survey provided a subjective evaluation of the system. Besides understanding what each subject internalized during the process, the survey looked to validate the objective data, or explain the discrepancies observed in it. The questions are shown in Table 8.

#	Question	Type
1	Have you ever played PC Games? If yes, list a few of them and when you played them.	Open
2	Have you ever played Console Games (XBOX, PlayStation, Nintendo)? If yes, list a few of them and when you played them	Open
5	How long have you been playing video games? Please circle one option.	Range¶
6	How often (approximately) do you currently play video games? Please circle one.	Range§
7	How would you describe your skill level at playing video games on a scale of 1-5, with 5 the being the most skilled and 1 the least skilled?	Range†
8	What gaming systems do you own or have you owned in the past? Please list them and specify if you still own them. Also, include if there are any systems you would like to own in the next year.	Open
9	Please list your favorite video games. List at least a couple, if possible, and tell us why.	Open

Table 7: Partial Entry Questionnaire

#	Question	Type
1	On a scale of 1 to 10, please rank how much easier you found the multi-touch display compared to the GamePad for 3D navigation. The higher you rank (10), the easier you found the multi-touch display versus the GamePad.	Scale 1-10
2	On a scale of 1 to 10, please rank how much easier you found the GamePad device compared to the multi-touch display. The higher you rank (10), the easier you found the GamePad device versus the multi-touch display.	Scale 1-10
12	Which device do you prefer: GamePad, multi-touch, No Difference (both) (please circle one).	multiple-choice
13	Which device did you find better to switch to the keyboard (when asked to type)? GamePad, multi-touch, No Difference (both) (Please circle one).	multiple-choice
23	Please rate the Hold-and-Roll gesture you used during the experiment (10 = very useful, 1= not useful at all)	Scale 1-10
24	Would you like to see this gesture in new games or applications? Please explain.	Open
25	Would you like to see this gesture in new applications? Please explain.	Open

Table 8: Partial Exit Survey

3.14. Objective Measurements

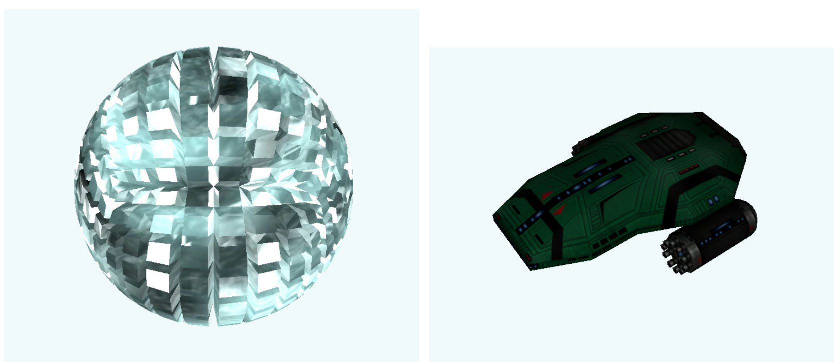
The measurements recorded include: travel time, switching time, and sentence error rate. The travel time was defined as the time between the start of the treatment and the final sentence typed. The switching time was defined as the time between the question prompt and the successful sentence completion using the keyboard. A different time can also be derived, it is the difference of the treatment time (GamePad or multi-touch display) and the keyboard time. The sentence error rate is the number of incorrect sentences typed after pressing the enter key. Please note that the switching time is not the same as the traditional homing time (as described in (Card et al. 1983)). The reason for this is that we wanted to know not only how fast the switch was performed, but also whether it had any effects (not only on errors but also on increasing the timing) when users typed. We consider the innate variation in understanding and typing speed between participants, however, this is not a concern given that our data is paired. This means that rather than analyzing the time spent we will consider the differences between the two devices to determine which was more efficient.

3.15. Visualizing the Experiment

This section provides the step by step procedure that subjects followed during the experiment. Participants started with an entry survey. Later, they watched a video and then completed a training segment followed by the "treatment" segment (actual experiment) – for each device (in randomized order). In the case of training, the hypercube (Figure 2a) was used in search. In the treatment there were five objects to find. The five objects for the search task in both treatments were a hypersphere (Figure 4a), a spaceship (Figure 4b), a green creature, a space satellite, and a tetrahedron. A series of static non-target objects were also placed in the virtual world, which included a red creature and a green space ship, among others. A screen-shot of the actual experiment display (on the multi-touch screen) is shown in Figure 3.

For the actual treatment, the participants were asked to use both multi-touch and a GamePad device (in random order) for the session. The participants advised when they were ready to start the experiment. Once ready, the experimenter pressed the special function key **N** (this corresponds to "9" on the keypad). When a target was found, the user was required to collide with the target. Once the collision was detected, an input text box message appeared in the middle of the screen asking the user to type a sentence. The user was only allowed to use the keyboard at this point. The sentence

Figure 3: 3D Navigation Experiment Display



(a) Hyper sphere (Target Object) (b) Space Ship (Target Object)

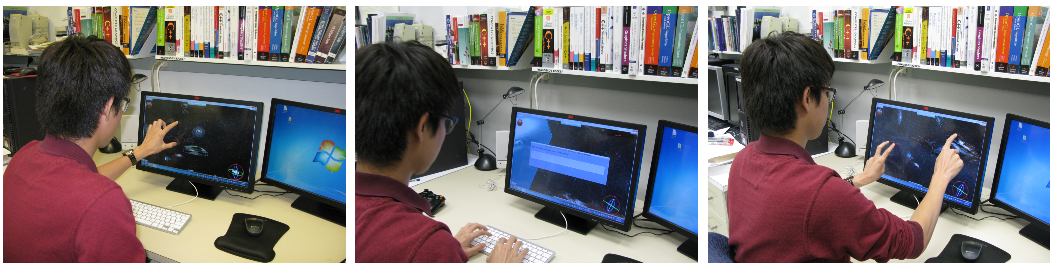
Figure 4: Target Objects

had to be typed correctly to move to the next phase. This would happen after collisions with each target. The next device treatment was the same, but the objects were swapped between them. The actual sentences for the experiment are found in Table 9.

A set of figures are provided to visualize the experiment trials. A subject is shown in Figure 5. The subject is performing different actions. In Figure 5a, a subject is performing a one-hand, two-finger rotation to perform a yaw rotation. The subject is also typing once an object has collided, shown in figure 5b. In Figure 5c, the subject is performing the Hold-and-Roll (bi-manual) gesture to acquire a target (by moving forward/back).

Sentence	Mode
Soccer is the greatest sport in the world.	Training
I have to type short sentences.	Treatment
The greatest coach of all time has traveled to France.	Treatment
I dream of a big library full of books.	Treatment
I have been told not to write in CAPS.	Treatment

Table 9: Sentences



(a) Subject: Yaw (b) Subject typing (c) Subject Hold-and-Roll

Figure 5: Subject

4. Results

The data collected consists of a combination of quantitative and qualitative data for 30 participants. The final pool of participants was reduced to 28 as a result of statistically significant outliers. The subjects were interviewed at a later time to see if the discrepancy could be understood. One of the users said they had given up after experiencing frustration with the GamePad. Another participant had a physical anomaly which made it difficult to interact with the multi-touch display.

The final subject pool was composed of 17 males and 11 females. The median age was 27, the age ranged was 19 to 42 years old. The population was primarily from the College of Engineering and Computing at Florida International University. It consisted of 15 undergraduate students (mostly juniors and seniors), 8 graduate students (Master's and PhD), and 5 professional subjects who had a Bachelor's degree or more.

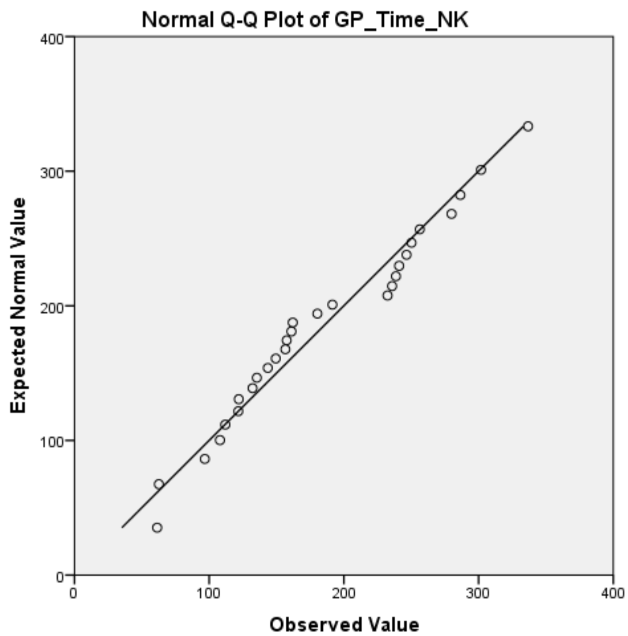


Figure 6: QQ Plot (Original Data) for GamePad

The quantitative data provided an objective understanding of the interaction of the user with each device. The most crucial measurements were the time taken in total for each device (referred to as T_d), the time taken to type sentences with the keyboard for each treatment (referred as T_k), and the difference between T_d and T_k ($T_{dnk} = T_d - T_k$). Another measurement that was taken is the number of attempts per device when typing on the keyboard, with the lowest count expected to be 5 (for a total of 5 sentences per device). When analyzing some of the objective data, a co-factor was taken into consideration. This co-factor being Experience Level, which is divided into two categories: casual gamers, which is category 1 (70% or lower), and experienced gamers, which is category 2 (above 70%). This is discussed in Section 3.12. It is important to note that this measure of expertise level refers to the person's skills in video game consoles or games that require the use of GamePad. We expected that regular GamePad users to be able to manipulate the controller better than other users. Finally, the time variables were recorded in milliseconds, however these were converted to seconds in order to make time differences more recognizable; therefore, unless otherwise stated,

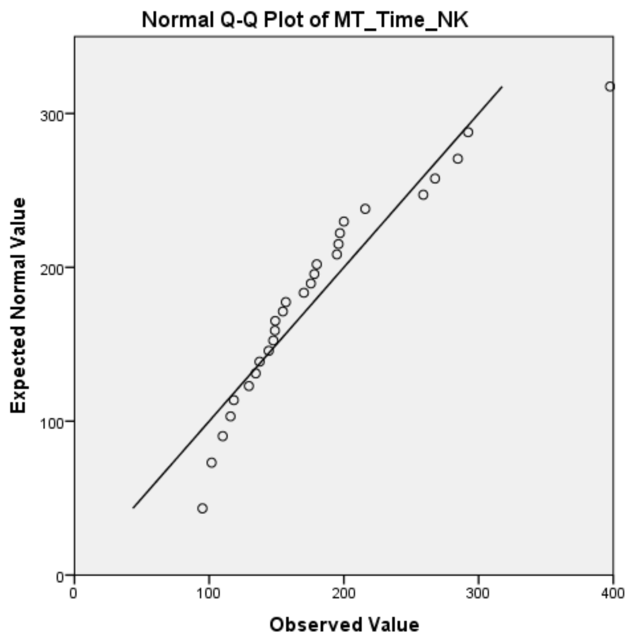


Figure 7: QQ Plot (Original Data) for Multi-Touch

	MT_TIME_S	GP_TIME_S
Mean	180.43	184.26
Std. Deviation	68.14	74.09
Skewness	1.452	0.249
Kurtosis	−0.857	−.857

Table 10: Descriptive Statistics for T_dnk

the default unit of measurement of time in this experiment are seconds.

4.1. Time: GamePad and Multi-Touch

The time considered for each treatment was from the start of the treatment to the completion of the final objective of the trial, **not including the time used for device switching**. This measurement (T_{dnk}) provides an unbiased look at the completion time for each device. Table 10 provides descriptive statistics. The variables MT_TIME_S and GP_TIME_S describe the time elapsed for the multi-touch treatment (in seconds) and GamePad, respectively. The mean for multi-touch is 180.43 seconds and for the GamePad is 184.26 seconds. This means that the multi-touch mean has a slight advantage of 4 seconds. Note that this time does not include the keyboard time. Only the time that users were active with the primary device.

After analyzing the descriptive statistics and showing that the mean for the multi-touch device (3 minutes) was smaller than the GamePad device (3 minutes, 4 seconds), further analysis was necessary to determine if the difference was significant. Based on the set-up of our experiment we have paired times for multi-touch and GamePad therefore our analysis will be based on these paired results. For this reason, before running a test to compare the difference in means we use the Shapiro-Wilk test for normality. The test shows p-value = 0.765, therefore, we can conclude that we do not have significant evidence to support the claim that the difference in time between multi-touch and GamePad is not normal. Based on these results we can proceed with a paired t-test to compare the means. The difference between the multi-touch device and the GamePad, yielded $t(27) = -.240$, $p > .05$. Based on these results we can conclude that the difference of the means was not statically significant at a 5% level of significance. Therefore, we conclude that both devices required approximately the same amount of time.

An additional t-test was performed using the game-level factor (see 3.12). In the subject pool, 12 subjects were classified as experienced gamers and 16 subjects were classified as casual gamers. We used used Levene's test of homogeneity of variances to determine whether we should consider equal, or unequal, variance for our two groups. The test yielded p-value = 0.545, therefore we can assume equal variances between our groups at a 95% confidence level. When comparing casual and experienced gamers, overall, we found no significant differences, p-value = 0.157. However, we do note that the average time difference for casual gamers is negative, meaning they spent more time with the GamePad, and the difference for experienced gamers was positive, which tells us they spent more time with the multi-touch device. From this observation we proceeded to test the time for multi-touch and GamePad independently for both groups. Once again we begin by testing for equal variances using Levene's test and conclude that there are no severe deviations from normality with p-values of 0.531 and 0.278 for multi-touch and GamePad, respectively. When considering the multi-touch device we found no significant differences between the two groups, p-value = 0.157.

There is a significant difference when we consider the time for the GamePad device, p-value = 0.002. Using the 95% confidence interval for the test we can conclude that experienced gamers spend at least 34 seconds less than casual gamers with the GamePad and at most 132 second (over 2 minutes) less than casual gamers. We explored the overall time differences between the two groups (casual and experienced gamers). We found no significant deviations from normality, p-values were 0.791 and 0.628, respectively. We then considered the time difference between the groups and found no significant differences.

4.2. Homing: Switching Devices

Participants were required to switch from either the GamePad or the multi-touch to use the keyboard. In the case of this study, the time is homing plus the time to complete a sentence successfully. This can be formulated as the sum of homing (H) and the time that it takes to successfully complete the sentence requested by the experiment using the keyboard (K), as shown in Equation 2. The data analysis used data in seconds (from milliseconds) because is a more common unit of measure.

In addition to the time S_t, the error rate for the keyboard (E_k) is also taken into account. For each device, the user was required to type five sentences correctly for each treatment. The correctness was tested for the entire sentence when the user pressed the <Enter> key. Any additional attempts after that are considered user errors. For example, a user with 6 attempts for the multi-touch would have a 0.20 error rate. This is calculated using Equation 3.

$$S_t = H_t + K_t \tag{2}$$

$$E_k = (ATTEMPTS/5) - 1 \tag{3}$$

4.2.1. Sentence Completion Time

The average time for the multi-touch display to keyboard, the completion time, was 82 seconds, and for the GamePad to keyboard, the completion time was 86 seconds. The data for the difference of time passed the normality test, p-value = 0.381. When looking at the entire population, without regard for the gaming experience factor, there was no significant difference between either device when switching to the keyboard and completing a correct sentence. The result yielded $t(27) = -1.071$, with $p > 0.05$. When looking at the separate game experience groups, there was also no significant difference, p-value = 0.904.

4.2.2. Error Rate

We define the error rate by the number of times the user hit enter with an incorrect answer, as described in Equation 3. However, the error rate is not normally distributed. For this reason, a non-parametric test, the Wilcoxon-Signed Rank Test was used to see if the assumption that users would have a more fluid interaction between two devices in the case of the the multi-touch and keyboard switch. This yielded a one-tailed significant difference.

The Wilcoxon-Signed Rank Test test allowed for analysis to determine whether there is a difference between the error rates for each device. As expected, there was a difference when users transitioned to the keyboard from each device. In particular, users had a higher error rate when using the GamePad and the keyboard (mean = 0.1857, SE = 0.335), compared to the multi-touch and the keyboard (mean = 0.0643, SE = 0.163). The Wilcoxon-Signed Rank Test results were: T=0, $p < 0.05$ (One tailed significance), r = -0.352. Users tended to make more errors when using the transition between the GamePad and keyboard. We speculate that this was because most users would place the GamePad to the left or right of the keyboard. This motion broke eye contact with the keyboard and potentially broke the users concentration. When switching from touch screen the users only had to glance down, which requires less steps.

4.3. Questionnaire

Participants were asked two questions (Q_1 and Q_2 – see Table 8), which are meant to be treated as a pair. The purpose of these questions was to get feedback from the user in regards to the experience of multi-touch versus the GamePad and vice versa, using a Likert scale rating from 1 to 10. The goal was to try to remove bias and examine whether the responses were coherent within each pair. We formulated questions such that one asks how much easier one device is over the other, interchanging the device that is described as easy. Therefore, we have to consider the correlation between the responses to determine if the negative correlation implied in the questions holds in the responses provided. For example, if the user found the multi-touch very easy to use, it was expected that they would rank the following question, which asked the opposite (easiness of GamePad), as not easy at all. Therefore, for this set of questions, the data analysis includes looking at each of them independently (e.g., mean), the bivariate correlation between them, and the ranking among both.

The (Q_2), which asked how much easier the gamepad was scored higher overall, with a mean of 7.86 (mode = 10.0, median = 8.0), versus (Q_1), which asked how much easier the multi-touch device was, with a mean of 5.46 (mode = 4.0, median = 5.00). Given the nature of the responses they are not expected to follow a normal distribution. Therefore, all correlation tests will employ non-parametric methods; Spearman's Rho (r_s) and Kendall's Tau (τ) tests were used. Both of them show a (2-tailed) significant difference, with $r_s = -0.485$, $p < 0.01$ and $\tau = -0.376$, $p < 0.05$. This relationship is as expected, if you consider the gamepad to be easier Q_2 will be scored on the higher end and Q_1 will have to be in the lower end as it references back to the comparison between the devices. This relationship is negative because as Q_1 increases, Q_2 decreases, and vice-versa. When looking at the Wilcoxon-Signed Rank non-parametric test, it shows a significance as well, where $Q_2 - Q_1$ is (2-tailed) significant with a negative ranking, with $p < 0.01$, $Z = -2.739$, and $r = -0.376$. This means that users found the GamePad controller to be easier for use than the multi-touch device for 3D navigation.

4.4. GamePad or Multi-Touch

Questions Q_{12} and Q_{13} from the exit survey, shown in Table 8 were specifically asked the users whether they preferred the GamePad controller or the multi-touch display. Question Q_{12} asked the participant to select the preferred device was, and question Q_{13} asked the subject to select the preferred device when switching to the keyboard. For both questions, the possible answers were multi-touch, GamePad, or both[6] devices.

Looking at the entire sample ($N = 28$), the preferred device (Q_{12}) was the GamePad, with 18 out of 28 votes. The preferred device when switching to keyboard was the multi-touch display, with 23 out of 28 votes.

There was a preference for the multi-touch display in the casual gamers group, with 8 users preferring the multi-touch display, and 7 preferring the GamePad.

4.5. Hold-And-Roll Questions

A subset of participants ($n = 21$), were asked to answer questions about the Hold-and-Roll gesture (some subjects did not answer). In particular,

[6]Which means that subject found them equal.

two questions can be quantified to understand the preference of the users: Q_{23} featured a scale from 1 to 10, with 10 being the highest ranking. The mean for Q_{23} was 7.70 (SD = 1.526), median of 8.0, mode of 7.0, and minimum/maximum of 5 and 10, respectively; Q_{24} asked the user if they would like to see this gesture incorporated into new games. From the 21 subjects asked, 14 of them said yes, 3 of them said no, and 4 of them said maybe. Q_{25} asked the user if they would like to see this gesture incorporated into new applications. From the 21 subjects asked, 13 of them said yes, 4 of them said no, and 4 of them said maybe.

5. Discussion

The primary aim of this research was to learn whether, when given a task (search) while navigating in 3D, would there be a significant difference between the multi-touch display and the GamePad controller. The question remains: Why was it not significant? Is the interaction of both devices comparable? We believe that there are a few factors that made a difference. The first factor is that there is a difference between experienced gamers and casual gamers. This is apparent when looking at hypothesis H_v, which proved to be true. Since the GamePad is one of the most prevalent game controllers, this may mean that experienced gamers had valuable previous exposure to the GamePad in comparison to the other subjects. As previously mentioned, experienced gamers performed significantly better with the GamePad than with the multi-touch, while casual gamers performed better with the multi-touch though not significantly so. The second factor, which may explain why H_t was not supported, is that experienced gamers may be better at navigating in 3D because of previous exposure to 3D environments. Perhaps the most significant aspect of this result is that it may be possible that a user-defined gesture set (see (Wobbrock et al. 2009)) would perform better.

Finally, our study examined some of the effects of switching of devices. In hypothesis H_y, there was a prediction that the sentence completion would take less time when using the multi-touch display. However, H_y could not be supported. Is it possible that there is no difference? 23 participants out of 28 preferred the multi-touch display (with 2 subjects having no preference). This leads us to think that further studies, with additional variables, could show a difference in time. Furthermore, this is corroborated by the error rate hypothesis H_z: the result was statistically significant, stating that users would have a higher error rate when switching from the GamePad to the keyboard. This underlines the belief that a larger sample of participants may show that the assumption made in H_y was correct after all.

5.1. Limitation of the Study

The study has limitations. The first limitation is that it worked with a subset of gestures that were highly optimized for the environment; this is true for the GamePad as well. If the same set of gestures were used in another environment, while it is possible that the behavior could be comparable, we cannot know that with certainty at this point. Second, this study used gestures selected in pre-trials by a small group of people. As suggested by (Wobbrock et al. 2009), it is best to find a gesture-set created by user agreement. Third, this study was performed with a desktop multi-touch display, fostering assumptions that are not always true with tablets or phones. Fourth, some 3D environments are plausibly more dense than the one we created. Finally, having a better understanding of user's behavior in terms of gaming (and their use of game controllers) will provide a more in-depth study. In addition, if a device is added, such as in our experiment, understanding their skill levels may also provide additional data to expand the study.

6. Conclusion

Upon reviewing the experiment, it is evident that experienced gamers can affect the comparison between GamePad and multi-touch devices. It is also notable that casual gamers (people unfamiliar with GamePads) performed significantly faster when using the multi-touch display. Furthermore, the study showed that users made a significantly higher number of errors when switching from the GamePad to the keyboard. However, the experiment did not find a significant difference when looking at the entire subject pool between multi-touch and the GamePad, even though the multi-touch average time was lower than the time for the GamePad. This was attributed to the previous use of the GamePad by experienced gamers. The following list details the primary findings of our research:

1. Casual gamers performed significantly better when they used the multi-touch display (analyzed as a group).
2. Upon comparing the groups, we found that the experienced gamers performed significantly better when using the GamePad compared to casual gamers.

3. When users switched from the GamePad to the keyboard, they performed significantly worse in typing a target sentence.
4. In the exit survey, most users reported preferring the GamePad for 3D navigation.
5. In the exit survey, most users reported preferring the multi-touch display when they were required to switch to the keyboard and type target sentences.

6.1. Recommendations

The following recommendations are based on the experiences during the experiment, and the users' comments:

- Rotation gestures must be dynamic. As the camera moves, the option for the gesture must also change.
- The mapping of gestures is important for each action. Further study is merited to find the most optimal gestures.

6.2. Future Work

A follow-up study will include a user-driven gesture set (Ortega et al. 2017) with a pseudo-universe that provides a more realistic environment (Galvan et al. 2017) and a multi-touch recognition system (Balcazar et al. 2017), which were not available at the time this study conducted (but motivated the development of them). In addition, the use of additional input devices and/or the the use of a multi-modal approach to 3D travel may provide a path for a better interactive system. Another option is to use domain-specific environments to perform similar studies. Also, Finding an appropriate general model to categorize users (gaming experience) is critical for this type of studies and similar studies in human-computer interaction. Finally, stereoscopic 3D multi-touch travel studies may show other results that will be interesting for the body of knowledge.

Acknowledgment

This work was sponsored by NSF grants I/UCRC IIP-1338922, AIR IIP-1237818, SBIR IIP-1330943, III-Large IIS-1213026, MRI CNS-1429345, MRI CNS-0821345, MRI CNS-1126619, CREST HRD-0833093, I/UCRC IIP-0829576, MRI CNS-0959985, and RAPID CNS-1507611 and U.S. DOT Grant ARI73.

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