Comparing Interface Affordances for Controlling a Push Broom in VR

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Noah Miller

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Pete Willemsen

July 2018

Acknowledgements

I wish to thank the Motion + Media Across Disciplines (MMAD) Lab at UMD, Lisa Fitzpatrick, Robert Feyen, Morris Levy, Darren Dutto, Dan Fitzpatrick, and Megan Johnson. I also wish to thank friends for the input and long hours of discussion of my work. These people are Chris Koster, Micheal Patchnik, Matthew Kraus, Alek Mintz, David Gale, and my entire 2018 graduating class of Master's students in Computer Science at UMD. In particular this work would not be possible without Lisa Fitzpatrick and Robert Feyen. Lisa Fitzpatrick made this research possible through the use of the MMAD Lab and assisted in more ways than can be counted. Robert Feyen volunteered many hours to attend meetings and provided key input towards the design and development of this work.

Dedication

I dedicate this thesis to my family for all of the incredible support and love over the years. I also dedicate this thesis to my mentor, Dr. Pete Willemsen, who believed in me, was willing to have long meeting discussing my work, and gave me opportunities I could have only dreamed of before working with him.

Abstract

This thesis explores how VR controller interfaces affect how participants hold a virtual push broom in VR. We aim to understand how the affordances provided by current VR controllers and a custom broom VR controller impact user hand grip in a visual VR broom task. We compare hand grip in two VR conditions against hand placement of a real push broom without VR. The goal is to understand the roles that interaction interfaces have on recreating physically accurate actions in VR training scenarios. The results from this study show an effect of the broom controller condition but also that the presentation order and subject demographics may have affected the way subjects held the VR and real push brooms.

Contents

List of Tables

List of Figures

1 Introduction

Commodity virtual reality (VR) systems have potential for consumers as more than game systems. Skill development and task training in VR can benefit a larger population of individuals as commodity VR becomes more accessible. VR training for professionals, such as with surgical simulators, has been shown to make VR trainees complete a task faster and make fewer errors as compared to trainees that received traditional training [7]. Many more examples from the research community also support the use of training with VR[29, 26, 8]. Recent improvements with commodity VR have produced better displays, larger tracking space, and improved controllers that match the ways humans naturally interact with virtual spaces. Our research begins to explore the quality of interactions that these commodity systems provide across different tasks and actions, focusing specifically on how current generalized interfaces may affect how a user naturally completes an action. Therefore the purpose of our study is to research commodity VR for the purpose of successful knowledge transfer between a virtual task and a real world task.

Current VR hand controllers select and manipulate objects through a variety of buttons, triggers and position tracking. These VR controllers are sufficient for entertainment purposes, but their effectiveness at simulating real world actions in a variety of skill-based training situations has yet to be studied fully. For VR training simulations, we hypothesize that the affordances created by the controller based on its design will have an impact on whether a user can perform the action as they do in a real situation. Moreover, we hypothesize that when the controllers provide affordances similar to the affordances present in the real situation, the VR experience will be more accurate.

From previous work, if an object is placed in an unusual way and the subject is mentally taxed, the subject will likely pick it up incorrectly when compared to the known affordance[5]. VR controller interfaces typically require virtual objects to be picked up using controller buttons and controller location inside or near the object. Thus, the affordance that an object has in the real world may be completely different in a virtual context with these controllers as the interaction interface. We hypothesize these problems can be mitigated by using interaction specific interfaces that attempt to better match the affordances of the real object and task.

For this study, we chose an object that exhibits a potential affordance discrepancy with typical VR controllers: a push broom. We perceived this as an identifiable object and related action that would cause a distinct difference in affordances between real and virtual conditions. Our experiment examines two different VR interfaces, the HTC Vive controllers and a tracked VR broom stick handle, and compares them with a real world push broom. The VR broom handle matches the same physical constraints and grip as the real broom while the VR controllers share very little physical characteristics and affordance with holding the real push broom.

This thesis will be presented in the following order. Chapter 2 will cover background knowledge needed to understand this work as well as some related work. Chapter 3 will contain a detailed discussion of the design choices of both the experiment and the virtual environment. Chapter 4 contains the results of our experiment and a discussion of how we interpret these results. Finally, Chapter 5 will provide a conclusion as well as a discussion of future work as this thesis aims to lay the ground work for future research in this area.

2 Background

2.1 Introduction

Virtual Reality(VR) has been around for over 50 years dating back to 1965 when Ivan Sutherland presented ”The Ultimate Display”[25]. The technology reached the point of providing high quality VR experiences to consumers with the Google Cardboard in 2014. In 2016, VR devices such as the Oculus Rift CV1 and the HTC Vive became available to the public and allowed users to physically move through the virtual environment and interact with the virtual world via tracked controllers. This technology can provide a sense of immersion that is unparalleled in all other types of current media. This medium provides the opportunity to simulate real world tasks within a Virtual Environment (VE) in a cost effective manner. A Virtual Reality Environment (VRE) is a virtual world that has the potential to be visually perceived as real as the physical world. Although the VRE may be visually realistic, the user is not able physically touch most of the environment and may only be able to interact with specific objects chosen by the designer of the world. Even when the user can interact with these objects, the object’s weight is often not simulated with current offerings. This creates interesting problems to solve when an illusion of realism must be fabricated to improve presence and immersion in a VR experience. In the field of VR research, a vast amount has been performed in areas such as perception, therapy, training, and presence[10, 1, 12, 7, 4]. This study strives to start filling a hole we observed in research of comparing holding real objects to holding an identical virtual object using generalized interaction interfaces in VR. The following sections will give an overview of current considerations to be taken with VR. These are followed by a discussion of a work related to our study.

2.1.1 What is virtual reality?

Virtual Reality aims to immerse the user into a virtual world through the accompaniment of cooperating hardware and software. Over the years, the term Virtual Reality has come to have many different semantics. One of these semantics is that VR could reference the feeling of being immersed into a book. For the purpose of this study, Virtual Reality consists of a cave automatic virtual environment (CAVE) system or a head mounted display in which the user's entire perception is immersed into a virtual environment. These two systems provide a level of presence that is needed to be able to complete tasks within encompassing virtual environments.

The CAVE implementation of VR uses multiple projections onto surfaces surrounding a user. These surfaces that can be in the shape of a dome, cube, or anything that can fully encompass a user's field of vision. Examples of this implementation of VR can be seen in many different VR studies. In an American football study training quarterbacks, the researchers created a 4 surface CAVE system consisting of one surface in front, one below, and one on each side of the user in a cube shape[8]. Another example of this, is the study looking at creating a tennis simulation[30]. For this study, the researchers only used two surfaces for projection, in front and to the right of the user. These examples show that one of the benefits of this type of system are that researchers can build a CAVE system to fit their needs. The costs of a CAVE system are the amount of space needed for set up and lack of portability. A CAVE system was not considered for this study as we intend to focus on effective motion training in commodity VR and CAVE systems are not currently being looked at for the consumer market. Even though we chose to use an HMD for our VR hardware, there has been much research using CAVE systems that relate to our study that we have taken into consideration[8, 30, 23].

Stereoscopic displays consist of using two displays that are offset by inter pupillary distance. Software then renders two separate images to provide users depth perception of a VE the same way they would in the real world. Typically these displays are mounted to the head and are referred to as Head Mounted Displays (HMD). Until recently, HMDs were incredibly expensive as well as cumbersome to use. The other issues early HMDs faced were low frame rate and low field of view causing a lot of simulation sickness[6]. Along with hardware limitations these systems were also typically physically taxing to use due to the weight of the headset as well as the mess of cords trailing from the HMD to the computer.

More recently the HMD systems have become a popular way to experience and research VR due to development kits and commercially available products. These systems are light weight, require much less cable management, are capable of high frame rates, and provide a much improved field of view. There are two different types of HMD systems at the moment. One type can be referred to as stationary VR. This type of VR typically consists of using a phone or standalone device to experience VEs while staying in place. The user is allowed to move their head in 360 degrees but translating in the real world does not cause their position in the VE to change. This is the most accessible version of VR at the moment due to price but it lacks the capabilities and quality of room scale VR.

Room scale VR is the other type of commercially available HMD system. This system requires a computer with a powerful GPU, an HMD, input devices, and a tracking system. The tracking system is used track the position of the user and input devices in a physical space and assist in translating that movement into the corresponding VE. In the past, this was accomplished through the use of motion capture systems that were extremely expensive and laborious to use. With the introduction of commercially available room scale VR systems, this is no longer necessary, making room scale VR one of the most attractive and affordable options for VR.

Tracking the movement of the HMD and any input devices provides the user with an unprecedented level of immersion. This sense of immersion is strong since the user is unable ignore or detach oneself from the experience[4]. This contrasts all other mediums because users can easily look away and detach themselves from the experience at any point. An HMD VR experience is constant and has potential to stimulate the senses of sight, sound, smell, and interaction to provide a consistent and compelling experience. Interaction for commodity HMD VR implementation comes through the use of hand controllers that are tracked and represented in the VRE. Implementation of touch interaction in VR studies have varied greatly. Some studies are using tracked objects to be manipulated in the VRE[1], while other studies use controllers[22], and yet other studies simply tracked the hand and fingers to interact with the VRE[14].

2.1.2 Norman's Affordances

Although there are a few different ways to define an affordance, our study will use Norman's definition. According to Norman, an affordance refers to "the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used."[16] This definition is important to our use of the term when referring to virtual objects. It leaves the possibility for the perceived properties of an object to be different than the actual properties.

Our perceived properties of an object are based from the previous experiences with the object or objects that have similar properties. In the real world, our perceived properties of objects that we have experienced usually have the same actual properties no matter the environment. This is not always the case in a VR. The actual properties of an object in a VR are completely dependent on the designer of the VRE. This might affect a user's perceptual properties of an object depending on the amount of experience that user has with VR. A user which has no VR experience may use their experience with the real world to generate perceptual properties for an object in a VE. On the other hand, a user that is experienced in VR may base their perceptual properties based on past experiences within a VRE instead of their experiences in the real world. For example, one perceived and actual property of a mug in the real world is that it can be picked up by its handle. Now a virtual mug in a typical VR application may have the perceived property of using a hand to picking it up by the handle but an actual property of inserting the interaction device into the virtual object and pressing a button to pick it up. An experienced user of VR may already have the perceived property of picking up the mug this way but an inexperienced user may have no idea that the mug has any affordance without instruction.

Even for real world objects that users are experienced with, the perceived properties can also be only partially correct with the actual affordance of an object based on properties of the environment. This is clearly shown in a series of physics experiment performed by Stappers[20]. While teaching a Newtonian physics class, Stappers asked his class what the trajectory of a rocket would look like if it was initially moving in a horizontal direction followed by 2 seconds of force applied in the vertical direction. Stappers realized that most students got this question wrong and decided to develop an experiment in which subjects would drop a ball[20]. The goal of the experiment was to walk in a straight line at a constant pace and drop a ball into a hole. The correct time to drop the ball was just before the subject walked by the hole but many of his subjects dropped the ball either directly over top or after they passed the hole. Although, his students had correct perceptual properties of the ball to pick it up and drop it, they did not know the actual properties of the ball with respect to gravity. Even though it can be argued that Newtonian physics is not intuitive, this shows that the user's perceptual properties of the ball where in conflict with its actual properties with respect to its environment. Therefore it is important that the user understands the actual properties of an object and its environment before they are tested on aspects such as performance of a task. This has been shown in many studies[17, 9], including the study that is most related to ours in which the subjects had to demonstrate that they could hit a dart board consistently before data was collected. In other words, the subjects had to demonstrate that their perceived properties of the darts were close enough to the actual properties that they could hit the dart board consistently in each condition. Once that baseline was established, the researchers recorded the data for the next three throws for their analysis[9].

Even when the perceived and actual properties of an object match for an affordance, if an object is presented in an obscure manor or the subject is mentally taxed the way an object is grabbed to be used can still be incorrect. A study performed by Creem et al. looked at the grasping an object while performing other tasks[5]. The subject's initial interaction with an object was used to grade performance. There were 10 objects in this study, all containing handles such as a fork, comb, and a hammer and these objects were presented to the subjects with the handle pointing towards them, away from them, and in a neutral position. The results showed that orientation of the object had a significant effect and that the percentage of correct grabs decreased from handles facing towards the subject, to handles in a neutral position, and finally the handles facing away from the subject. Also, the mean for correctly grabbing the object across all orientations was 72% of the time. When subjects were asked to perform a task that requires retrieving information from memory while trying to grab an object, the subject only grabbed these same objects correctly 17% of the time.[5]. This relates to our study as we are going to have subjects grab objects to perform tasks. This study shows that it is important for the object to be grabbed to be placed in a favorable orientation to the user and that distractions can cause a decrease in performance across conditions.

2.1.3 Training

There has been quite a lot of research performed in the field of VR training across many different areas of practice. The medical industry has been looking to this type of training for years since training medical procedures, especially surgeons, is inefficient, expensive, and has potential to cause disease, due to the common use of cadavers for this type of training[26]. Meta-analyses of surgical training in general[7], and for the specific use of VR training in orthopedic procedures have been performed. Both meta-analyses show that, VR training for the surgical field improves speed and reduces errors for the procedures performed when transferred to a real world scenario[7, 26]. The training application even provides a way to assess the skills of a surgeon. It has been shown that surgeons with more experience complete the training faster and with less error[7, 26]. Even though the results of these studies tend to be positive towards the use of VR for training of surgical procedures, there is still more research to be done to decide a definitive role that VR training plays in surgical training.

One of the benefits VR applications can provide are the ability to create situations that closely resemble real life. One such example of this is the training of quarterbacks through a VR application called SIDEKIQ[8]. This application was designed for the purpose of training quarterbacks to correctly choose a passing route within a few seconds of a snap. This application works by immersing the user onto a virtual football field in which a play occurs and the user could witnesses the play through first person, over the shoulder third person, or a top down perspective. In this scenario, the user will take a virtual snap of the ball and within 3 seconds must decide the correct place to throw the ball. Once the user answers, a voice over will tell the user what the correct decision is and why it is better than the other decisions. This gives the user experience in making split second decisions when on the field without the need of other players. It also provides the coaches with a new way to observe errors in a quarterback's decision making by showing exactly where the quarterback looks after taking the snap. This provides more immediate feedback to the quarterback because a coach's ability to correct the quarterback's gaze is much easier than before.

There are many more sports training VR research, of which many can be found in the 2012 review of virtual environments for training in ball sports[13]. This review shows a plethora of different sports from tennis[30], rugby[3], handball[27], and table tennis[11]. All of the papers reviewed did not contain an HMD or CAVE system for their chosen technology but the HMD and CAVE experiments did show some of the best results. Across the 25 studies some of the training benefited from VEs while others did not. The authors state that even though all studies did not produce positive results, the ones that did show promise for future training in ball sports and that they believe that the issues discussed in their paper will be mitigated over time.[13]

2.1.4 Visual Bias

VR gives us a novel way to learn about human perception and how we can use that knowledge to manipulate perception with software. This means that we have a way to manipulate how a user perceives their actions compared to what they are actually doing. Therefore a method can be developed to map this difference in action and we can use that to our advantage when creating models for performing actions. A technique called haptic retargeting is a good example of this. In a study performed by Azmandian et al., subjects used an HMD to see a VE and were tasked with picking up cubes. The VE contained a surface with three colored cubed and the participants were able to see their arm and hands move in the environment. The subjects were asked to pick up a specific cube in the real world on a table in front of them and then place it back down after. The subjects picked up the three different virtual cubes before the session ended. When the subjects took the HMD off, they saw only a single cube on the table. What happened here is that the researchers created an environment which would translate slightly when the subject was reaching for the virtual cube in order for the virtual cube to line up with the physical cube by the time their hand reached the virtual cube in the VE. This happened so subtly that almost all of the participants thought that there were three physical cubes on the desk during the session.[1].

Redirected walking in a virtual environment with an HMD is another area of successful VR research that uses knowledge of visual bias[24]. Redirected walking is a technique in which the user's visual perception is shifted in small increments over time to give the user the illusion of walking in a straight line when in reality they are making loops in their physical environment[24]. This creates a false sense of space for the user as they believe they are in an environment much bigger than they physically are. This also further enhances immersion as the user feels that they can walk anywhere within that virtual world without running into anything physical objects.

2.1.5 Providing Subjects a Comfortable VR Experience

When designing a VRE for the purpose of successful knowledge transfer between the virtual task and the real world task, creating a quality experience that subjects are comfortable in is key. It is a known problem that using VR in some cases can create discomfort and sometimes nausea also known as simulation sickness[6, 21]. If simulation sickness was to occur, it would affect the performance of the subject and their experience of the VRE.

Scene movement is one factor in VR that can cause simulation sickness[19]. Locomotion is one of the main methods of scene movement for room scale VR, therefore it is vital to choose the correct type of locomotion for a given study. Locomotion is defined as the movement or the ability to move from one place to another. Different methods have been researched to determine which method of locomotion is accurate and reduces the risk of simulation sickness[18]. In one study, participants were put in a VE and told to traverse it using the method of locomotion assigned to them[18]. In this study performed by Ruddle et al., 2 different experiments were performed, one where the participants traveled 24 meter course and another where participants traversed a 270 meter course. The first study contained three different modes of traversal. The interaction and display pairs were a joystick and monitor, a controller and an HMD, and physically walking with an HMD. The second study consisted of traversing a 270 meter course. This study contained five different modes of traversal. The interaction and display pairs were a joystick and a monitor, view traversal using an HMD, a linear treadmill with a controller and an HMD, and an omni-directional treadmill with an HMD. The results of this experiment showed that physical walking with the HMD and the omni-directional treadmill with the HMD both vastly outperformed all other methods of traversal in terms of speed, accuracy, presence, and simulation sickness. Physically walking through a VRE is the best method for realistic representation of performing a task in VR[18].

There are other factors to be considered when reducing simulation sickness and creating a realistic VRE. One for example is considering the VE design in which to run experiments. In studies that had the user ”blind walk” to a destination, the user would always travel a shorter distance than the actual distance[22]. This study also compared performing this task in a replica VE of the physical environment and in a new environment that the user had not seen before. The results showed that although the distance traveled was still compressed in the both VREs, that the distance traveled was more accurate in the replica lab VRE. More work by Steinicke has shown successful results with performing experiments in a replica VRE of the lab environment. This practice was shown to increase self-presence and reduced simulation sickness. The study in particular that achieved this feat was another study of his on depth perception in VR[21].

2.2 Related Work

The study that most closely relates to ours looks at throwing darts for the purpose of occupational therapy. This study performed by Kehoe and Rice at the University of Toledo was interested in the quality of movement obtained from throwing darts[9]. Similar to our study, they look at two different ways of throwing a dart compared to the normal condition of throwing darts.

The conditions this study looked at were throwing darts normally, Kinect dart throwing, and imaginary dart throwing. The normal condition used a regulation dart thrown at a dart board at the regulation length away, according to the rules followed by professional dart players. The Kinect dart throwing was performed using a Microsoft Xbox 360 and a Kinect sensor. The software used for Kinect dart throwing was a game called Kinect Sports: Season Two which contained a dart game as one of the sports on the disc. The imaginary dart throwing was performed by having subjects stand in front of a dart board at the regulation length away and then have the subject imagine they were throwing the physical dart at the dart board. To measure the quality of movement the researchers used eight motion capture cameras to observe 11 motion capture markers placed on the body and dominant arm of the subject. Of these eleven markers, the only marker that was analyzed was the index finger of the dominant hand that was used to throw the darts. The only exception to this was that the data from the thumb was used to calculate max distance between the index finger and thumb during the throw, and was called the max aperture. The data that was analyzed using only the index finger marker data was the average displacement, peak velocity, movement time, percentage of movement time to peak velocity, and movement units of the throws[9].

The results of this study showed that the quality of movement between the real throwing and imaginary throwing were similar but contained statistically significant differences with peak velocity, max aperture, and percentage of movement time to peak velocity. The researchers discussed that these differences may have occurred because the subject had to overcome the weight of throwing a dart and received feedback from their throws when the darts hit the board. This being said, the similarities that they saw between the conditions was due to the imaginary throwing being based on past experience of throwing real darts. The results of the real throwing and Kinect throwing showed statistically significant differences for average displacement, movement time, and max aperture. For all of these attributes, the Kinect condition scored lower values. The researchers hypothesize that this may be caused by the motivation of the Kinect throwing to succeed in the game. This notion of achieving success in the game could have affected the subjects focus on trying to throw the dart as they would in the real condition.

While this study shows important data for occupational therapy, it could be argued that the use of a commercial game for Kinect throwing may have confounded entertainment for therapy training when looking at a virtual condition. The commercial game was made for the Kinect sensor to be a form of entertainment and showcase the Kinect's capabilities. There were no claims to say that the Kinect game elicits the correct quality of motion when playing a game of darts. This accompanied with the game containing reward signals for the subjects and a reticle to show a rough estimate for where the dart with land makes it a questionable choice for a virtual condition. The researchers' discussed in their paper that the results of their study may have been affected by this choice. With that in mind, the researchers state that the results of their study suggest that when developing a skill the real throwing is the preferred method[9]. For the Kinect condition, the researchers say that depending on the purposes of the client, the virtual condition may meet all the desired needs for the patient. They said if the goals are to increase range of motion of the upper extremity, increase muscle strength, endurance, or cannot physically play real darts that the Kinect darts throwing may be the correct method to use.

Although this study was performed with different equipment and the results may have been skewed by the gamification of the Kinect condition, there were a lot of good practices performed in the study that will be incorporated in our study. The first being that the participants had to show that they could hit the dart board multiple times in a row before data was recorded for the analysis of the motion[9]. This type of training is necessary to make sure the subject understands the task and is able to complete it before starting data collection. Second, the type of data that they observed when throwing was important and interesting parts of motion to observe. This relates to looking at the biomechanics of our physical task when compared to the virtual task. This study makes it clear that more research needs to be done to understand how performing a task with different interfaces affects actions. For virtual conditions, this study shows that the task should be as similar as possible within the confines of the interface. It also shows that having different feedback between conditions may cause a change in behavior for the subjects. We take this into consideration for the design of our study which is discussed in the next section.

3 Implementation

3.1 Introduction

The main contribution of this thesis is designing and performing a human subject experiment to compare how subjects perform tasks in the real world and a virtual environment. The purpose of this research is to work towards understanding the requirements for effective training with commodity level interfaces in virtual reality. There has been no research that we have found looking at this specific topic. Therefore this section will discuss the thought process that went into the design of an initial study for this area of research.

This section begins with a description of technology that was used in this experiment followed by the design. This is followed up by a detailed description of the experiment procedure and how we decided to collect the data. We will then discuss the design decisions of the virtual environment and the interaction mechanisms for the study. Finally, we will discuss the pros and cons of this approach as well as what we learned from performing this study.

3.2 Technologies Used in our Experiments

- Unity Game Engine was used because it is a free and versatile game engine which allows designers to rapidly prototype ideas and experiments.
- All programming was written in C# as it is the native object oriented language used

with the Unity Game Engine.

- 3ds Max was used to create the virtual environment in which the subjects performed the virtual task.

- A Vicon motion capture system (with 12 Vicon T40-S cameras) recorded the position and orientation data of the subjects' hands, the real broom, and the broom handle. This system was also used with VRPN to receive the position and orientation of the virtual broom in the virtual broom handle condition with the software Vicon Tracker.

- The HTC Vive was our chosen HMD for the experiment. We had the option to use the Oculus CV1 but chose the HTC Vive for several reasons. First the HTC Vive has a much bigger tracking space, which is preferred so the subjects have adequate space to maneuver. The HTC Vive's controllers contain more similar attributes to the grip of a broom handle than the Oculus Rift CV1 controllers. These two reasons alone made us prefer the HTC Vive system for this study. We are aware of the issues presented by [15] but we found this paper after we started testing. None of the subjects noted any of these issues while performing the study, therefore we believe that our study was unaffected by these findings.

- IBM SPSS was the statistics software package used to analyze our data and generate some of our tables and plots.

3.3 Study: Differences in Hand Grip Afforded by Different Interfaces for a Push Broom

The goal of this experiment is to compare the hand grip afforded by different interfaces for a push broom. We are particularly interested in looking at the way subjects hold the same

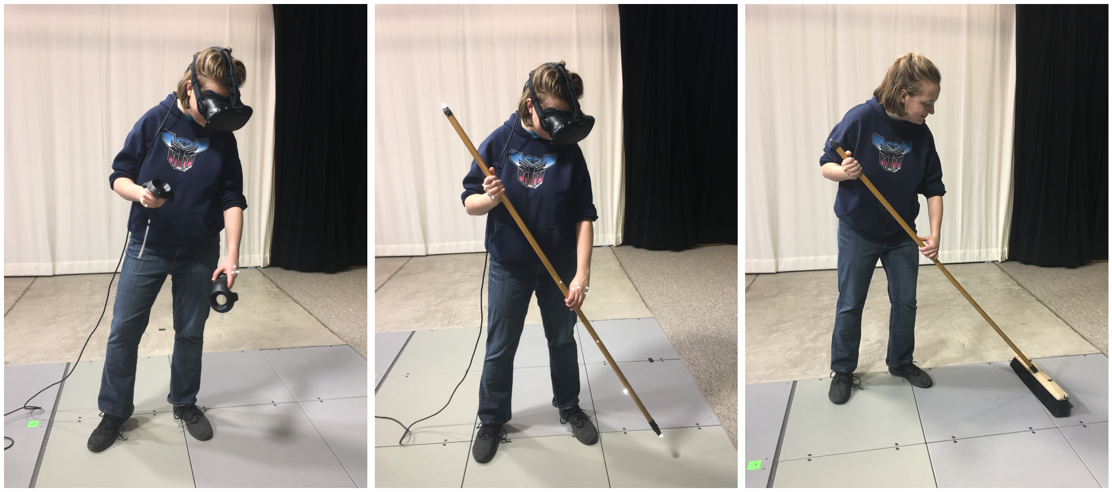

Figure 3.1: Broom interfaces from left to right the conditions are the VR Controller, VR Broom, and Normal condition.

object in a real environment when compared to a virtual environment using different interfaces. This study looks at three different interfaces for holding a push broom. The condition that acts as the control is holding a push broom in the lab setting without any VR equipment or modifications to the broom. This condition allows us to see how a subject would normally prefer to grip a broom. We hypothesized that due to different perceived properties and physical attributes that each subjects would have their own version of a preferred grip for push broom sweeping. The two other conditions for which we observe different generalized interfaces for interaction with are with a virtual broom. Commodity VR controllers is one of these interfaces. This condition looks at how consumer products that are designed to fit any action will compare when the subjects hold a virtual broom. This condition aims to look at the differences of preferred grips for a push broom when an interface lacks almost all physical attributes of the original object. This will give us an idea of how visual bias plays a role when designing training interaction in VR. The other VR condition is a tracked broom handle. This is simply the handle of the normal broom condition tracked to appear in the virtual environment. This interface aims to look at using an object that contains some physical attributes of the original object in a virtual environment. The goal of looking at

Figure 3.2: Example asymmetrical configuration of five 4mm markers on the hands. Used to create rigid bodies in Vicon Tracker for position and orientation tracking.

this condition is to look at the use of a generalized interface for effective training in VR. In this study, we use the exact same handle as the real broom but it can be thought of as generalized tracked pole for the use of any implement that adheres to some of the pole's physical attributes. Each of the three broom conditions can be observed in Figure 3.1.

To record attributes of hand grip across conditions, five $4mm$ half sphere motion capture markers were be placed on the back of the hands of each subject. An example marker configuration can been seen in Figure 3.2. The main comparison metric for hand grip was measured by distance between the hands when holding the broom in a ready to sweep position. In the normal and VR broom handle conditions, we use position data of the hands. For the VR controllers condition, we used the motion capture data as well as similar data recorded in Unity.

We hypothesized that there would be a difference in hand grip between the normal condition and the VR conditions. Specifically, the difference between the normal and broom handle condition will be slightly different due to the shift in center of mass of the broom handle due to the removal of the broom head. For the VR controller condition, we hypothesized that the normal and controller conditions would be quite different in terms of position on the broom and orientation of the hands. Comparing these different interfaces will give us a better understanding of how subjects use a common tool in VR given different interfaces. This will give us a better understanding of the requirements for developing a model for effective training of push broom in VR.

3.3.1 The Virtual Experience

This section discusses the design choices of the virtual environment and the virtual reality interaction mechanisms used in the study.

The Virtual Environment

The virtual environment was designed to ease transition in and out of the virtual experience. The virtual environment we used was replica model of the lab space used to run the experiments. This environment was designed to scale and contained general features of the lab but lacked furniture and extra physical items that are in the lab space. A picture of the MMAD lab and its virtual counterpart can be seen in the images of Figure 3.3. We used this environment due to distance estimation, immersion, and simulation sickness findings for performing experiments in a replica VE to the lab space that is shown in research performed by Steinicke et al[22]. This environment was developed by a previous student working in the MMAD lab, Wesley Darton, and we believe that this environment helped provide the most realistic results possible for the experiment.

Design of the Virtual Interaction Mechanisms

The goal of the design of the virtual interaction mechanisms were to provide a frustration free and nonrestrictive experience when using the virtual brooms. The virtual broom in the VR broom condition simply used the position and orientation data provided by Vi-

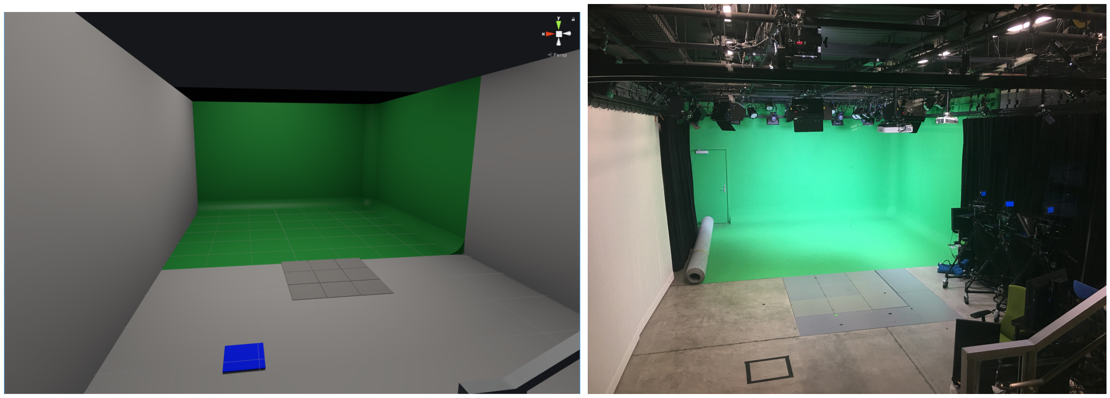

Figure 3.3: Left: Virtual Environment for all VR trials. Right: Lab space where experiments were performed.

con Tracker for its interaction. No other manipulations were involved with this condition. The VR controllers condition on the other hand had to be designed from scratch. For this interaction, first there will be a discussion of how the broom was attached to the controllers and its behavior once attached. Then there will be a discussion of how users changed the position of their hands on the broom model.

In the virtual controllers condition, the virtual controllers were represented in the VE as red spheres. These objects were parented to the invisible controller models and placed in an approximately the middle of where the hands would grip the controllers. The spheres were shown instead of the virtual models of the controllers to keep a consistent representation of the position for hands across both VR conditions.

We wanted to have each of the conditions to be similar as possible, therefore we wanted the subjects to pick up the broom each time in the virtual controllers condition. To pick up the broom the subjects had to walk over to the broom and place both red spheres into the virtual broom, causing the broom to attach to the controllers. It was empirically determined that this was the best method to pick up an object to reduce potential confusion. The typical VR commercial game solution to picking up objects is prompting a user insert their virtual controller into the virtual object to be picked up and the squeeze the specified interaction

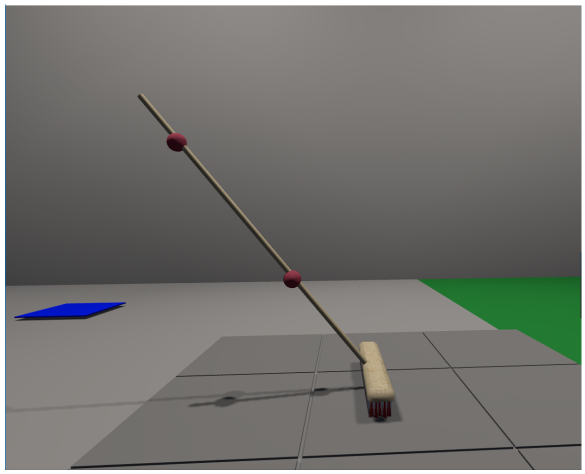

Figure 3.4: VR Broom in the virtual environment. Red spheres represent hand positions.

button. When these actions are preformed the object attaches to the controller object while the button is depressed and detaches when the button is released. This interaction mechanism is not a natural way to pick up objects in the real world so we decided to use our method instead.

Once attached, the virtual broom is controlled in the following manor. The control hand (back hand) on the broom controls the position of the broom and the guide hand (front hand) controls the orientation of the broom. The broom handle is oriented on a vector between the guide (front) and control (back) controllers at all times. This can be seen in Figure 3.4. The control hand can manipulate the virtual broom's position. The broom stays attached to the back controller and moves the virtual broom with respect the vector going through the controllers. The guide hand only controls orientation of the broom. Therefore when moving the guide hand and keeping the control hand still, the virtual broom stays in place, only changing in orientation when the guide hand changes the direction of the vector.

This implementation of the broom was chosen for two reasons. One, is that through empirical testing between several researchers, it was decided that it was the most comfortable and intuitive way to use the broom. The other reason is that since this study is focused on how a subject holds a broom, the feeling of using a broom to sweep is not as important as it is to provide a less confusing mechanism to move the hands on the broom. Some other configurations were tested in which the front hand controlled 25% or 50% and the back hand controlled 75% and 50% respectively of the position of the broom. It was determined that 100% control from the back hand and 0% control on the front hand was the best method for this study.

The decision to keep the broom in the hands of the user at all times was chosen to allow the subjects complete freedom in how they oriented the controllers on the virtual broom. Another option would have been to force the subjects to orient the controllers so they would line up with the vector of the virtual broom handle. In this solution, the broom would detach from the controllers when the subject exceeded a certain threshold of orientation away from the broom handle. This would cause confusion and restrict the user on how they felt it was natural to hold the broom using the controllers.

For future studies we believe this implementation could be viable. For our purposes though, keeping the broom attached at all time was preferred. The only confusion or complaint that could have been affected by this decision was that after the subjects had completed one trial of holding the broom with the virtual controllers, the subject would return to the starting square with the virtual broom still attached. This confused some subjects as this phenomenon did not happen in other conditions and making this interaction uncomfortable. Once the next trial started the broom would teleport from the controllers back to the position in the middle of the room. We do not think this affected our data but it is worth considering in future studies.

Another design decision for this study was how a subject would change the position of their hands on the virtual broom. To perform this interaction, the subject would click the trigger on the back controller and hold it, then the subject would move their hand up or down the broom handle to change hand position. This mechanism worked since the back hand was locked into position and the front hand is free to move without changing the position of the broom. Therefore the moving the back hand changes how the virtual broom behaves. To find the correct grip the subjects would move the back hand on the virtual broom and then readjust the front hand until it was in their preferred position. The only drawback to this approach is that the front hand being free also allows the front hand to move on the broom without the subject feeling that they need to readjust their grip. If the guide hand moves forward along the broom handle vector while trying to hold the ready position, there will be no change in the broom therefore reducing the chance the subject notices a difference. If this difference is not noted the subject will keep their hand at the new position instead of readjusting back to their original desired grip.

The final thing to be discussed in this section is the interaction of the broom with the floor. Since a goal of this study was to observe the natural way of holding a broom, the decision was made to allow the broom to go through the floor in the virtual environment. If the broom was not allowed to go through the floor we would have two different options. One option is that the broom detaches from both controllers when it goes through the floor and has to be picked up again. This first option seems problematic because we wanted the subject to be focusing on how they preferred to hold a broom and not focusing on not going through the floor. This also could have caused frustration with the task therefore affecting data. The second option would be the broom stays above the floor but one or both hands detach from the vector of the broom handle but do not relinquish control. This keeps the broom above the floor even though at least one of the controllers are no longer located on the broom handle. This second implementation is also problematic since the hands disconnect from the broom but the subject is still in control of it. This could result in one or more hands not being visually connected to the broom at all but the users visual representation of the broom is what they prefer so they say to record the position anyway. Therefore even though allowing the broom to go through the floor may affect the immersion of the experience, we think that the benefits outweigh the costs for the purposes of this study.

Calibration Vicon and HTC Vive

One critical issue that we had to fix for our study's virtual environment to stay immersive for the VR broom handle condition was collocating the origins for Vicon Tracker and HTC Vive tracking space. First, we had to swap the Y and Z values for position and orientation as well as negate the W value for orientation to perform the coordinate transformation from Vicon Tracker to Unity. Once that was applied, the origins of both systems had to be aligned. To do this we placed six 14mm markers on the HTC Vive controller and created a rigid body within Vicon Tracker to represent the controller. Then we assigned a blue puck in Unity to the rigid body object of the controller in Vicon Tracker and got its position and orientation using the VRPN. Once both systems were running, both the Vicon object and the HTC Vive controller object had their orientations aligned. Then we took the difference of both systems in six different directions and corrected the difference. We repeated this process once more to receive an even more precise collocation of the origins of the systems. Once both systems were aligned correctly, the virtual broom and virtual hand spheres both showed up in the virtual environment where they were located in the real world.

3.3.2 Experiment Design

We chose a within-subjects experimental design in which each subject experienced all three broom interface conditions. Due to potential order effects related to when subjects experienced each condition, we counter-balanced the presentation order of the three conditions into six (6) groups. With 30 subjects, this resulted in exactly five (5) subjects in each presentation order grouping.

3.3.3 Experiment Protocol

The experiment protocol began with obtaining consent from each subject and then the subject filled out a pre-experiment questionnaire. Each subject was randomly assigned a presentation order. Presentation order determined when subjects were trained for VR so that training only occurred before it was needed in presentation order. Before any VR conditions, subjects were allowed to acclimate to the VR space by walking a path through the space. Before the virtual broom condition with the VR Controllers, subjects were trained on how to grab and change their hand position with a virtual object that was different than the virtual broom. In all conditions, subjects began on a starting position on the floor that was represented in both virtual and real environments. Next, subjects walked over to the broom and picked it up. Once holding the broom, subjects adjusted their hand positions on the current broom until they felt hands were placed correctly for them to perform a sweeping action. Once achieved, the subject verbally notified the researcher that the broom felt and looked correct in their hands. Then the subjects held the broom in a ready to sweep position and the researcher recorded the distance between the subject's hands using the motion capture system. After the data was collected, the subject returned back to the starting position. Each condition was performed three times. Finally, the subject filled out a post-experiment questionnaire consisting of task and presence related questions. This procedure was exactly the same for all subjects with the only difference being the order in which the conditions were presented.

The following sections will contain a discussion of all of the different aspects of the experiment procedure in the general order that they appeared in the study.

Pre-Experiment Questionnaire

This pre-experiment questionnaire was used to obtain demographic information as well as how much experience each subject had with VR or video games in general. A copy of the pre-experiment questionnaire is located in Appendix A.

Acclimation

The first task that subjects performed when they were presented their first VR condition was designed to acclimate the subject with the virtual environment. The subjects were instructed to stand in a black taped square on the floor and were then given the HMD. Once in the virtual environment, the subject could look down and see the taped square in the lab was now a blue square on the floor of the virtual environment. We refer to this square as the starting position for each iteration. The subjects would then start in the starting position, and see three green cubes located on the floor of the virtual environment. These green cubes were designed to turn red when a subject walked over them. The subjects were instructed to walk to all green cubes in any order they preferred and once all three cubes had turned red, return back to the starting position. In the experiment, we turned the proximity wall included with SteamVR off so we wouldn't break immersion when the subjects were near the edge of the tracking space. Instead, in order to give subjects an idea of the area in which they could move comfortably in the environment, we placed the three green cubes at different corners of the tracking space. This allowed the subjects to know they could safely walk within that entire area. This acclimation step was performed so the users would feel comfortable moving in the virtual environment before any data collection was performed.

Training

The only condition that required training was the VR controller condition. Therefore to not affect other conditions, training for the VR controller condition was performed directly before actually testing this interface. This training consisted of the subjects interacting with a rectangular cuboid, shown in Figure 3.5, in the same way that they interact with the virtual broom. The training starts by the subject being instructed to place both red spheres, located where their hands are gripping the VR controllers, into the rectangular cuboid. The rectangular cuboid then attaches to the controllers and acts in the same way that the virtual broom was described above. Then the subject received a verbal explanation of how their control and guide hands manipulated the virtual object. The subject then interacts with the object to understand how it moves. Once they are comfortable controlling the object, they are told that they can change their grip on the pole using the triggers on the controllers. If the trigger is held with the control hand, the control hand will slide up and down the object as the object stays in place. Once they understood this, the subjects were asked to place the control hand in the blue cube on the rectangular cuboid and the guide hand in the green cube on the pole. When completed, the subjects were asked to return to the starting position. As we think this interaction may not be intuitive, this procedure was repeated using a different colored rectangular cuboid and cubes placed on the object in different spots. Once the subjects verbally confirmed that they felt comfortable with the interaction mechanism, the VR controller condition test was performed.

Testing the Conditions

This study was performed with a between subject design on ordering. Since there were multiple presentation orders, we decide to discuss the conditions in the following order: VR controllers, VR broom handle, and normal condition.

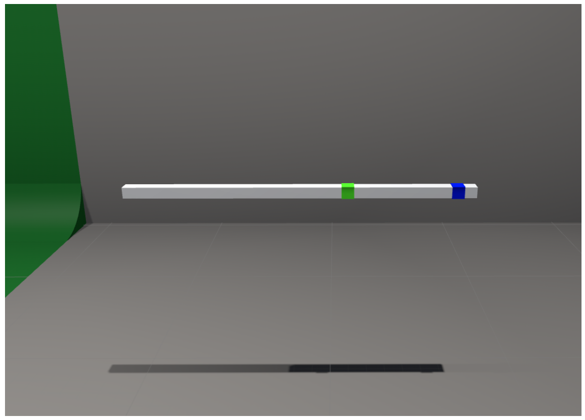

Figure 3.5: Rectangular cuboid used for training subjects to change hand grip on the virtual broom in the VR controllers condition. The blue cube represents the desired spot for the control hand and the green cube is the desired placement for the guide hand.

The VR controllers condition was performed in a similar way that subjects were trained with the rectangular cuboid. The subject walks over to the broom and places both red spheres in the virtual broom handle to attach to the controllers. Once attached, the subject was asked to find a position for his hands on the push broom that felt natural. Once the subject expresses that they feel that their hands on the broom are in the preferred positions, they were asked to put the broom on the virtual floor in a ready to sweep position. Then while the subjects held the position, the data was recorded in Unity and Vicon Tracker. The subject was then asked to return to the starting position and then this process was repeated two more times.

The VR broom handle condition was performed in a similar way with some minor differences. The first difference is that in this condition, the position of the hands in the virtual space was based off of the markers on the back of the subject's hands instead of the controllers. The subjects performed the same procedure of walking for the starting position to the virtual broom but this time they grabbed the broom handle based off where they saw the virtual broom in the virtual environment. The broom handle was held by a researcher in a way that the subject could grab the broom without hitting any other objects or touching the researcher. The subject was again asked to find natural hand positions on the broom and place the virtual broom head on the virtual floor in a ready to sweep position. Once they held this position, the subject verbally notified the researcher and the data for that trial was collected. The subject then handed the researcher the broom handle, returned to the starting square, and then repeated the process two more times.

The normal condition had the same procedure just without an HMD and one other minor difference. The only difference for this condition is that the broom was placed on a small table so the subjects could grab the broom in a similar way they did on the other conditions. The rest of the procedure was the same and was repeated two more times

4 Results

4.1 Introduction

This chapter contains all of the analysis of the data obtained in our experiment. Table 4.1 summarizes the means and standard deviations across all subjects and conditions while also providing the data from each group ordering. This section starts with the statistical results of running two-way mixed ANOVAs where the within subjects factor are the push broom interfaces and the between subjects factor is chosen from one of our independent variables. This is followed up by the results of a one-way ANOVA using only the first condition seen by the subjects for data. Finally, there will be a discussion of these results and how we interpret them.

Table 4.1: Means and Standard Deviations of distance between hands for all conditions and groups. Distances are in mm. for presentation order, *C* is VR Controllers, *H* is VR broom Handle controller, and *R* is the Real push broom.

Distances Between Hands in All Conditions							
Presentation Order		VR Controller		VR Broom		Real Broom	
No.	Acronym	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	CHR	557.4	151.9	670.4	81.5	673.2	46.0
2	CRH	542.0	78.4	582.3	77.5	647.9	92.1
3	HCR	445.9	73.4	420.4	78.7	559.2	96.5
4	HRC	432.9	89.1	429.4	82.0	465.6	77.0
5	RCH	578.1	123.8	649.3	111.6	635.8	78.6
6	RHC	562.5	135.8	632.3	156.6	603.7	137.8
All Orders		519.8	124.1	564.0	142.6	597.6	113.4

4.2 Analysis

Results for running a two-way mixed ANOVA using conditions as the within subjects factor and presentation order being the between subjects factor. There were 4 outliers, assessed by box plots. When the data was assessed with the Shapiro-Wilk test, the data was normally distributed on all conditions and orderings except the VRBroom with order 2 and the Normal condition with order 1. There was homogeneity of variances ($p > .05$) and covariances ($p > .05$), as assessed by Levene's test of homogeneity of variances and Box's M test, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $X^2(2) = 2.979, p = .225$.

There was no statistically significant interaction between the condition and presentation order on hand distance, $F(10, 48) = 1.8884$, $p = 0.071$, partial $\eta^2 = .282$. The main effect of condition showed a statistically significant difference in mean hand distance with the different conditions, $F(2, 48) = 13.015$, $p < .0005$, partial $\eta^2 = .352$. The main effect of presentation order showed that there was a statistically significant difference in mean hand distance between presentation orderings $F(5, 24) = 4.112$, $p = .008$, partial $\eta^2 = .461$.

Due to the outliers observed, we also decided to remove two subjects to eliminate outliers and run the two-way mixed ANOVA with the same between and within subject factors. The two outliers that were removed was the outlier in the order one VR controller condition that contained the lowest hand distance and the only outlier in order 4 which was from the Normal Condition. This resulted in no outliers, as assessed by boxplot. The data was not normally distributed for two cases, as assessed by the violation of the Shapiro-Wilk's test for VR Controller condition with presentation order 4 ($p = .018$) and for the VR Broom condition with presentation order 2 ($p = .044$). The data was normally distributed for all other condition and presentation order pairings, as assessed by Shapiro-Wilk's test of normality ($p > .05$). Since a two-way mixed ANOVA is robust against the data not being

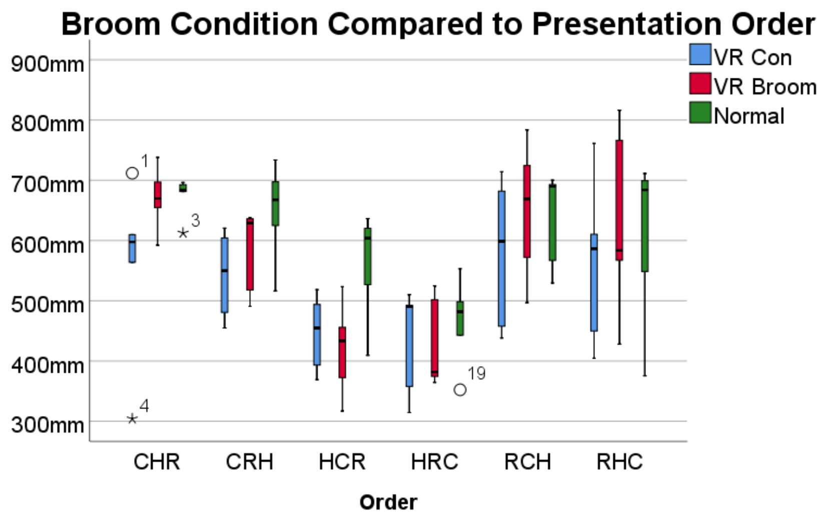

Figure 4.1: Conditions vs Presentation Ordering Box Plot Showing Outliers

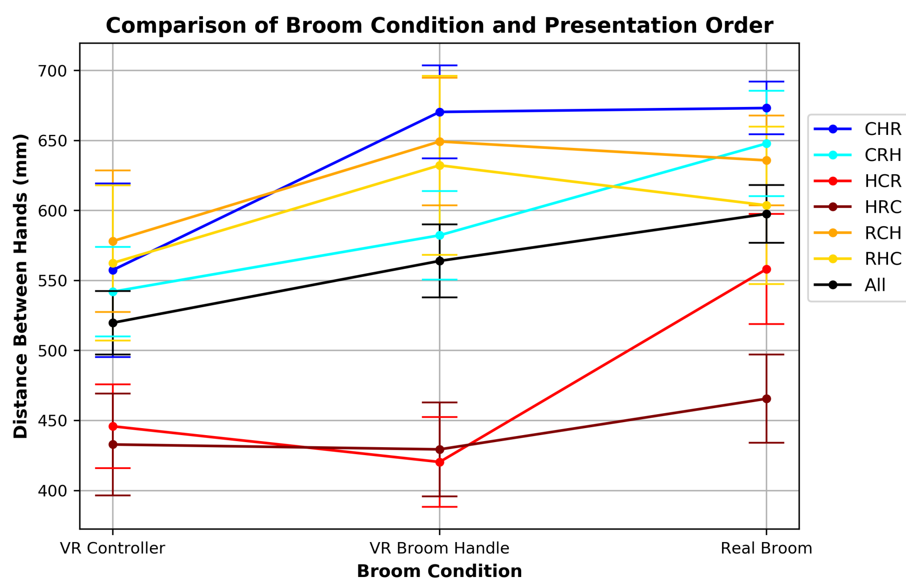

Figure 4.2: Means of broom conditions within their presentation order containing outliers.

normally distributed, we decided to continue with the analysis. There was homogeneity of variances ($p > .05$) and covariances ($p > .05$), as assessed by Levene's test of homogeneity of variances and Box's M test, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = .150$, $p = .928$.

There was a statistically significant interaction between the presentation order and condition on hand distance, $F(10, 44) = 2.186$, $p < .037$, partial $\eta^2 = .332$. There was a statistically significant difference in hand distance between presentation orderings for the broom handle condition, $F(5, 22) = 5.192$, $p = .003$, partial $\chi^2 = .541$. Data are mean ± standard error, unless otherwise stated. Hand Distance was statistically significantly lower in presentation order 3 (-253.8529 ± 68.77mm, $p = .014$) and presentation order 4 (-232.9078 ± 72.49843mm, $p = .041$) when compared to presentation order 1. Hand Distance was statistically significantly greater in presentation order 5 ($-228.850107 \pm 64.844566$mm, $p = .020$) and presentation order 6 ($-211.856088 \pm 64.844566$mm, $p = .036$) when compared to presentation order 3. All other comparisons were not statistically significant but can be observed in Figure 4.4.

There was a statistically significant effect of presentation order on hand distance for presentation order 2, $F(2, 8) = 5.225$, $p = .035$, partial $\chi^2 = .566$. For presentation order 2, hand distance was not statistically significantly different between the VRCons and the VRBroom($M = -40.279$, $SE = 40.334$ mm, $p = 1.00$) and the VRBroom and the Normal condition($M = -65.600$, $SE = 34.182$mm, $p = .382$), but the hand distance was statistically significantly reduced when the VR Controller compared to the Normal condition($M = -105.879$, $SE = 22.009$mm, $p = .026$). There was a statistically significant effect of presentation order on hand distance for presentation order 3, $F(2, 8) = 23.262$, $p < .0005$, partial $\chi^2 = .853$. For presentation order 3, hand distance was not statistically significantly different between the VRCons and the VRBroom($M = 25.455959$, $SE = 17.660026$mm, $p = 0.668718$), but hand distance was statistically significantly greater when the Normal condition is compared to the VR controllers($M = 113.374540$, $SE = 26.098173$mm, $p = 0.036639$) and the Normal condition is compared to the VR Broom($M = 138.830498$, $SE = 20.395342$mm, $p = .007302$). There was a statistically significant effect of presentation order on hand distance for presentation order 5,

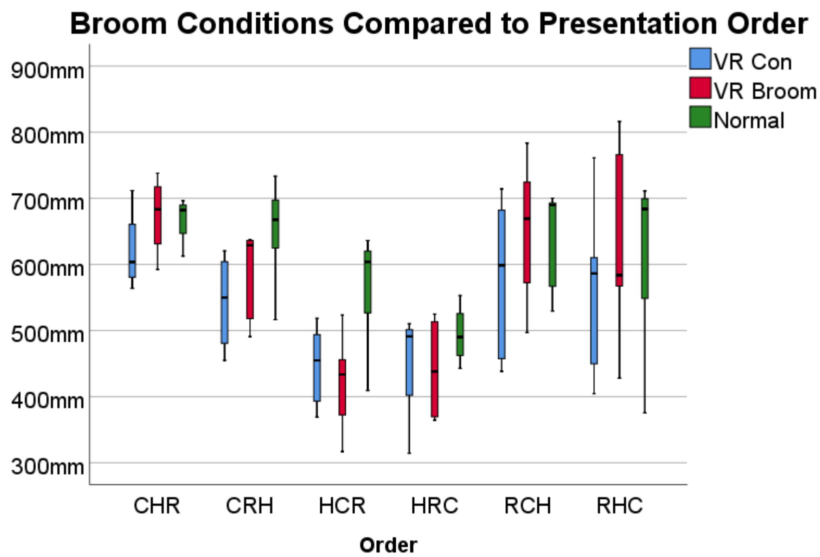

Figure 4.3: Conditions vs Presentation Ordering Box Plot with no outliers after removing cases 4 and 19.

$F(2,8) = 5.138$, $p = .037$, partial $\chi^2 = .562$. For presentation order 5, hand distance was not statistically significantly different between the VRCons and the VRBroom ($M = -71.115472$, $SE = 21.912124$mm, $p = .095$), the VRBroom and the Normal condition ($M = 13.406410$, $SE = 21.075863$mm, $p = 1.00$), or the VR Controller compared to the normal condition ($M = -57.709063$, $SE = 27.259941$mm, $p = 0.305058$).

Results for running a two-way mixed ANOVA using conditions for the within subjects factor and gender for the between subjects factor. There was one outlier, as assessed by boxplot. The analysis was run with and without this outlier but the results were largely similar. The differences in analysis will be mentioned when it is considered important. The data was not normally distributed for Normal condition with Males ($p = .006$), as assessed by the violation of the Shapiro-Wilk's test. The data was normally distributed for all other condition and gender pairings, as assessed by Shapiro-Wilk's test of normality ($p > .05$). Since a two-way mixed ANOVA is robust against the data not being normally distributed, we decided to continue with the analysis. There was homogeneity of variances ($p > .05$)

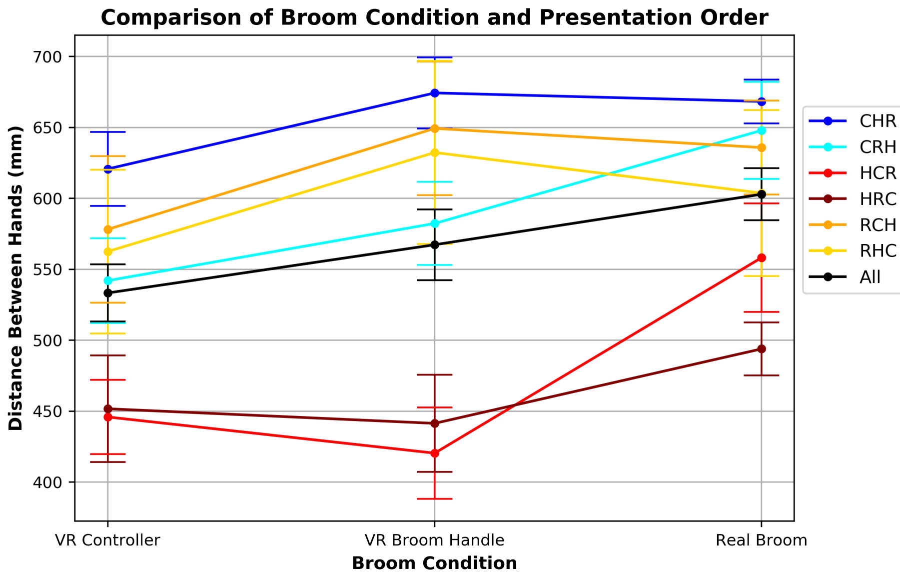

Figure 4.4: Means of broom conditions within their presentation order containing no outliers.

and covariances ($p > .05$), as assessed by Levene's test of homogeneity of variances and Box's M test, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = .459$, $p = .795$.

There was no statistically significant interaction between the conditions and gender on hand distance, $F(2, 56) = .084$, $p = .919$, partial $\eta^2 = .003$. The main effect of condition showed a statistically significant difference in mean hand distance with the different conditions, $F(2, 56) = 10.477$, $p < .0005$, partial $\eta^2 = .272$. The main effect of gender showed that there was no statistically significant difference in mean hand distance between genders $F(1, 28) = 1.861$, $p = .183$, partial $\eta^2 = .062$. Although it is not statistically significant results, when the male subjects hand distance were compared to the female subjects, male subjects had 55.316 ± 40.553mm greater hand distance with $p = .183$. When the outlier observed in the box plot was removed, the analysis showed that male subjects had 71.880 ± 40.026mm greater hand distance than female subjects with $p = .084$.

Results for running a two-way mixed ANOVA on VR experience (subjects with VR ex-

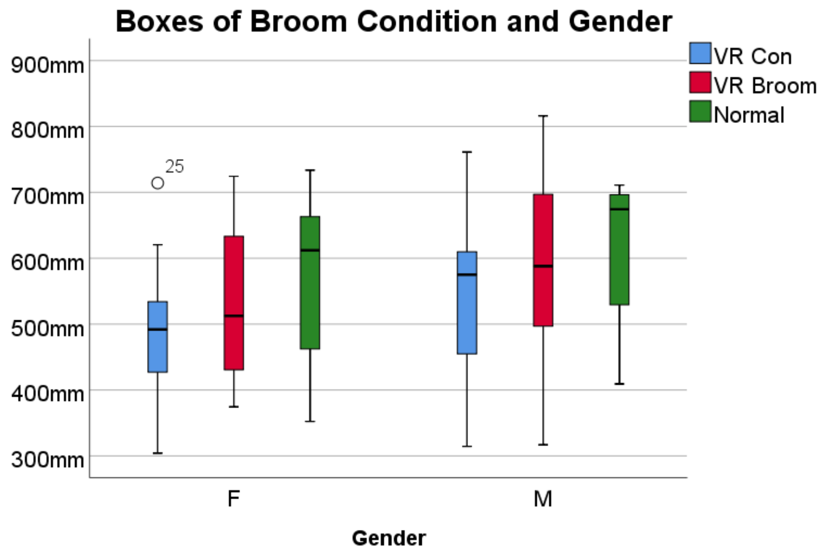

Figure 4.5: Gender vs Conditions Box Plot with one outlier.

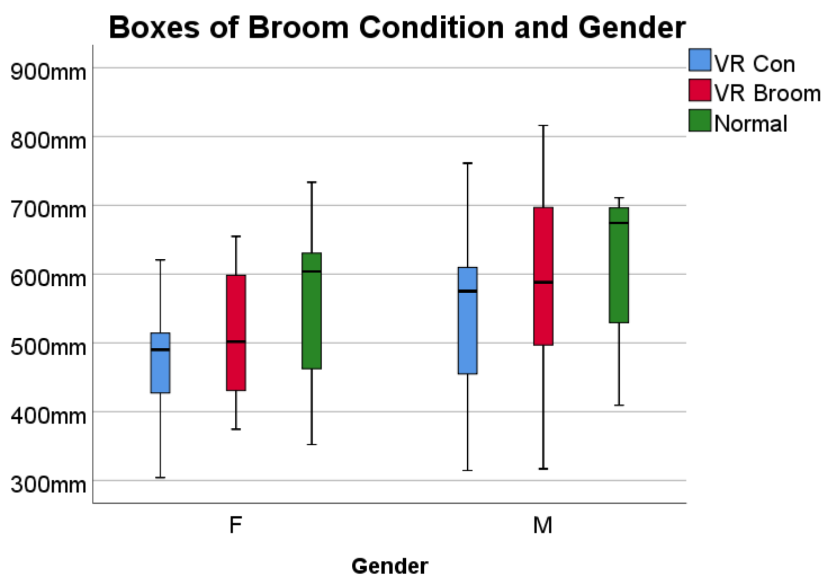

Figure 4.6: Gender vs Conditions Box Plot with outlier removed.

perience and without VR experience) vs conditions (VR Controllers, VR Broom, and Normal). There were no outliers, as assessed by boxplot. The data was not normally distributed for Normal condition with no VR experience ($p = .037$), as assessed by the Shapiro-Wilk's

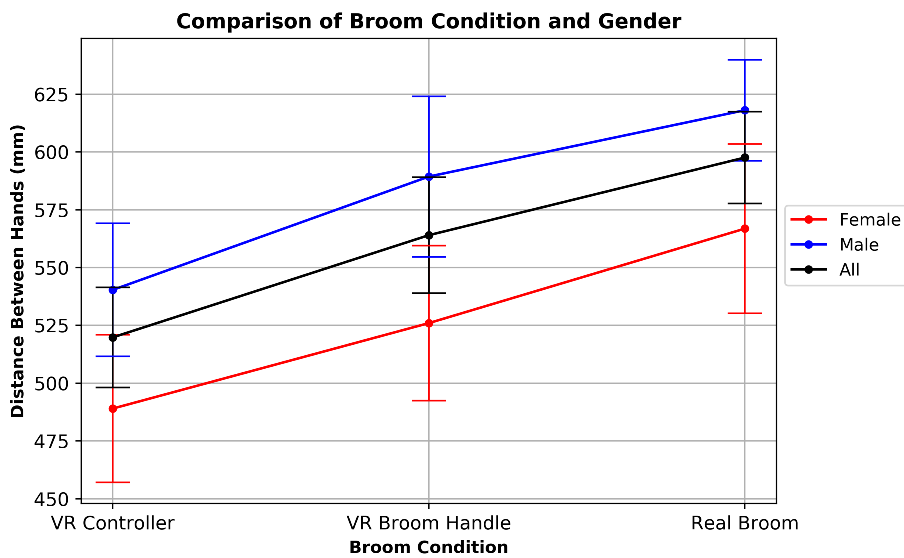

Figure 4.7: Gender vs Conditions means with error bars across conditions with one outlier.

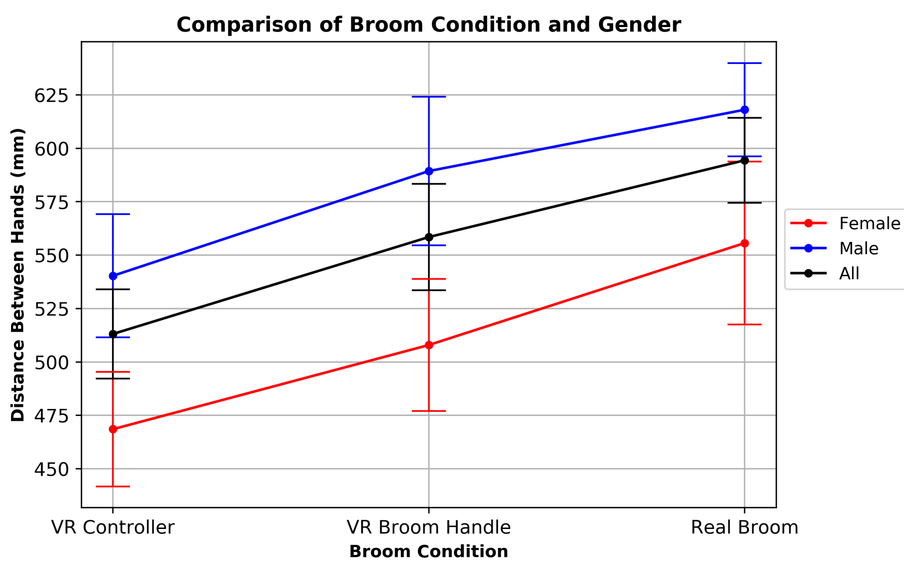

Figure 4.8: Gender vs Conditions means with error bars across conditions with the outlier removed.

test. The data was normally distributed for all other condition and VR experience pairings, as assessed by Shapiro-Wilk's test of normality ($p > .05$). Since a two-way mixed ANOVA is robust against the data not being normally distributed, we decided to continue with the analysis. There was homogeneity of variances ($p > .05$) and covariances ($p > .05$),

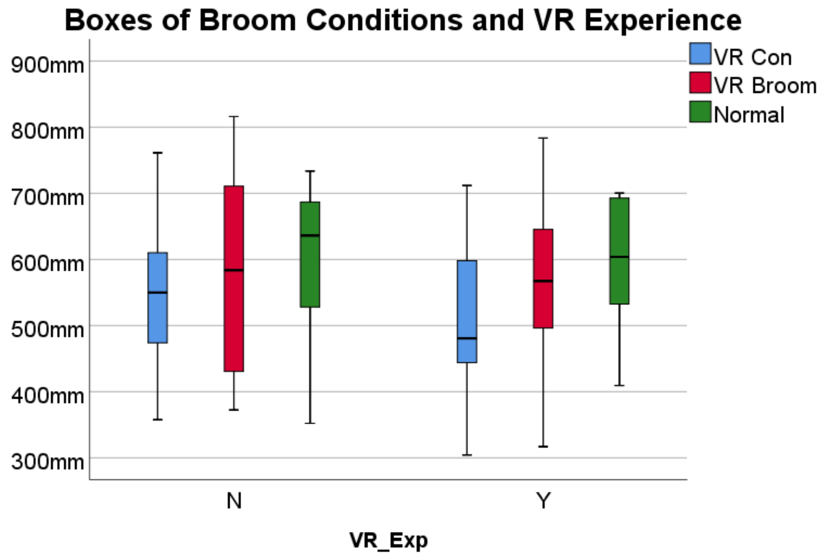

Figure 4.9: VR experience vs Conditions Box Plot.

as assessed by Levene's test of homogeneity of variances and Box's M test, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = .400$, $p = .819$.

There was no statistically significant interaction between the conditions and VR experience on hand distance, $F(2, 56) = .510$, $p = .603$, partial $\eta 2 = .018$. The main effect of condition showed a statistically significant difference in mean hand distance with the different conditions, $F(2, 56) = 11.104$, $p < .0005$, partial $\eta^2 = .284$. The main effect of VR experience showed that there was no statistically significant difference in mean hand distance between subjects with and without VR experience $F(1, 28) = .318$, $p = .577$, partial $\eta^2 = .011$. Although it is not statistically significant results, when the VR experienced subjects hand distance were compared to the subjects without VR experience, the subjects without VR experience had 22.316 ± 40.804mm greater hand distance with $p = .577$.

A one-way ANOVA was conducted to determine if the hand distance was different for subjects with different initial conditions. Subjects were classified into three groups: VR

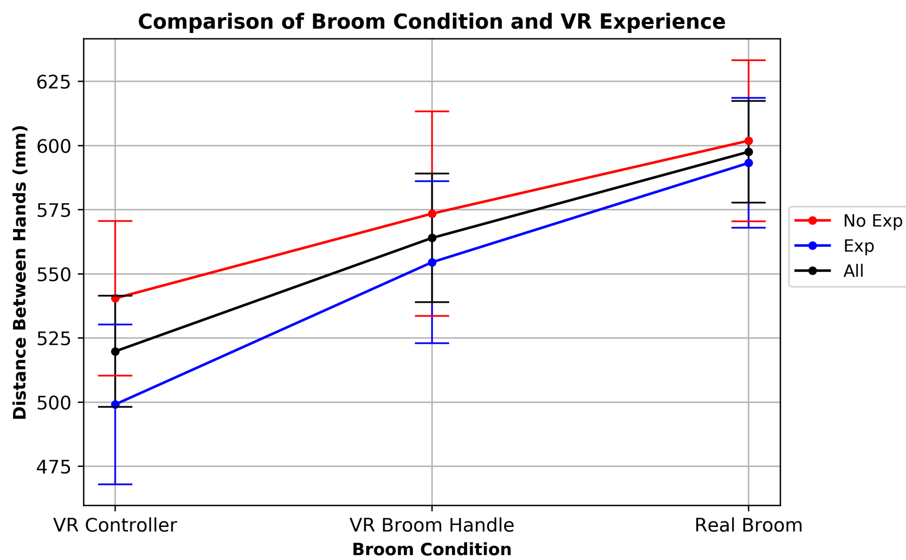

Figure 4.10: VR experience vs Conditions Means with error bars.

controllers ($n = 10$), VR Broom ($n = 10$), and Normal ($n = 10$). There were no outliers, as assessed by boxplot. The data was normally distributed for each group except Normal with $p = .012$, as assessed by Shapiro-Wilk test ($p > .05$). As ANOVAs are robust to data that isn't normalized, we decided to continue analysis. There was homogeneity of variances, as assessed by Levene's test of homogeneity of variances ($p = .510$). Data is presented as mean ± standard deviation. Hand distance was statistically significantly different between different push broom interfaces, $F(2, 27) = 9.576$, $p = .001$, $\omega^2 = 0.36376$. Hand distance increased from the VR Broom ($424.9217 \pm 73.833mm$), to VR Controllers (549.7245 ± 112.73664mm), to Normal (619.7687 ± 111.15842mm) broom interface, in that order. Tukey post hoc analysis revealed that the differences from VR Broom to VR controllers (124.80276 ± 45.105mm [mean ± standard error], $p = .026$), VR Broom to Normal (194.8469 ± 45.105mm, $p = .001$) were statistically significant but no other group differences were statistically significant.

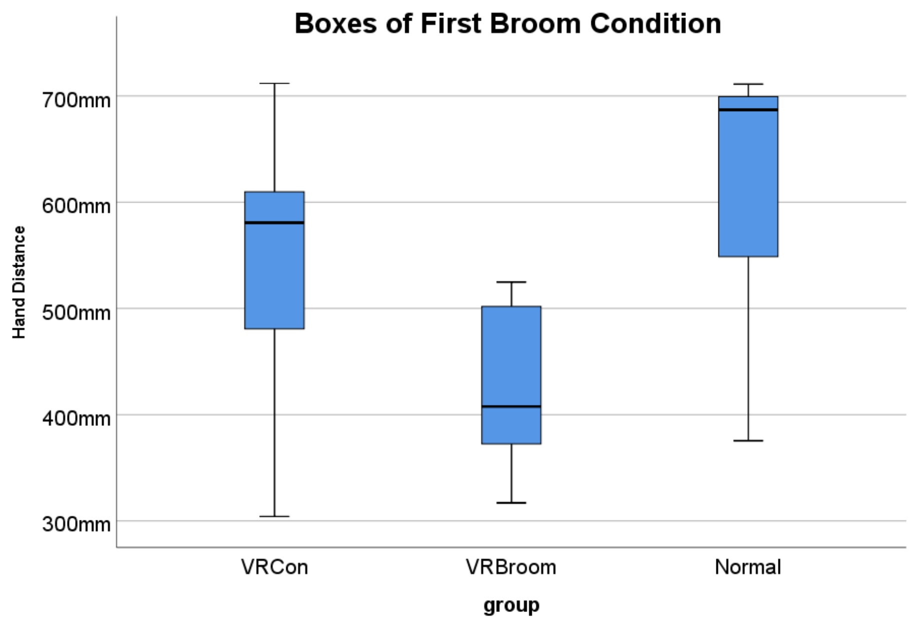

Figure 4.11: First Condition vs Hand Distance Box Plot.

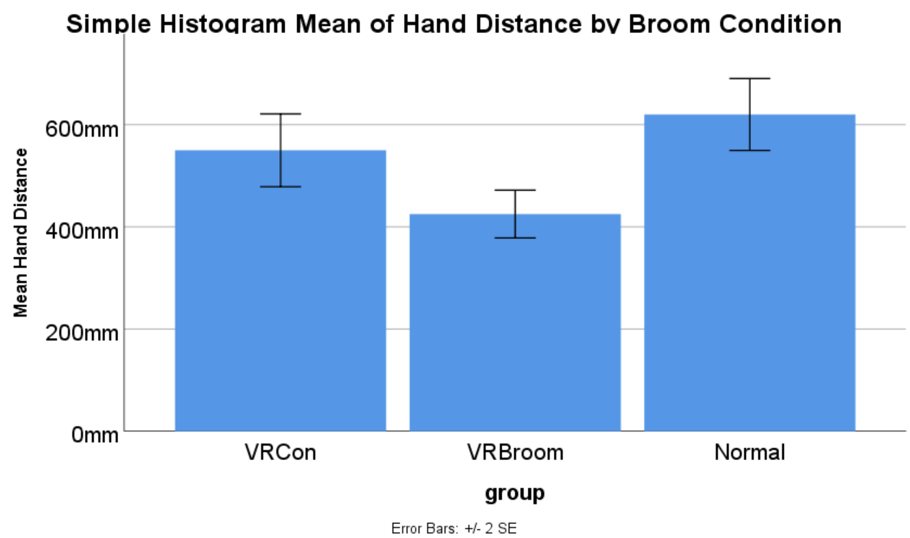

Figure 4.12: First Condition vs Hand Distance Histogram.

4.3 Discussion

Our analysis suggests that there is a statistically significant difference mainly with our VR Broom condition, both with grand means and presentation ordering in which the ordering started with the VR Broom. Although these results are significant, upon further analysis of the data it seems this finding as well as the other findings that weren't significant might be due to several factors. First of all, the metric we use to measure difference in hand grip across subjects is the distance between hands on the broom when in a ready to sweep position. Each piece of data that we used for hand distance was based on an average of hand distances across three different trials within one condition. This allows us to find as close to a true value for each hand distance per condition per subject. While this was the most consistent and reliable data that we could gather, there is the problem that we cannot normalize this data in order to look at each subject equally.

The problem with this raw value is that we expect that subjects which are taller or have a wider shoulder width will naturally have larger hand distances than subjects that are shorter or have a more narrow shoulder width. Considering that most of the analysis techniques use the mean to calculate differences between conditions, a hand distance of 700mm will have the same weight as 300mm. With a giant subject pool this might not be an issue but when we only have 5 subjects per presentation ordering and 10 subjects that started with a condition this can lead to inconsistent results. For example, say that out of our 30 subjects we ended up having all of our shortest subjects start with a certain category. This would make our results show one particular condition having a much lower mean for hand distance when looking at first conditions and any presentation ordering with this condition first would also contain much lower means.

We propose that this wouldn't be an issue if we have recorded the height and shoulder width of the subjects because with this data we could divide their hand distance by their size to normalize the data. Since we don't have this data, we have to assume that this could affect our findings. As mentioned above, we found statistically significant results for the VR Broom condition across the two-way mixed ANOVA with two removed outliers and for the one-way ANOVA. These results are showin in plots 4.4 and 4.12 or the corresponding tables in Appendix C. As you can see in each plot, the presentation orderings that start with VR Broom condition and the first condition VR Broom condition analysis shows a much lower mean than the other conditions. When looking at the demographic of subjects in that group, we find that 6 out of the 10 subjects that started with the VR Broom condition were female. This is significant because, on average, female subjects are shorter than male subjects. Therefore if our theory is true then logically it makes sense that these means are lower than the other conditions. To back this up further, when we ran a two-way mixed ANOVA with conditions as the within subjects factor and gender as the between subjects factor we see that there is a 55.316 ± 40.553mm increase in hand distance when males are compared to females. This number also increases to 71.880 ± 40.026mm when an outlier assessed by boxplot was removed from the data before analysis. In other words, on average (without the outlier in the data), male subject's hand distances were 14.07% larger than female subjects. Therefore it is logical to assume that the low means that we are observing across the VR Broom condition and the presentation orderings starting with the VR Broom condition may be due to the fact that half the subjects in this category were female and therefore shorter.

There is one other reason that we believe having height to normalize the hand distance data would benefit us greatly. If our hypothesis is correct, by normalizing the data we will receive more statistically significant results since we already see these trends showing without normalization. Also, the metric of a ratio of hand distance over height would be more useful for creating a model of broom sweeping for training. If we continued to use average hand distance, the final broom model would be great for any average person but this would cause people that are above or below the average to have less accurate interactions. On the other hand, if we can find a generalized model with respect to height, the model will be flexible to people of different sized and increase the quality of interactions for all subjects.

The final analysis that is worth discussing is the result from the two-way mixed ANOVA with conditions for the within subjects factor and VR experience for the between subjects factor. Although these results were not statistically significant, they do show an interesting trend that might become an issue for future studies and training applications. Since there was no statistically significant results, we will discuss the means of each condition in general. The point of this analysis is to observe which perceived property of affordance a user is using when trying to imitate the use of a real world object in VR.

Plot 4.10 shows that on average the subjects with VR experience held the VR controllers closer to than the subjects without. It also shows that this trend continues with the VR Broom to a much lesser extent and then closes in within 10mm for the normal condition. What is particularly interesting with this data is that earlier we discussed that on average female subjects are shorter and have lower hand distances on the broom. For our VR experience attribute, we had an even split of 15 subjects with no experience and the other 15 subjects with experience. This being said, 8 out of the 12 female subjects reported having no VR experience and the remaining 4 did have VR experience. This is interesting because with 8 female subjects in the no VR experience group, hand distance would be expected to be lower for but as observed in 4.10 this is not the case. We hypothesize that this occurs since subjects that have VR experience use their perceived properties of virtual objects for an affordance when trying to use an object correctly in VR.

Due to the lack of restriction VR puts on the user when using objects in VR, particularly with commodity VR controllers, we think that VR experienced subjects would not consider physical constraints of the real object when using the virtual object. The contrast to this is that subjects without VR experience can only reference the real object's perceptual properties for an affordance of a virtual object for the first time. Therefore it is logical that their hand distances were larger and had less variation across conditions. When VR becomes more mainstream this may pose a problem for future training applications with commodity controllers. If most subjects create habits of not considering constraints when using VR and then constraints are put used, subjects perceived properties of affordances for virtual objects would have to adjust. Therefore it may be harder to effectively train these individuals due to the initial barrier of having to change their habits before any training could be performed.

5 Conclusions

This study has shown interesting results, particularly for how the VR Broom condition was significantly different in many different statistical tests. Although the two-way mixed ANOVA was not significant when all subjects were included, removing two subjects that were outliers according to the box plot provided a significant result. Unfortunately, due to some technical difficulties and a few oversights on our part, the variability of the data seems to be too large to draw any solid conclusions. We believe that the data that we were able to analyze shows interesting results and provides just cause to continue this area of research.

By performing this study and future studies we will gain a better understanding of how affordances affect action in VR. The other thing that this research path could develop is a new way to assess quality of interaction in VR. We envision that this research area will eventually help improve the quality of a training simulation and quality of actions across VR. Hopefully resulting in an increase immersion and the quality of the simulation itself. Therefore the next few sections will discuss the future work for this area of research.

5.1 Follow Up

The follow-up study that needs to be performed should use the knowledge gained from this thesis to perform a slightly bigger study. Due to the lack of related work on this topic, it wasn't clear what data would be useful to assess this work so we decided to capture distance between hands when holding the broom in a ready to sweep position. This provided a good way to receive reliable data and show interesting results but discussed here will be all the data we need to aggregate in future studies.

One piece of data that needs to be captured in future studies is a correct estimate of hand orientation. Initially, it was hypothesized that due to the physical constraints of holding a physical broom handle, that the only measure of hand orientation needed is for the VR controllers. Due to the freedom of orientation that we used in our VR Controller condition implementation, the hands for holding the broom could be held in any orientation. We specifically left the implementation this way to look at how people would translate their perceived properties of using a broom in the real world into VR. We decided to use the HTC Vive controllers over the Oculus rift controllers because the HTC Vive controllers provided a more similar grip to holding a broom handle than the Rift controllers. We thought with a similar grip, that people may align their hands with the virtual broom in an orientation that their hands would be in the normal condition. A big problem we have for this is that we did not get reliable data for the orientation of hands.

This resulted from two different flaws. The first flaw is that we hypothesized that subjects would hold the broom in with a common orientation of the hands with the only difference between subjects being their dominant hand. This was an incorrect assumption as the way subjects griped the broom varied much more than anticipated. We expected subjects to hold the broom with one hand towards the top of the broom and the other hand towards the middle of the broom. With this, we expected the top hand of the broom to be gripped with the back of the hand facing away from the body and the corresponding lower hand would have the back of the hand facing towards the body. This was not always the case. Some subjects preferred to hold the broom with both hands placed so the back of both hands pointed away and others contained an opposite configuration with the back of the hand lower on the broom facing away and the corresponding back of the upper hand facing towards. Considering some of the subjects used their right hand as their upper hand and some used their left hand for the upper hand, we have a set of at least six different ways to hold a broom.

This affects our calculation of orientation of the hands with the broom handle conditions vs the controller conditions. With the current data, we can look at the orientation of the controller compared to the vector of the broom handle but we can't compare it to the actual orientation of the hand for each subjects corresponding grip preference. This is the data we really need to be able to analyze this attribute.

The other part caused by technical difficulties is the orientation of the hands when recording using the motion capture system. Our configuration of motion capture markers on the hands for data collection is shown in Figure3.2. This worked great for capturing hand position but, due to the markers being placed on a relatively flat plane of the back of the hand, there is not enough variance between markers in a 3D space to accurately capture the orientation. This caused the reconstruction of the rigid body in Vicon Tracker to have issues where it would flip in different directions if there was occlusion of one or more markers. The other issue is that even if all markers are showing up, we can't confidently gauge the orientation of the hand. Considering how people could hold a broom six different ways, it is data that we need a reliable way to acquire.

It is not clear but this also may have played a part in our hand distance data. Since subjects orientated their hands in different ways, this may have also caused the distance between hands to be adjusted to compensate for the preference of orientation. For example, subjects who held the real broom higher up in a way to sweep with a downwards motion instead of an outward motion would naturally put their hands to be closer together. Aspects such as this may be the reason for the results of our study. Therefore in future studies, a consideration of requiring subjects to hold the broom in a specified way should be strongly considered.

For future studies we suggest that two things are done to mitigate the issue of orientation data. First of all, there should be a written record of the way each subject is holding the broom with attributes of which hand (right or left) is on the upper part of the broom, and the orientation of both hands on the broom. Beyond this, it is suggested that there be a picture taken of hand positions in the normal condition as a reference of that corresponding subjects grip preference and for later documentation of all different grip preferences. This will clear up the issue presented by not knowing the grip preference per subject with respect to the VR controllers but we still need to fix the orientation issue for the motion capture software.

For the issue of data capture of the orientation there are a few suggestions. One idea is to make a custom marker configuration for each hand that contains more markers than our original configuration and this configuration is used across all subjects. An addition to this idea would be to put markers on the fingers of subjects. Even if no data is being recorded from the finger markers, it would give a visual way to confirm orientation of the hand. Another option would be to use an elevated marker on the hands with the existing marker to get a more reliable 3D rigid body. The issue with this approach is that it may affect the users comfort when performing the task and there is also the issue of securing this object to the person's hand. A way to fix that may be to use gloves but that would jeopardize tactile feedback. We think that the easiest solution is to use the current marker set up, but with larger markers and add a rigid body around the wrist consisting of three markers. This rigid body would have one marker on each side of the wrist placed about a half inch behind the wrist. The final marker will be placed on the inside of the forearm another half inch behind where the two side markers were placed. This setup would keep the simplicity of our current setup while also giving us a reliable way to obtain the orientation of the hand.

Finally, another important aspect to add to the follow up study is a real broom condition with VR equipment. With the study we performed, we were focused on looking at commodity VR controllers, a generalized interface in VR, and then the normal broom without VR to serve as our condition to compare against. We realize now that it was an mistake of ours to not include the real broom in a VR condition to confirm that distance between hands between the VR and normal condition are similar. We know that some research has shown that distance perception in VR is compressed[22] and there are other researchers discussing whether virtual and real affordances can be considered the same or not[2]. Performing our study with a real broom in VR would help confirm or deny that the grip preference between VR and the real world of the same object are in fact the same.

We can even take this research a little further for a more rigorous look into affordances between real world and VR. First we could have someone hold the VR broom handle without VR and record that data. We could also have the subjects hold the VR controllers and tell them to imagine they are holding a virtual broom and record that data. An imaginary condition was used in the dart throwing study discussed at the beginning of this paper[9] and could provide interesting results.

5.2 Future Work

Once the initial follow up study has been performed, there should be two findings. The first is a generalized error between holding a broom in three different conditions both with VR and in the real world. The second is the error observed from holding the same objects in VR and in the real world. With this data, we will have a solid baseline of the differences between conditions without restricting the user in the VR controller interface. From the results of our first study, we expect the results of the subsequent study to show that there is a difference in grip preference depending on the actual properties of affordance provided by a given object. Due to factors such as posture, arm extension and flexion, and other factors of a biomechanical analysis, we hypothesize that there is no way to achieve biomechanical similarities between tasks without first having the same hand distance and orientation on an object. Before we can achieve correct biomechanics for broom sweeping, there first needs to be a method that manipulates subjects to hold the broom in the VR conditions the same way they do in the normal condition. Hence mechanisms should be put in place to try and correct the subject to hold the broom this way.

The main concern would be the controllers as they allow the most modification. Although they are the easiest to modify, if the trend of the broom condition containing the lowest hand distance continues in future studies, equal amount of thought must be put into how to adjust that hand position. There are many different methods we can apply to potentially evoke similar hand grips. The first method is to change the interaction that the subjects have with the VR controllers and the virtual broom. For our study, we wanted to give the subjects as much freedom as possible in order to promote natural behavior. This lack of interference may have affected the realism and the immersion of the simulation. Therefore software constraints should be implemented to influence on how subjects hold the broom. This should provoke subjects to have a more similar hand grip and will benefit from the added realism of holding the broom.

One constraint could be to require the subjects hold the broom in an orientation aligned with the virtual broom handle. If the subject orients their hands such that it is more than a specified threshold away from the broom handle then the VR controller will detach from the broom. Upon detachment, the broom should fall to the floor and the subjects should have to pick it back up. This should help enforce the fact that holding a broom that would not be possible in the real world should be akin to dropping the broom. Also upon detachment, the user should be able to know which hand caused the detachment with a visual marker. For example, a red X could appear where the hand was on the broom to indicate the hand. In this case, if both hands detach the broom then two red Xs would appear on the broom.

This implementation of detaching the broom can be done with or without reinforcement. A system without reinforcement would cause the broom to detach when subjects exceed the threshold without any warning. A system with reinforcement can warn the user through an indicator that they are about to exceed the threshold and detach the broom. Reinforcement works the best with training when it is used as a guide for learning[28]. Reinforcement can make learning a skill more efficient as long as it is not overused or a subject will become dependent on it. Therefore if a reinforcement is used in training, the amount and frequency of reinforcement should reduce over time for the best effects[28]. Therefore the study may see the best results with a reinforcement system designed with this methodology. Considering that it will be hard to determine which method is better, a more in depth study would have two grouping where one group had no reinforcement and the other group had reinforcement.

Implementing these methods to adjust the user to use the VR interfaces in a more similar way to the normal conditions may not come from the first study. There are still many decisions to be made in this experiment, such as whether we design one way of holding a broom or let the user choose their preferred way. Many of these intricacies could be analyzed on their own to see how they affect the studies. The goal of these experiments will be to develop a method to make the subject hold a broom in the same manner they hold the broom in the normal condition. Once this feat can be achieved, research can move towards performing a biomechanical analysis of a task.

The biomechanical analysis of a task in VR has always been the big picture goal of this research. This study can be performed once there is a successful way to assure similar implement grip and use between the VR controller condition and the normal condition. The current idea on how to perform this study is to use pucks as objects and sweep these pucks across a line. There will be three pucks per trial to ensure three sweeping cycles. These loops can be compared for a number of things such as duration, distance between hands change in the trial, back posture and much more. In a similar fashion to the affordance study, this part of the research will have to be iterated using software constraints and other techniques to adjust the subject's behavior to achieve correct biomechanics. If this is possible to achieve, it will be a giant step forward in training with generalized interaction interfaces. Once this is achieved, the next step is comparing this training against training without VR.

From here this field really opens up unto whatever the researcher deems the most important aspect to explore. At this point, there should be a solid understanding of how two handed objects can be manipulated in VR for the purpose of effective training. It will not be known at this point if application of this technique to other rigid two handed objects will be as effective. It will also be unknown the ease of using a one handed object or the difference that weight plays when training an object that has similar physical constraints.

My hope is that this research inspires others to continue this work towards effective training and quality interactions in VR through quantitative analysis. Eventually, there should be cheap and effective training simulations available for commodity VR. We hope this helps others pursue this goal.

References

[1] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. "Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Santa Clara, California, USA: ACM, 2016, pp. 1968–1979. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858226. URL: http://doi.acm.org/10.1145/2858036.2858226 (cit. on pp. 3, 6, 11).

[2] K. Blom. "Virtual Affordances: pliable user expectations". In: *2nd IEEE VR Workshop on Perceptual Illusions in Virtual Environments (PIVE), IEEE VR 2010*. Jan. 2010 (cit. on p. 50).

[3] S. Brault, B. Bideau, C. Craig, and R. Kulpa. "Balancing Deceit and Disguise: How to successfully fool the defender in a 1 vs. 1 situation in rugby". In: 29 (Apr. 2010), pp. 412–25 (cit. on p. 10).

[4] J. Cho, T.-H. Lee, J. Ogden, A. Stewart, T.-Y. Tsai, J. Chen, and R. Vituccio. "Imago: Presence and Emotion in Virtual Reality". In: *ACM SIGGRAPH 2016 VR Village*. SIGGRAPH '16. Anaheim, California: ACM, 2016, 6:1–6:2. ISBN: 978-1-4503-4377-0. DOI: 10.1145/2929490.2931000. URL: http://doi.acm.org/10.1145/2929490.2931000 (cit. on pp. 3, 6).

[5] S. H. Creem and D. Proffitt. “Grasping objects by their handles: a necessary interaction between cognition and action.” In: *J Exp Psychol Hum Percept Perform* 27.1 (Feb. 2001), pp. 218–228 (cit. on pp. 2, 8).

[6] S. Davis, K. Nesbitt, and E. Nalivaiko. “A Systematic Review of Cybersickness”. In: *Proceedings of the 2014 Conference on Interactive Entertainment*. IE2014. Newcastle, NSW, Australia: ACM, 2014, 8:1–8:9. ISBN: 978-1-4503-2790-9. DOI: 10.1145/2677758.2677780. URL: http://doi.acm.org/10.1145/2677758.2677780 (cit. on pp. 5, 11).

[7] S. Haque and S. Srinivasan. “A meta-analysis of the training effectiveness of virtual reality surgical simulators”. In: *IEEE Transactions on Information Technology in Biomedicine* 10.1 (Jan. 2006), pp. 51–58. ISSN: 1089-7771. DOI: 10.1109/TITB.2005.855529 (cit. on pp. 1, 3, 9).

[8] Y. Huang, L. Churches, and B. Reilly. “A Case Study on Virtual Reality American Football Training”. In: *Proceedings of the 2015 Virtual Reality International Conference*. VRIC ’15. Laval, France: ACM, 2015, 6:1–6:5. ISBN: 978-1-4503-3313-9. DOI: 10.1145/2806173.2806178. URL: http://doi.acm.org/10.1145/2806173.2806178 (cit. on pp. 1, 4, 5, 9).

[9] R. Kehoe and M. Rice. “Reality, virtual reality, and imagery: Quality of movement in novice dart players”. In: *British Journal of Occupational Therapy* 79.4 (2016), pp. 244–251. DOI: 10.1177/0308022615616820. eprint: http://dx.doi.org/10.1177/0308022615616820. URL: http://dx.doi.org/10.1177/0308022615616820 (cit. on pp. 8, 13–15, 50).

[10] M. Lee, K. Kim, S. Daher, A. Raij, R. Schubert, J. Bailenson, and G. Welch. “The wobbly table: Increased social presence via subtle incidental movement of a real-

virtual table". In: *2016 IEEE Virtual Reality (VR)*. Mar. 2016, pp. 11–17. DOI: 10.1109/VR.2016.7504683 (cit. on p. 3).

[11] Y. Li, L. K. Shark, S. J. Hobbs, and J. Ingham. "Real-Time Immersive Table Tennis Game for Two Players with Motion Tracking". In: *2010 14th International Conference Information Visualisation*. July 2010, pp. 500–505. DOI: 10.1109/IV.2010.97 (cit. on p. 10).

[12] I. Mahalil, M. E. Rusli, A. M. Yusof, M. Z. M. Yusof, and A. R. R. Zainudin. "Virtual reality-based technique for stress therapy". In: *2014 4th International Conference on Engineering Technology and Technopreneuship (ICE2T)*. Aug. 2014, pp. 295–300. DOI: 10.1109/ICE2T.2014.7006265 (cit. on p. 3).

[13] H. C. Miles, S. R. Pop, S. J. Watt, G. P. Lawrence, and N. W. John. "A review of virtual environments for training in ball sports". In: *Computers And Graphics* 36.6 (2012). 2011 Joint Symposium on Computational Aesthetics (CAe), Non-Photorealistic Animation and Rendering (NPAR), and Sketch-Based Interfaces and Modeling (SBIM), pp. 714–726. ISSN: 0097-8493. DOI: https://doi.org/10.1016/j.cag.2012.04.007. URL: http://www.sciencedirect.com/science/article/pii/S0097849312000957 (cit. on p. 10).

[14] J. P. Molina, A. S. García, D. Martinez, F. J. Manjavacas, V. Blasco, V. López, and P. González. "The Development of Glove-based Interfaces with the TRES-D Methodology". In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. VRST '06. Limassol, Cyprus: ACM, 2006, pp. 216–219. ISBN: 1-59593-321-2. DOI: 10.1145/1180495.1180539. URL: http://doi.acm.org/10.1145/1180495.1180539 (cit. on p. 6).

[15] D. C. Niehorster, L. Li, and M. Lappe. "The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific

Research". In: *i-Perception* 8.3 (2017), p. 2041669517708205. DOI: 10.1177/2041669517708205. eprint: https://doi.org/10.1177/2041669517708205. URL: https://doi.org/10.1177/2041669517708205 (cit. on p. 17).

[16] D. Norman. *The Psychology of Everyday Things*. Basic Books, 1988. ISBN: 9780385267748. URL: https://books.google.com/books?id=01NSRAAACAAJ (cit. on p. 6).

[17] E. D. Ragan, D. A. Bowman, R. Kopper, C. Stinson, S. Scerbo, and R. P. McMahan. "Effects of Field of View and Visual Complexity on Virtual Reality Training Effectiveness for a Visual Scanning Task". In: *IEEE Transactions on Visualization and Computer Graphics* 21.7 (July 2015), pp. 794–807. ISSN: 1077-2626. DOI: 10.1109/TVCG.2015.2403312 (cit. on p. 8).

[18] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. "Learning to Walk in Virtual Reality". In: *ACM Trans. Appl. Percept.* 10.2 (June 2013), 11:1–11:17. ISSN: 1544-3558. DOI: 10.1145/2465780.2465785. URL: http://doi.acm.org/10.1145/2465780.2465785 (cit. on p. 12).

[19] R. H. Y. So, A. Ho, and W. T. Lo. "A Metric to Quantify Virtual Scene Movement for the Study of Cybersickness: Definition, Implementation, and Verification". In: *Presence* 10.2 (Apr. 2001), pp. 193–215. ISSN: 1054-7460. DOI: 10.1162/105474601750216803 (cit. on p. 11).

[20] P. J. Stappers. "Experiencing non-Newtonian physics in VR Page 1/8 Experiencing non-Newtonian physics in Virtual Reality". In: 2000 (cit. on p. 7).

[21] F. Steinicke, G. Bruder, K. Hinrichs, S. Kuhl, M. Lappe, and P. Willemsen. "Judgment of Natural Perspective Projections in Head-mounted Display Environments". In: *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*. VRST '09. Kyoto, Japan: ACM, 2009, pp. 35–42. ISBN: 978-1-60558-869-

8. DOI: 10.1145/1643928.1643940. URL: http://doi.acm.org/10.1145/1643928.1643940 (cit. on pp. 11, 12).

[22] F. Steinicke, G. Bruder, K. Hinrichs, M. Lappe, B. Ries, and V. Interrante. "Transitional Environments Enhance Distance Perception in Immersive Virtual Reality Systems". In: *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*. APGV '09. Chania, Crete, Greece: ACM, 2009, pp. 19–26. ISBN: 978-1-60558-743-1. DOI: 10.1145/1620993.1620998. URL: http://doi.acm.org/10.1145/1620993.1620998 (cit. on pp. 6, 12, 20, 50).

[23] C. Stinson and D. A. Bowman. "Feasibility of Training Athletes for High-Pressure Situations Using Virtual Reality". In: *IEEE Transactions on Visualization and Computer Graphics* 20.4 (Apr. 2014), pp. 606–615. ISSN: 1077-2626. DOI: 10.1109/TVCG.2014.23 (cit. on p. 5).

[24] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte. "Leveraging change blindness for redirection in virtual environments". In: *2011 IEEE Virtual Reality Conference*. Mar. 2011, pp. 159–166. DOI: 10.1109/VR.2011.5759455 (cit. on p. 11).

[25] I. E. Sutherland. "The Ultimate Display". In: *Proceedings of the IFIP Congress*. 1965, pp. 506–508 (cit. on p. 3).

[26] N. Vaughan, V. N. Dubey, T. W. Wainwright, and R. G. Middleton. "Does virtual-reality training on orthopaedic simulators improve performance in the operating room?" In: *2015 Science and Information Conference (SAI)*. July 2015, pp. 51–54. DOI: 10.1109/SAI.2015.7237125 (cit. on pp. 1, 9).

[27] N. Vignais, R. Kulpa, C. Craig, and B. Bideau. "Virtual Thrower Versus Real Goalkeeper: The Influence of Different Visual Conditions on Performance". In: *Presence*

19.4 (Aug. 2010), pp. 281–290. ISSN: 1054-7460. DOI: 10.1162/PRES_a_00003 (cit. on p. 10).

[28] A. W. Salmoni, R. A. Schmidt, and C. B. Walter. "Knowledge of results and motor learning: A review and critical reappraisal". In: 95 (June 1984), pp. 355–86 (cit. on p. 52).

[29] E. van Wyk and R. de Villiers. "Virtual Reality Training Applications for the Mining Industry". In: *Proceedings of the 6th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa*. AFRIGRAPH '09. Pretoria, South Africa: ACM, 2009, pp. 53–63. ISBN: 978-1-60558-428-7. DOI: 10.1145/1503454.1503465. URL: http://doi.acm.org/10.1145/1503454.1503465 (cit. on p. 1).

[30] S. Xu, P. Song, C. L. Chin, G. G. Chua, Z. Huang, and S. Rahardja. "Tennis Space: An Interactive and Immersive Environment for Tennis Simulation". In: *2009 Fifth International Conference on Image and Graphics*. Sept. 2009, pp. 652–657. DOI: 10.1109/ICIG.2009.102 (cit. on pp. 4, 5, 10).

A Appendix A

Appendix A contains a copy of the pre-experiment questionnaire given to each subject before testing. This questionnaire's purpose was to obtain demographic information about our subjects to aid in the analysis of our results. The questionnaire contains general questions and questions pertaining to video game and VR experience as we believe this may affect how a subject acts in a VR environment.

Pre-Experiment Questionnaire

Please state your relationship with the University:

- ❏ Student
- ❏ Staff
- ❏ Faculty
- ❏ Duluth Community Member
- ❏ Other

If you are a student, what is your major? ________________

Age __________ Gender _________

To what extent have you experienced motion sickness? ____________________

Approximately how many hours in the last month have you used virtual reality systems? ____________________

How much total experience do you have with virtual reality systems. Please select one option:

- ❏ 0-5 hours
- ❏ 5-30 hours
- ❏ 30-60 hours
- ❏ 60-100 hours
- ❏ 100+ hours

If you have had used virtual reality, please describe the types of experiences (such as games, simulations, movies or other immersive activities) that you have participated in including how you interacted with the virtual objects and environment.

Approximately how many hours each week do you play video games? ________________

If you have had experience with virtual reality, please indicate which virtual reality systems you regularly use:

- ❏ Oculus Rift with Hand Controllers
- ❏ Oculus Rift with Xbox Controller
- ❏ HTC VIVE with
- ❏ PlayStation VR
- ❏ Samsung Gear VR
- ❏ Google Cardboard
- ❏ Other __________________________________

B Appendix B

Appendix B contains all of the results of the tests run on the data obtained in this study. This output was generated by running multiple two-way mixed ANOVAs and a single one-way ANOVA using IBM SPSS Statistics 25. The output is grouped such that each section only relates to that particular ANOVA. These tables provide exact numbers to the statistical tests and results discussed in Chapter 4.

3 Conditions vs 6 Orderings (contains outliers)

Two-way Mixed ANOVA

Explore

Order

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Order	Statistic	df	Sig.	Statistic	df	Sig.
VRCon HD	1.00	.317	5	.113	.861	5	.232
	2.00	.202	5	.200*	.913	5	.484
	3.00	.196	5	.200*	.935	5	.630
	4.00	.337	5	.066	.815	5	.106
	5.00	.230	5	.200*	.884	5	.329
	6.00	.187	5	.200*	.951	5	.744
VRBroom HD	1.00	.186	5	.200*	.986	5	.962
	2.00	.343	5	.056	.769	5	.044
	3.00	.166	5	.200*	.989	5	.975
	4.00	.331	5	.076	.791	5	.068
	5.00	.169	5	.200*	.970	5	.877
	6.00	.220	5	.200*	.936	5	.637
Normal HD	1.00	.391	5	.012	.718	5	.015
	2.00	.193	5	.200*	.936	5	.635
	3.00	.283	5	.200*	.855	5	.210
	4.00	.186	5	.200*	.965	5	.842
	5.00	.347	5	.049	.785	5	.061
	6.00	.312	5	.126	.819	5	.114

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

3 Conditions vs 6 Orderings (contains outliers)

General Linear Model

Within-Subjects Factors

Measure: Hand_Distance

conditions	Dependent Variable
1	VR_Con
2	VR_Broom
3	Normal_Broom

Between-Subjects Factors

		N
Order	1.00	5
	2.00	5
	3.00	5
	4.00	5
	5.00	5
	6.00	5

Descriptive Statistics

	Order	Mean	Std. Deviation	N
VRCon HD	1.00	557.4090	151.93683	5
	2.00	542.0400	73.23975	5
	3.00	445.8617	63.88075	5
	4.00	432.9113	90.07616	5
	5.00	578.1404	126.33744	5
	6.00	562.4816	141.40225	5
	Total	519.8073	118.48915	30
VRBroom HD	1.00	670.3726	53.86694	5
	2.00	582.3185	71.84004	5
	3.00	420.4057	79.08454	5
	4.00	429.4377	77.20280	5
	5.00	649.2558	115.35600	5
	6.00	632.2618	158.16787	5
	Total	564.0087	137.20507	30
Normal HD	1.00	673.2215	34.49075	5
	2.00	647.9186	83.70703	5
	3.00	559.2362	93.77639	5

	4.00	465.6319	74.74957	5
	5.00	635.8494	81.23748	5
	6.00	603.6879	143.37166	5
	Total	597.5909	108.61541	30

Box's Test of Equality of Covariance Matrices[a]

Box's M	35.541
F	.783
df1	30
df2	1301.720
Sig.	.793

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Order

Within Subjects Design: conditions

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
conditions	Pillai's Trace	.480	10.604[b]	2.000	23.000	.001	.480
	Wilks' Lambda	.520	10.604[b]	2.000	23.000	.001	.480
	Hotelling's Trace	.922	10.604[b]	2.000	23.000	.001	.480
	Roy's Largest Root	.922	10.604[b]	2.000	23.000	.001	.480
conditions * Order	Pillai's Trace	.598	2.049	10.000	48.000	.048	.299
	Wilks' Lambda	.461	2.177[b]	10.000	46.000	.037	.321
	Hotelling's Trace	1.042	2.293	10.000	44.000	.029	.343
	Roy's Largest Root	.899	4.317[c]	5.000	24.000	.006	.474

a. Design: Intercept + Order

Within Subjects Design: conditions

b. Exact statistic

c. The statistic is an upper bound on F that yields a lower bound on the significance level.

Mauchly's Test of Sphericity[a]

Measure: Hand_Distance

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
conditions	.879	2.979	2	.225	.892	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Order

Within Subjects Design: conditions

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Hand_Distance

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Sphericity Assumed	91318.137	2	45659.068	13.015	.000	.352
	Greenhouse-Geisser	91318.137	1.783	51206.625	13.015	.000	.352
	Huynh-Feldt	91318.137	2.000	45659.068	13.015	.000	.352
	Lower-bound	91318.137	1.000	91318.137	13.015	.001	.352
conditions * Order	Sphericity Assumed	66076.902	10	6607.690	1.884	.071	.282
	Greenhouse-Geisser	66076.902	8.917	7410.522	1.884	.081	.282
	Huynh-Feldt	66076.902	10.000	6607.690	1.884	.071	.282
	Lower-bound	66076.902	5.000	13215.380	1.884	.135	.282
Error(conditions)	Sphericity Assumed	168391.430	48	3508.155			
	Greenhouse-Geisser	168391.430	42.800	3934.394			
	Huynh-Feldt	168391.430	48.000	3508.155			

Lower-bound	168391.430	24.000	7016.310			

Tests of Within-Subjects Contrasts

Measure: Hand_Distance

Source	conditions	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Linear	90754.308	1	90754.308	21.337	.000	.471
	Quadratic	563.829	1	563.829	.204	.656	.008
conditions * Order	Linear	18184.521	5	3636.904	.855	.525	.151
	Quadratic	47892.381	5	9578.476	3.467	.017	.419
Error(conditions)	Linear	102081.220	24	4253.384			
	Quadratic	66310.210	24	2762.925			

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
VRCon HD	Based on Mean	.880	5	24	.509
	Based on Median	.449	5	24	.810
	Based on Median and with adjusted df	.449	5	14.669	.808
	Based on trimmed mean	.824	5	24	.545
VRBroom HD	Based on Mean	2.620	5	24	.050
	Based on Median	.920	5	24	.485
	Based on Median and with adjusted df	.920	5	16.646	.492
	Based on trimmed mean	2.610	5	24	.051
Normal HD	Based on Mean	2.163	5	24	.092
	Based on Median	.530	5	24	.751
	Based on Median and with adjusted df	.530	5	13.591	.750
	Based on trimmed mean	1.996	5	24	.116

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Order

Within Subjects Design: conditions

Tests of Between-Subjects Effects

Measure: Hand_Distance

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	28271292.802	1	28271292.802	1187.574	.000	.980
Order	489393.903	5	97878.781	4.112	.008	.461
Error	571342.066	24	23805.919			

Estimated Marginal Means

1. conditions

Estimates

Measure: Hand_Distance

conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	519.807	20.629	477.231	562.383
2	564.009	18.043	526.769	601.248
3	597.591	16.622	563.285	631.897

Pairwise Comparisons

Measure: Hand_Distance

(I) conditions	(J) conditions	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-44.201*	16.279	.036	-86.098	-2.305
	3	-77.784*	16.839	.000	-121.122	-34.446
2	1	44.201*	16.279	.036	2.305	86.098
	3	-33.582*	12.372	.036	-65.423	-1.742
3	1	77.784*	16.839	.000	34.446	121.122
	2	33.582*	12.372	.036	1.742	65.423

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.480	10.604[a]	2.000	23.000	.001	.480
Wilks' lambda	.520	10.604[a]	2.000	23.000	.001	.480
Hotelling's trace	.922	10.604[a]	2.000	23.000	.001	.480
Roy's largest root	.922	10.604[a]	2.000	23.000	.001	.480

Each F tests the multivariate effect of conditions. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. Order

Estimates

Measure: Hand_Distance

Order	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.00	633.668	39.838	551.446	715.889
2.00	590.759	39.838	508.538	672.980
3.00	475.168	39.838	392.946	557.389
4.00	442.660	39.838	360.439	524.882
5.00	621.082	39.838	538.860	703.303
6.00	599.477	39.838	517.256	681.699

Pairwise Comparisons

Measure: Hand_Distance

(I) Order	(J) Order	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1.00	2.00	42.909	56.339	1.000	-140.666	226.484
	3.00	158.500	56.339	.144	-25.075	342.075
	4.00	191.007*	56.339	.036	7.432	374.583
	5.00	12.586	56.339	1.000	-170.989	196.161
	6.00	34.191	56.339	1.000	-149.385	217.766

2.00	1.00	-42.909	56.339	1.000	-226.484	140.666
	3.00	115.591	56.339	.769	-67.984	299.166
	4.00	148.099	56.339	.221	-35.476	331.674
	5.00	-30.323	56.339	1.000	-213.898	153.252
	6.00	-8.718	56.339	1.000	-192.293	174.857
3.00	1.00	-158.500	56.339	.144	-342.075	25.075
	2.00	-115.591	56.339	.769	-299.166	67.984
	4.00	32.508	56.339	1.000	-151.068	216.083
	5.00	-145.914	56.339	.241	-329.489	37.661
	6.00	-124.309	56.339	.558	-307.884	59.266
4.00	1.00	-191.007*	56.339	.036	-374.583	-7.432
	2.00	-148.099	56.339	.221	-331.674	35.476
	3.00	-32.508	56.339	1.000	-216.083	151.068
	5.00	-178.422	56.339	.062	-361.997	5.154
	6.00	-156.817	56.339	.155	-340.392	26.758
5.00	1.00	-12.586	56.339	1.000	-196.161	170.989
	2.00	30.323	56.339	1.000	-153.252	213.898
	3.00	145.914	56.339	.241	-37.661	329.489
	4.00	178.422	56.339	.062	-5.154	361.997
	6.00	21.605	56.339	1.000	-161.970	205.180
6.00	1.00	-34.191	56.339	1.000	-217.766	149.385
	2.00	8.718	56.339	1.000	-174.857	192.293
	3.00	124.309	56.339	.558	-59.266	307.884
	4.00	156.817	56.339	.155	-26.758	340.392
	5.00	-21.605	56.339	1.000	-205.180	161.970

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: Hand_Distance

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	163131.301	5	32626.260	4.112	.008	.461
Error	190447.355	24	7935.306			

The F tests the effect of Order. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

3. Order * conditions

Measure: Hand_Distance

Order	conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.00	1	557.409	50.530	453.120	661.698
	2	670.373	44.197	579.154	761.591
	3	673.222	40.716	589.189	757.255
2.00	1	542.040	50.530	437.751	646.329
	2	582.319	44.197	491.100	673.537
	3	647.919	40.716	563.886	731.952
3.00	1	445.862	50.530	341.572	550.151
	2	420.406	44.197	329.188	511.624
	3	559.236	40.716	475.203	643.269
4.00	1	432.911	50.530	328.622	537.201
	2	429.438	44.197	338.219	520.656
	3	465.632	40.716	381.599	549.665
5.00	1	578.140	50.530	473.851	682.430
	2	649.256	44.197	558.038	740.474
	3	635.849	40.716	551.816	719.882
6.00	1	562.482	50.530	458.192	666.771
	2	632.262	44.197	541.044	723.480
	3	603.688	40.716	519.655	687.721

Post Hoc Tests

Order

Multiple Comparisons

Measure: Hand_Distance

	(I) Order	(J) Order	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tukey HSD	1.00	2.00	42.9087	56.33935	.971	-131.2887	217.1061
		3.00	158.4998	56.33935	.089	-15.6976	332.6972
		4.00	191.0074*	56.33935	.026	16.8100	365.2048
		5.00	12.5858	56.33935	1.000	-161.6116	186.7832

		6.00	34.1906	56.33935	.989	-140.0068	208.3880
	2.00	1.00	-42.9087	56.33935	.971	-217.1061	131.2887
		3.00	115.5912	56.33935	.344	-58.6062	289.7886
		4.00	148.0987	56.33935	.129	-26.0987	322.2961
		5.00	-30.3228	56.33935	.994	-204.5202	143.8746
		6.00	-8.7181	56.33935	1.000	-182.9155	165.4793
	3.00	1.00	-158.4998	56.33935	.089	-332.6972	15.6976
		2.00	-115.5912	56.33935	.344	-289.7886	58.6062
		4.00	32.5076	56.33935	.992	-141.6898	206.7050
		5.00	-145.9140	56.33935	.138	-320.1114	28.2834
		6.00	-124.3092	56.33935	.271	-298.5066	49.8882
	4.00	1.00	-191.0074*	56.33935	.026	-365.2048	-16.8100
		2.00	-148.0987	56.33935	.129	-322.2961	26.0987
		3.00	-32.5076	56.33935	.992	-206.7050	141.6898
		5.00	-178.4216*	56.33935	.042	-352.6190	-4.2242
		6.00	-156.8168	56.33935	.095	-331.0142	17.3806
	5.00	1.00	-12.5858	56.33935	1.000	-186.7832	161.6116
		2.00	30.3228	56.33935	.994	-143.8746	204.5202
		3.00	145.9140	56.33935	.138	-28.2834	320.1114
		4.00	178.4216*	56.33935	.042	4.2242	352.6190
		6.00	21.6048	56.33935	.999	-152.5926	195.8022
	6.00	1.00	-34.1906	56.33935	.989	-208.3880	140.0068
		2.00	8.7181	56.33935	1.000	-165.4793	182.9155
		3.00	124.3092	56.33935	.271	-49.8882	298.5066
		4.00	156.8168	56.33935	.095	-17.3806	331.0142
		5.00	-21.6048	56.33935	.999	-195.8022	152.5926
Games-Howell	1.00	2.00	42.9087	38.18958	.859	-97.0035	182.8209
		3.00	158.4998*	42.10435	.047	1.9448	315.0548
		4.00	191.0074*	38.82278	.010	48.5281	333.4867
		5.00	12.5858	53.47860	1.000	-198.1225	223.2941
		6.00	34.1906	67.38093	.994	-246.3302	314.7113
	2.00	1.00	-42.9087	38.18958	.859	-182.8209	97.0035
		3.00	115.5912	43.85334	.195	-45.7305	276.9128
		4.00	148.0987	40.71298	.051	-.6882	296.8857
		5.00	-30.3228	54.86620	.991	-242.2161	181.5704
		6.00	-8.7181	68.48743	1.000	-288.3246	270.8884
	3.00	1.00	-158.4998*	42.10435	.047	-315.0548	-1.9448
		2.00	-115.5912	43.85334	.195	-276.9128	45.7305

		4.00	32.5076	44.40585	.972	-130.4901	195.5052
		5.00	-145.9140	57.65962	.229	-362.4119	70.5839
		6.00	-124.3092	70.74504	.546	-403.8638	155.2453
	4.00	1.00	-191.0074*	38.82278	.010	-333.4867	-48.5281
		2.00	-148.0987	40.71298	.051	-296.8857	.6882
		3.00	-32.5076	44.40585	.972	-195.5052	130.4901
		5.00	-178.4216	55.30880	.103	-390.8632	34.0200
		6.00	-156.8168	68.84251	.331	-436.2636	122.6299
	5.00	1.00	-12.5858	53.47860	1.000	-223.2941	198.1225
		2.00	30.3228	54.86620	.991	-181.5704	242.2161
		3.00	145.9140	57.65962	.229	-70.5839	362.4119
		4.00	178.4216	55.30880	.103	-34.0200	390.8632
		6.00	21.6048	78.05155	1.000	-269.1575	312.3670
	6.00	1.00	-34.1906	67.38093	.994	-314.7113	246.3302
		2.00	8.7181	68.48743	1.000	-270.8884	288.3246
		3.00	124.3092	70.74504	.546	-155.2453	403.8638
		4.00	156.8168	68.84251	.331	-122.6299	436.2636
		5.00	-21.6048	78.05155	1.000	-312.3670	269.1575

Based on observed means.

The error term is Mean Square(Error) = 7935.306.

*. The mean difference is significant at the .05 level.

Homogeneous Subsets

Hand_Distance

			Subset	
	Order	N	1	2
Tukey HSD[a,b]	4.00	5	442.6603	
	3.00	5	475.1679	475.1679
	2.00	5	590.7590	590.7590
	6.00	5	599.4771	599.4771
	5.00	5		621.0819
	1.00	5		633.6677

Sig.		.095	.089

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 7935.306.
a. Uses Harmonic Mean Sample Size = 5.000.
b. Alpha = .05.

3 Conditions vs 6 Orderings (outliers removed)

Two-way Mixed ANOVA

Explore

Order

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Order	Statistic	df	Sig.	Statistic	df	Sig.
VRCon HD	1.00	.319	4	.	.882	4	.349
	2.00	.202	5	.200*	.913	5	.484
	3.00	.196	5	.200*	.935	5	.630
	4.00	.411	4	.	.717	4	.018
	5.00	.230	5	.200*	.884	5	.329
	6.00	.187	5	.200*	.951	5	.744
VRBroom HD	1.00	.221	4	.	.968	4	.827
	2.00	.343	5	.056	.769	5	.044
	3.00	.166	5	.200*	.989	5	.975
	4.00	.288	4	.	.822	4	.147
	5.00	.169	5	.200*	.970	5	.877
	6.00	.220	5	.200*	.936	5	.637
Normal HD	1.00	.383	4	.	.783	4	.075
	2.00	.193	5	.200*	.936	5	.635
	3.00	.283	5	.200*	.855	5	.210
	4.00	.212	4	.	.982	4	.916
	5.00	.347	5	.049	.785	5	.061
	6.00	.312	5	.126	.819	5	.114

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

General Linear Model

Within-Subjects Factors

Measure: Hand_Distance

conditions	Dependent Variable
1	VR_Con
2	VR_Broom
3	Normal_Broom

Between-Subjects Factors

		N
Order	1.00	4
	2.00	5
	3.00	5
	4.00	4
	5.00	5
	6.00	5

Descriptive Statistics

	Order	Mean	Std. Deviation	N
VRCon HD	1.00	620.7143	63.73944	4
	2.00	542.0400	73.23975	5
	3.00	445.8617	63.88075	5
	4.00	451.7032	92.00037	4
	5.00	578.1404	126.33744	5
	6.00	562.4816	141.40225	5

	Total	533.2960	110.43686	28
VRBroom HD	1.00	674.2586	61.38556	4
	2.00	582.3185	71.84004	5
	3.00	420.4057	79.08454	5
	4.00	441.3508	83.67130	4
	5.00	649.2558	115.35600	5
	6.00	632.2618	158.16787	5
	Total	567.2731	136.65037	28
Normal HD	1.00	668.3269	37.76812	4
	2.00	647.9186	83.70703	5
	3.00	559.2362	93.77639	5
	4.00	493.9862	45.71895	4
	5.00	635.8494	81.23748	5
	6.00	603.6879	143.37166	5
	Total	602.9540	100.37748	28

Box's Test of Equality of Covariance Matrices[a]

Box's M	38.192
F	.786
df1	30
df2	960.002
Sig.	.788

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Order
Within Subjects Design: conditions

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
conditions	Pillai's Trace	.542	12.423[b]	2.000	21.000	.000	.542
	Wilks' Lambda	.458	12.423[b]	2.000	21.000	.000	.542
	Hotelling's Trace	1.183	12.423[b]	2.000	21.000	.000	.542
	Roy's Largest Root	1.183	12.423[b]	2.000	21.000	.000	.542
conditions * Order	Pillai's Trace	.572	1.761	10.000	44.000	.097	.286
	Wilks' Lambda	.469	1.932[b]	10.000	42.000	.067	.315
	Hotelling's Trace	1.045	2.090	10.000	40.000	.049	.343
	Roy's Largest Root	.954	4.199[c]	5.000	22.000	.008	.488

a. Design: Intercept + Order

Within Subjects Design: conditions

b. Exact statistic

c. The statistic is an upper bound on F that yields a lower bound on the significance level.

Mauchly's Test of Sphericity[a]

Measure: Hand_Distance

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
conditions	.993	.150	2	.928	.993	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Order

Within Subjects Design: conditions

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Hand_Distance

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Sphericity Assumed	64058.199	2	32029.099	12.742	.000	.367

	Greenhouse-Geisser	64058.199	1.986	32256.703	12.742	.000	.367
	Huynh-Feldt	64058.199	2.000	32029.099	12.742	.000	.367
	Lower-bound	64058.199	1.000	64058.199	12.742	.002	.367
conditions * Order	Sphericity Assumed	54939.420	10	5493.942	2.186	.037	.332
	Greenhouse-Geisser	54939.420	9.929	5532.983	2.186	.037	.332
	Huynh-Feldt	54939.420	10.000	5493.942	2.186	.037	.332
	Lower-bound	54939.420	5.000	10987.884	2.186	.093	.332
Error(conditions)	Sphericity Assumed	110604.506	44	2513.739			
	Greenhouse-Geisser	110604.506	43.690	2531.602			
	Huynh-Feldt	110604.506	44.000	2513.739			
	Lower-bound	110604.506	22.000	5027.478			

Tests of Within-Subjects Contrasts

Measure: Hand_Distance

Source	conditions	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Linear	64044.746	1	64044.746	25.780	.000	.540
	Quadratic	13.453	1	13.453	.005	.943	.000
conditions * Order	Linear	12909.145	5	2581.829	1.039	.420	.191
	Quadratic	42030.276	5	8406.055	3.305	.022	.429
Error(conditions)	Linear	54654.552	22	2484.298			
	Quadratic	55949.954	22	2543.180			

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
VRCon HD	Based on Mean	1.582	5	22	.206
	Based on Median	.955	5	22	.466
	Based on Median and with adjusted df	.955	5	14.938	.475
	Based on trimmed mean	1.586	5	22	.206
VRBroom HD	Based on Mean	2.150	5	22	.097
	Based on Median	.856	5	22	.526

	Based on Median and with adjusted df	.856	5	13.012	.535
	Based on trimmed mean	2.156	5	22	.096
Normal HD	Based on Mean	2.393	5	22	.071
	Based on Median	.527	5	22	.753
	Based on Median and with adjusted df	.527	5	12.235	.752
	Based on trimmed mean	2.167	5	22	.095

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Order

Within Subjects Design: conditions

Tests of Between-Subjects Effects

Measure: Hand_Distance

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	26728195.735	1	26728195.735	1126.009	.000	.981
Order	417761.824	5	83552.365	3.520	.017	.444
Error	522216.353	22	23737.107			

Estimated Marginal Means

1. conditions

Estimates

Measure: Hand_Distance

conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
1	533.490	18.968	494.154	572.827

2	566.642	19.483	526.236	607.048
3	601.501	17.302	565.619	637.382

Pairwise Comparisons

Measure: Hand_Distance

(I) conditions	(J) conditions	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-33.152	13.991	.081	-69.404	3.101
	3	-68.011*	13.395	.000	-102.720	-33.302
2	1	33.152	13.991	.081	-3.101	69.404
	3	-34.859*	13.019	.041	-68.593	-1.125
3	1	68.011*	13.395	.000	33.302	102.720
	2	34.859*	13.019	.041	1.125	68.593

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.542	12.423[a]	2.000	21.000	.000	.542
Wilks' lambda	.458	12.423[a]	2.000	21.000	.000	.542
Hotelling's trace	1.183	12.423[a]	2.000	21.000	.000	.542
Roy's largest root	1.183	12.423[a]	2.000	21.000	.000	.542

Each F tests the multivariate effect of conditions. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. Order

Estimates

Measure: Hand_Distance

Order	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.00	654.433	44.476	562.196	746.670
2.00	590.759	39.780	508.260	673.258
3.00	475.168	39.780	392.669	557.667
4.00	462.347	44.476	370.110	554.584
5.00	621.082	39.780	538.583	703.581
6.00	599.477	39.780	516.978	681.976

Pairwise Comparisons

Measure: Hand_Distance

(I) Order	(J) Order	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1.00	2.00	63.674	59.670	1.000	-132.695	260.043
	3.00	179.265	59.670	.098	-17.103	375.634
	4.00	192.087	62.898	.087	-14.904	399.077
	5.00	33.351	59.670	1.000	-163.017	229.720
	6.00	54.956	59.670	1.000	-141.413	251.325
2.00	1.00	-63.674	59.670	1.000	-260.043	132.695
	3.00	115.591	56.258	.780	-69.547	300.729
	4.00	128.412	59.670	.639	-67.957	324.781
	5.00	-30.323	56.258	1.000	-215.461	154.815
	6.00	-8.718	56.258	1.000	-193.856	176.420
3.00	1.00	-179.265	59.670	.098	-375.634	17.103
	2.00	-115.591	56.258	.780	-300.729	69.547
	4.00	12.821	59.670	1.000	-183.548	209.190
	5.00	-145.914	56.258	.249	-331.052	39.224
	6.00	-124.309	56.258	.568	-309.448	60.829
4.00	1.00	-192.087	62.898	.087	-399.077	14.904
	2.00	-128.412	59.670	.639	-324.781	67.957
	3.00	-12.821	59.670	1.000	-209.190	183.548
	5.00	-158.735	59.670	.214	-355.104	37.634
	6.00	-137.130	59.670	.471	-333.499	59.238
5.00	1.00	-33.351	59.670	1.000	-229.720	163.017

	2.00	30.323	56.258	1.000	-154.815	215.461
	3.00	145.914	56.258	.249	-39.224	331.052
	4.00	158.735	59.670	.214	-37.634	355.104
	6.00	21.605	56.258	1.000	-163.534	206.743
6.00	1.00	-54.956	59.670	1.000	-251.325	141.413
	2.00	8.718	56.258	1.000	-176.420	193.856
	3.00	124.309	56.258	.568	-60.829	309.448
	4.00	137.130	59.670	.471	-59.238	333.499
	5.00	-21.605	56.258	1.000	-206.743	163.534

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: Hand_Distance

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	139253.941	5	27850.788	3.520	.017	.444
Error	174072.118	22	7912.369			

The F tests the effect of Order. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

3. Order * conditions

Measure: Hand_Distance

				95% Confidence Interval	
Order	conditions	Mean	Std. Error	Lower Bound	Upper Bound
1.00	1	620.714	49.907	517.213	724.215
	2	674.259	51.264	567.943	780.574
	3	668.327	45.524	573.916	762.738
2.00	1	542.040	44.638	449.466	634.614
	2	582.319	45.852	487.227	677.410
	3	647.919	40.718	563.475	732.362
3.00	1	445.862	44.638	353.288	538.436
	2	420.406	45.852	325.314	515.497
	3	559.236	40.718	474.793	643.680
4.00	1	451.703	49.907	348.202	555.204

	2	441.351	51.264	335.035	547.666
	3	493.986	45.524	399.575	588.397
5.00	1	578.140	44.638	485.566	670.714
	2	649.256	45.852	554.165	744.347
	3	635.849	40.718	551.406	720.293
6.00	1	562.482	44.638	469.908	655.056
	2	632.262	45.852	537.171	727.353
	3	603.688	40.718	519.244	688.131

Post Hoc Tests

Order

Multiple Comparisons

Measure: Hand_Distance

	(I) Order	(J) Order	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1.00	2.00	63.6742	59.67048	.889	-122.2075	249.5559
		3.00	179.2654	59.67048	.063	-6.6164	365.1471
		4.00	192.0865	62.89821	.057	-3.8500	388.0231
		5.00	33.3514	59.67048	.993	-152.5303	219.2331
		6.00	54.9561	59.67048	.937	-130.9256	240.8379
	2.00	1.00	-63.6742	59.67048	.889	-249.5559	122.2075
		3.00	115.5912	56.25787	.346	-59.6598	290.8421
		4.00	128.4123	59.67048	.299	-57.4694	314.2940
		5.00	-30.3228	56.25787	.994	-205.5738	144.9281
		6.00	-8.7181	56.25787	1.000	-183.9691	166.5329
	3.00	1.00	-179.2654	59.67048	.063	-365.1471	6.6164
		2.00	-115.5912	56.25787	.346	-290.8421	59.6598

		4.00	12.8212	59.67048	1.000	-173.0606	198.7029
		5.00	-145.9140	56.25787	.141	-321.1650	29.3370
		6.00	-124.3092	56.25787	.273	-299.5602	50.9417
	4.00	1.00	-192.0865	62.89821	.057	-388.0231	3.8500
		2.00	-128.4123	59.67048	.299	-314.2940	57.4694
		3.00	-12.8212	59.67048	1.000	-198.7029	173.0606
		5.00	-158.7352	59.67048	.124	-344.6169	27.1466
		6.00	-137.1304	59.67048	.237	-323.0121	48.7513
	5.00	1.00	-33.3514	59.67048	.993	-219.2331	152.5303
		2.00	30.3228	56.25787	.994	-144.9281	205.5738
		3.00	145.9140	56.25787	.141	-29.3370	321.1650
		4.00	158.7352	59.67048	.124	-27.1466	344.6169
		6.00	21.6048	56.25787	.999	-153.6462	196.8557
	6.00	1.00	-54.9561	59.67048	.937	-240.8379	130.9256
		2.00	8.7181	56.25787	1.000	-166.5329	183.9691
		3.00	124.3092	56.25787	.273	-50.9417	299.5602
		4.00	137.1304	59.67048	.237	-48.7513	323.0121
		5.00	-21.6048	56.25787	.999	-196.8557	153.6462
Games-Howell	1.00	2.00	63.6742	34.28995	.494	-68.2563	195.6048
		3.00	179.2654*	38.60224	.024	27.2297	331.3011
		4.00	192.0865*	33.87345	.013	51.3458	332.8272
		5.00	33.3514	50.76728	.980	-178.7605	245.4633
		6.00	54.9561	65.24987	.945	-229.7933	339.7055
	2.00	1.00	-63.6742	34.28995	.494	-195.6048	68.2563
		3.00	115.5912	43.85334	.195	-45.7305	276.9128
		4.00	128.4123	39.75416	.100	-22.9380	279.7626
		5.00	-30.3228	54.86620	.991	-242.2161	181.5704
		6.00	-8.7181	68.48743	1.000	-288.3246	270.8884
	3.00	1.00	-179.2654*	38.60224	.024	-331.3011	-27.2297
		2.00	-115.5912	43.85334	.195	-276.9128	45.7305
		4.00	12.8212	43.52844	1.000	-152.1986	177.8409
		5.00	-145.9140	57.65962	.229	-362.4119	70.5839
		6.00	-124.3092	70.74504	.546	-403.8638	155.2453
	4.00	1.00	-192.0865*	33.87345	.013	-332.8272	-51.3458
		2.00	-128.4123	39.75416	.100	-279.7626	22.9380
		3.00	-12.8212	43.52844	1.000	-177.8409	152.1986
		5.00	-158.7352	54.60686	.158	-372.8184	55.3481
		6.00	-137.1304	68.27985	.437	-418.2064	143.9456

	5.00	1.00	-33.3514	50.76728	.980	-245.4633	178.7605
		2.00	30.3228	54.86620	.991	-181.5704	242.2161
		3.00	145.9140	57.65962	.229	-70.5839	362.4119
		4.00	158.7352	54.60686	.158	-55.3481	372.8184
		6.00	21.6048	78.05155	1.000	-269.1575	312.3670
	6.00	1.00	-54.9561	65.24987	.945	-339.7055	229.7933
		2.00	8.7181	68.48743	1.000	-270.8884	288.3246
		3.00	124.3092	70.74504	.546	-155.2453	403.8638
		4.00	137.1304	68.27985	.437	-143.9456	418.2064
		5.00	-21.6048	78.05155	1.000	-312.3670	269.1575

Based on observed means.

The error term is Mean Square(Error) = 7912.369.

*. The mean difference is significant at the .05 level.

Homogeneous Subsets

Hand_Distance

			Subset	
	Order	N	1	2
Tukey HSD[a,b,c]	4.00	4	462.3467	
	3.00	5	475.1679	475.1679
	2.00	5	590.7590	590.7590
	6.00	5	599.4771	599.4771
	5.00	5	621.0819	621.0819
	1.00	4		654.4332
	Sig.		.113	.056

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square(Error) = 7912.369.

a. Uses Harmonic Mean Sample Size = 4.615.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

c. Alpha = .05.

3 Conditions vs 2 Genders (outliers included)

Two-way Mixed ANOVA

Explore

Gender

Case Processing Summary

		Cases					
		Valid		Missing		Total	
	Gender	N	Percent	N	Percent	N	Percent
VRCon HD	F	12	100.0%	0	0.0%	12	100.0%
	M	18	100.0%	0	0.0%	18	100.0%
VRBroom HD	F	12	100.0%	0	0.0%	12	100.0%
	M	18	100.0%	0	0.0%	18	100.0%
Normal HD	F	12	100.0%	0	0.0%	12	100.0%
	M	18	100.0%	0	0.0%	18	100.0%

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Gender	Statistic	df	Sig.	Statistic	df	Sig.
VRCon HD	F	.145	12	.200*	.976	12	.964
	M	.147	18	.200*	.969	18	.778
VRBroom HD	F	.146	12	.200*	.942	12	.521
	M	.096	18	.200*	.963	18	.670
Normal HD	F	.198	12	.200*	.924	12	.325
	M	.258	18	.002	.843	18	.006

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

General Linear Model

Within-Subjects Factors

Measure: Hand_Distance

conditions	Dependent Variable
1	VR_Con
2	VR_Broom
3	Normal_Broom

Between-Subjects Factors

		N
Gender	F	12
	M	18

Descriptive Statistics

	Gender	Mean	Std. Deviation	N
VRCon HD	F	489.0094	110.47325	12
	M	540.3393	122.21791	18
	Total	519.8073	118.48915	30
VRBroom HD	F	525.9772	116.07852	12
	M	589.3630	147.28672	18
	Total	564.0087	137.20507	30
Normal HD	F	566.8520	126.78038	12
	M	618.0835	92.80541	18
	Total	597.5909	108.61541	30

Box's Test of Equality of Covariance Matrices[a]

Box's M	12.383
F	1.806
df1	6
df2	3706.946
Sig.	.094

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Gender
Within Subjects Design: conditions

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
conditions	Pillai's Trace	.421	9.823[b]	2.000	27.000	.001	.421
	Wilks' Lambda	.579	9.823[b]	2.000	27.000	.001	.421
	Hotelling's Trace	.728	9.823[b]	2.000	27.000	.001	.421
	Roy's Largest Root	.728	9.823[b]	2.000	27.000	.001	.421
conditions * Gender	Pillai's Trace	.006	.085[b]	2.000	27.000	.919	.006
	Wilks' Lambda	.994	.085[b]	2.000	27.000	.919	.006
	Hotelling's Trace	.006	.085[b]	2.000	27.000	.919	.006
	Roy's Largest Root	.006	.085[b]	2.000	27.000	.919	.006

a. Design: Intercept + Gender
Within Subjects Design: conditions
b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: Hand_Distance

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
conditions	.983	.459	2	.795	.983	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Gender

Within Subjects Design: conditions

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Hand_Distance

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Sphericity Assumed	87468.772	2	43734.386	10.477	.000	.272
	Greenhouse-Geisser	87468.772	1.967	44471.237	10.477	.000	.272
	Huynh-Feldt	87468.772	2.000	43734.386	10.477	.000	.272
	Lower-bound	87468.772	1.000	87468.772	10.477	.003	.272
conditions * Gender	Sphericity Assumed	703.385	2	351.692	.084	.919	.003
	Greenhouse-Geisser	703.385	1.967	357.618	.084	.917	.003
	Huynh-Feldt	703.385	2.000	351.692	.084	.919	.003
	Lower-bound	703.385	1.000	703.385	.084	.774	.003
Error(conditions)	Sphericity Assumed	233764.948	56	4174.374			
	Greenhouse-Geisser	233764.948	55.072	4244.705			
	Huynh-Feldt	233764.948	56.000	4174.374			
	Lower-bound	233764.948	28.000	8348.748			

Tests of Within-Subjects Contrasts

Measure: Hand_Distance

Source	conditions	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Linear	87146.168	1	87146.168	20.289	.000	.420
	Quadratic	322.604	1	322.604	.080	.780	.003
conditions * Gender	Linear	.035	1	.035	.000	.998	.000
	Quadratic	703.350	1	703.350	.174	.680	.006
Error(conditions)	Linear	120265.706	28	4295.204			
	Quadratic	113499.242	28	4053.544			

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
VRCon HD	Based on Mean	.898	1	28	.351
	Based on Median	.574	1	28	.455
	Based on Median and with adjusted df	.574	1	27.990	.455
	Based on trimmed mean	.871	1	28	.359
VRBroom HD	Based on Mean	.585	1	28	.451
	Based on Median	.597	1	28	.446
	Based on Median and with adjusted df	.597	1	25.642	.447
	Based on trimmed mean	.604	1	28	.443
Normal HD	Based on Mean	1.675	1	28	.206
	Based on Median	.611	1	28	.441
	Based on Median and with adjusted df	.611	1	27.578	.441
	Based on trimmed mean	1.620	1	28	.214

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Gender

Within Subjects Design: conditions

Tests of Between-Subjects Effects

Measure: Hand_Distance

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	26607357.151	1	26607357.151	749.018	.000	.964
Gender	66092.353	1	66092.353	1.861	.183	.062
Error	994643.617	28	35522.986			

Estimated Marginal Means

1. conditions

Estimates

Measure: Hand_Distance

conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	514.674	21.940	469.732	559.617
2	557.670	25.320	505.803	609.537
3	592.468	20.021	551.457	633.478

Pairwise Comparisons

Measure: Hand_Distance

(I) conditions	(J) conditions	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-42.996	17.817	.068	-88.367	2.375
	3	-77.793*	17.271	.000	-121.773	-33.814
2	1	42.996	17.817	.068	-2.375	88.367
	3	-34.798	15.935	.113	-75.376	5.780
3	1	77.793*	17.271	.000	33.814	121.773
	2	34.798	15.935	.113	-5.780	75.376

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.421	9.823[a]	2.000	27.000	.001	.421
Wilks' lambda	.579	9.823[a]	2.000	27.000	.001	.421
Hotelling's trace	.728	9.823[a]	2.000	27.000	.001	.421
Roy's largest root	.728	9.823[a]	2.000	27.000	.001	.421

Each F tests the multivariate effect of conditions. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. Gender

Estimates

Measure: Hand_Distance

Gender	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
F	527.280	31.413	462.934	591.625
M	582.595	25.648	530.057	635.133

Pairwise Comparisons

Measure: Hand_Distance

(I) Gender	(J) Gender	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
F	M	-55.316	40.553	.183	-138.386	27.754
M	F	55.316	40.553	.183	-27.754	138.386

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: Hand_Distance

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	22030.784	1	22030.784	1.861	.183	.062
Error	331547.872	28	11840.995			

The F tests the effect of Gender. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

3. Gender * conditions

Measure: Hand_Distance

Gender	conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
F	1	489.009	33.990	419.385	558.634
	2	525.977	39.226	445.626	606.329
	3	566.852	31.016	503.319	630.385
M	1	540.339	27.752	483.491	597.188
	2	589.363	32.028	523.756	654.970
	3	618.084	25.324	566.209	669.958

3 Conditions vs 2 Genders (outliers removed)

Two-way Mixed ANOVA

Explore

Gender

Case Processing Summary

	Gender	Valid N	Valid Percent	Missing N	Missing Percent	Total N	Total Percent
VRCon HD	F	11	100.0%	0	0.0%	11	100.0%
	M	18	100.0%	0	0.0%	18	100.0%
VRBroom HD	F	11	100.0%	0	0.0%	11	100.0%
	M	18	100.0%	0	0.0%	18	100.0%
Normal HD	F	11	100.0%	0	0.0%	11	100.0%
	M	18	100.0%	0	0.0%	18	100.0%

Tests of Normality

	Gender	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
VRCon HD	F	.144	11	.200*	.978	11	.957
	M	.147	18	.200*	.969	18	.778
VRBroom HD	F	.154	11	.200*	.920	11	.318
	M	.096	18	.200*	.963	18	.670
Normal HD	F	.194	11	.200*	.939	11	.507
	M	.258	18	.002	.843	18	.006

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

General Linear Model

Within-Subjects Factors

Measure: Hand_Distance

conditions	Dependent Variable
1	VR_Con
2	VR_Broom
3	Normal_Broom

Between-Subjects Factors

		N
Gender	F	11
	M	18

Descriptive Statistics

	Gender	Mean	Std. Deviation	N
VRCon HD	F	468.5402	88.84901	11
	M	540.3393	122.21791	18
	Total	513.1052	114.65338	29
VRBroom HD	F	507.9342	102.58838	11
	M	589.3630	147.28672	18
	Total	558.4762	136.18560	29
Normal HD	F	555.6704	126.61054	11
	M	618.0835	92.80541	18
	Total	594.4096	109.10624	29

Box's Test of Equality of Covariance Matrices[a]

Box's M	16.336
F	2.358
df1	6
df2	2919.174
Sig.	.028

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Gender
Within Subjects Design: conditions

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
conditions	Pillai's Trace	.450	10.640[b]	2.000	26.000	.000	.450
	Wilks' Lambda	.550	10.640[b]	2.000	26.000	.000	.450
	Hotelling's Trace	.818	10.640[b]	2.000	26.000	.000	.450
	Roy's Largest Root	.818	10.640[b]	2.000	26.000	.000	.450
conditions * Gender	Pillai's Trace	.012	.162[b]	2.000	26.000	.851	.012
	Wilks' Lambda	.988	.162[b]	2.000	26.000	.851	.012
	Hotelling's Trace	.012	.162[b]	2.000	26.000	.851	.012
	Roy's Largest Root	.012	.162[b]	2.000	26.000	.851	.012

a. Design: Intercept + Gender

Within Subjects Design: conditions

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: Hand_Distance

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
conditions	.979	.544	2	.762	.980	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Gender

Within Subjects Design: conditions

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Hand_Distance

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Sphericity Assumed	92961.928	2	46480.964	11.026	.000	.290
	Greenhouse-Geisser	92961.928	1.959	47443.197	11.026	.000	.290
	Huynh-Feldt	92961.928	2.000	46480.964	11.026	.000	.290
	Lower-bound	92961.928	1.000	92961.928	11.026	.003	.290
conditions * Gender	Sphericity Assumed	1234.476	2	617.238	.146	.864	.005
	Greenhouse-Geisser	1234.476	1.959	630.016	.146	.860	.005
	Huynh-Feldt	1234.476	2.000	617.238	.146	.864	.005
	Lower-bound	1234.476	1.000	1234.476	.146	.705	.005
Error(conditions)	Sphericity Assumed	227639.041	54	4215.538			
	Greenhouse-Geisser	227639.041	52.905	4302.806			
	Huynh-Feldt	227639.041	54.000	4215.538			
	Lower-bound	227639.041	27.000	8431.076			

Tests of Within-Subjects Contrasts

Measure: Hand_Distance

Source	conditions	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Linear	92799.131	1	92799.131	21.869	.000	.448
	Quadratic	162.797	1	162.797	.039	.845	.001
conditions * Gender	Linear	300.741	1	300.741	.071	.792	.003
	Quadratic	933.735	1	933.735	.223	.641	.008
Error(conditions)	Linear	114572.583	27	4243.429			
	Quadratic	113066.458	27	4187.647			

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
VRCon HD	Based on Mean	2.407	1	27	.132
	Based on Median	1.633	1	27	.212
	Based on Median and with adjusted df	1.633	1	26.010	.213
	Based on trimmed mean	2.405	1	27	.133
VRBroom HD	Based on Mean	1.363	1	27	.253
	Based on Median	1.396	1	27	.248
	Based on Median and with adjusted df	1.396	1	23.336	.249
	Based on trimmed mean	1.367	1	27	.253
Normal HD	Based on Mean	1.549	1	27	.224
	Based on Median	.647	1	27	.428
	Based on Median and with adjusted df	.647	1	26.630	.428
	Based on trimmed mean	1.553	1	27	.223

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Gender

Within Subjects Design: conditions

Tests of Between-Subjects Effects

Measure: Hand_Distance

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	24483599.372	1	24483599.372	746.125	.000	.965
Gender	105829.935	1	105829.935	3.225	.084	.107
Error	885986.953	27	32814.332			

Estimated Marginal Means

1. conditions

Estimates

Measure: Hand_Distance

conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
1	504.440	21.247	460.845	548.035
2	548.649	25.355	496.625	600.672
3	586.877	20.395	545.030	628.724

Pairwise Comparisons

Measure: Hand_Distance

(I) conditions	(J) conditions	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-44.209	18.604	.075	-91.695	3.278
	3	-82.437*	17.628	.000	-127.433	-37.442
2	1	44.209	18.604	.075	-3.278	91.695
	3	-38.228	16.409	.083	-80.113	3.656
3	1	82.437*	17.628	.000	37.442	127.433
	2	38.228	16.409	.083	-3.656	80.113

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.450	10.640[a]	2.000	26.000	.000	.450
Wilks' lambda	.550	10.640[a]	2.000	26.000	.000	.450
Hotelling's trace	.818	10.640[a]	2.000	26.000	.000	.450
Roy's largest root	.818	10.640[a]	2.000	26.000	.000	.450

Each F tests the multivariate effect of conditions. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

2. Gender

Estimates

Measure: Hand_Distance

Gender	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
F	510.715	31.534	446.013	575.417
M	582.595	24.651	532.016	633.175

Pairwise Comparisons

Measure: Hand_Distance

(I) Gender	(J) Gender	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
F	M	-71.880	40.026	.084	-154.006	10.245
M	F	71.880	40.026	.084	-10.245	154.006

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: Hand_Distance

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	35276.645	1	35276.645	3.225	.084	.107
Error	295328.984	27	10938.111			

The F tests the effect of Gender. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

3. Gender * conditions

Measure: Hand_Distance

Gender	conditions	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
F	1	468.540	33.478	399.849	537.232
	2	507.934	39.951	425.962	589.906
	3	555.670	32.136	489.733	621.608
M	1	540.339	26.171	486.641	594.038
	2	589.363	31.231	525.282	653.444
	3	618.084	25.122	566.538	669.630

3 Conditions vs 2 VR Experience

Two-Way Mixed ANOVA

Explore

VR_Exp

Case Processing Summary

	VR_Exp	Cases					
		Valid		Missing		Total	
		N	Percent	N	Percent	N	Percent
VRCon HD	N	15	100.0%	0	0.0%	15	100.0%
	Y	15	100.0%	0	0.0%	15	100.0%
VRBroom HD	N	15	100.0%	0	0.0%	15	100.0%
	Y	15	100.0%	0	0.0%	15	100.0%
Normal HD	N	15	100.0%	0	0.0%	15	100.0%
	Y	15	100.0%	0	0.0%	15	100.0%

Tests of Normality

	VR_Exp	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
VRCon HD	N	.113	15	.200*	.971	15	.879
	Y	.130	15	.200*	.956	15	.622
VRBroom HD	N	.151	15	.200*	.922	15	.206
	Y	.106	15	.200*	.978	15	.958
Normal HD	N	.226	15	.037	.857	15	.022
	Y	.178	15	.200*	.901	15	.100

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

General Linear Model

Within-Subjects Factors

Measure: Hand_Distance

conditions	Dependent Variable
1	VR_Con
2	VR_Broom
3	Normal_Broom

Between-Subjects Factors

		N
VR_Exp	N	15
	Y	15

Descriptive Statistics

	VR_Exp	Mean	Std. Deviation	N
VRCon HD	N	540.4912	116.80404	15
	Y	499.1235	120.50829	15
	Total	519.8073	118.48915	30
VRBroom HD	N	573.4835	154.53831	15
	Y	554.5339	122.15016	15
	Total	564.0087	137.20507	30
Normal HD	N	601.9302	121.62059	15
	Y	593.2516	98.00695	15
	Total	597.5909	108.61541	30

Box's Test of Equality of Covariance Matrices[a]

Box's M	7.932
F	1.167
df1	6
df2	5680.302
Sig.	.321

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + VR_Exp
Within Subjects Design: conditions

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
conditions	Pillai's Trace	.439	10.557[b]	2.000	27.000	.000	.439
	Wilks' Lambda	.561	10.557[b]	2.000	27.000	.000	.439
	Hotelling's Trace	.782	10.557[b]	2.000	27.000	.000	.439
	Roy's Largest Root	.782	10.557[b]	2.000	27.000	.000	.439
conditions * VR_Exp	Pillai's Trace	.034	.470[b]	2.000	27.000	.630	.034
	Wilks' Lambda	.966	.470[b]	2.000	27.000	.630	.034
	Hotelling's Trace	.035	.470[b]	2.000	27.000	.630	.034
	Roy's Largest Root	.035	.470[b]	2.000	27.000	.630	.034

a. Design: Intercept + VR_Exp

Within Subjects Design: conditions

b. Exact statistic

Mauchly's Test of Sphericity[a]

Measure: Hand_Distance

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
conditions	.985	.400	2	.819	.985	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + VR_Exp

Within Subjects Design: conditions

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Hand_Distance

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Sphericity Assumed	91318.137	2	45659.068	11.104	.000	.284
	Greenhouse-Geisser	91318.137	1.971	46331.217	11.104	.000	.284
	Huynh-Feldt	91318.137	2.000	45659.068	11.104	.000	.284
	Lower-bound	91318.137	1.000	91318.137	11.104	.002	.284
conditions * VR_Exp	Sphericity Assumed	4191.609	2	2095.805	.510	.603	.018
	Greenhouse-Geisser	4191.609	1.971	2126.657	.510	.601	.018
	Huynh-Feldt	4191.609	2.000	2095.805	.510	.603	.018
	Lower-bound	4191.609	1.000	4191.609	.510	.481	.018
Error(conditions)	Sphericity Assumed	230276.723	56	4112.084			
	Greenhouse-Geisser	230276.723	55.188	4172.618			
	Huynh-Feldt	230276.723	56.000	4112.084			
	Lower-bound	230276.723	28.000	8224.169			

Tests of Within-Subjects Contrasts

Measure: Hand_Distance

Source	conditions	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
conditions	Linear	90754.308	1	90754.308	21.857	.000	.438
	Quadratic	563.829	1	563.829	.138	.713	.005
conditions * VR_Exp	Linear	4007.168	1	4007.168	.965	.334	.033
	Quadratic	184.441	1	184.441	.045	.833	.002
Error(conditions)	Linear	116258.572	28	4152.092			
	Quadratic	114018.151	28	4072.077			

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
VRCon HD	Based on Mean	.009	1	28	.926
	Based on Median	.001	1	28	.975
	Based on Median and with adjusted df	.001	1	27.755	.975
	Based on trimmed mean	.006	1	28	.936
VRBroom HD	Based on Mean	2.316	1	28	.139
	Based on Median	2.192	1	28	.150
	Based on Median and with adjusted df	2.192	1	27.879	.150
	Based on trimmed mean	2.345	1	28	.137
Normal HD	Based on Mean	.648	1	28	.428
	Based on Median	.149	1	28	.702
	Based on Median and with adjusted df	.149	1	23.009	.703
	Based on trimmed mean	.469	1	28	.499

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + VR_Exp

Within Subjects Design: conditions

Tests of Between-Subjects Effects

Measure: Hand_Distance

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	28271292.802	1	28271292.802	754.739	.000	.964
VR_Exp	11901.113	1	11901.113	.318	.577	.011
Error	1048834.857	28	37458.388			

Estimated Marginal Means

1. VR_Exp

Estimates

Measure: Hand_Distance

VR_Exp	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
N	571.968	28.851	512.869	631.068
Y	548.970	28.851	489.870	608.069

Pairwise Comparisons

Measure: Hand_Distance

(I) VR_Exp	(J) VR_Exp	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
N	Y	22.999	40.802	.577	-60.581	106.578
Y	N	-22.999	40.802	.577	-106.578	60.581

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Measure: Hand_Distance

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	3967.038	1	3967.038	.318	.577	.011
Error	349611.619	28	12486.129			

The F tests the effect of VR_Exp. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. conditions

Estimates

Measure: Hand_Distance

conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	519.807	21.666	475.426	564.189
2	564.009	25.431	511.917	616.101
3	597.591	20.165	556.285	638.896

Pairwise Comparisons

Measure: Hand_Distance

(I) conditions	(J) conditions	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-44.201	17.364	.050	-88.419	.016
	3	-77.784*	16.637	.000	-120.150	-35.417
2	1	44.201	17.364	.050	-.016	88.419
	3	-33.582	15.623	.121	-73.367	6.202
3	1	77.784*	16.637	.000	35.417	120.150
	2	33.582	15.623	.121	-6.202	73.367

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.439	10.557[a]	2.000	27.000	.000	.439
Wilks' lambda	.561	10.557[a]	2.000	27.000	.000	.439
Hotelling's trace	.782	10.557[a]	2.000	27.000	.000	.439
Roy's largest root	.782	10.557[a]	2.000	27.000	.000	.439

Each F tests the multivariate effect of conditions. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic

3. VR_Exp * conditions

Measure: Hand_Distance

VR_Exp	conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
N	1	540.491	30.641	477.727	603.256
	2	573.483	35.964	499.814	647.153
	3	601.930	28.517	543.515	660.345
Y	1	499.123	30.641	436.359	561.888
	2	554.534	35.964	480.865	628.203
	3	593.252	28.517	534.837	651.666

3 Conditions

One-way ANOVA

Explore

group

Case Processing Summary

		Cases					
		Valid		Missing		Total	
	group	N	Percent	N	Percent	N	Percent
Hand Distance	VRCon	10	100.0%	0	0.0%	10	100.0%
	VRBroom	10	100.0%	0	0.0%	10	100.0%
	Normal	10	100.0%	0	0.0%	10	100.0%

Tests of Normality

	group	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Hand Distance	VRCon	.200	10	.200*	.918	10	.340
	VRBroom	.220	10	.184	.910	10	.279
	Normal	.318	10	.005	.792	10	.012

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Oneway

Descriptives

Hand Distance

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	Upper Bound	Minimum	Maximum
VRCon	10	549.7245	112.73664	35.65046	469.0776	630.3714	304.19	711.78
VRBroom	10	424.9217	73.83352	23.34821	372.1044	477.7390	316.96	524.76
Normal	10	619.7687	111.15842	35.15138	540.2507	699.2866	375.47	711.08
Total	30	531.4716	127.23565	23.22994	483.9611	578.9822	304.19	711.78

Test of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
Hand Distance	Based on Mean	.690	2	27	.510
	Based on Median	.138	2	27	.871
	Based on Median and with adjusted df	.138	2	19.880	.872
	Based on trimmed mean	.575	2	27	.570

ANOVA

Hand Distance

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	194824.201	2	97412.101	9.576	.001
Within Groups	274654.194	27	10172.378		
Total	469478.395	29			

Robust Tests of Equality of Means

Hand Distance

	Statistic[a]	df1	df2	Sig.
Welch	11.501	2	17.214	.001

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Hand Distance

	(I) group	(J) group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tukey HSD	VRCon	VRBroom	124.80279*	45.10516	.026	12.9683	236.6373
		Normal	-70.04417	45.10516	.283	-181.8787	41.7904
	VRBroom	VRCon	-124.80279*	45.10516	.026	-236.6373	-12.9683
		Normal	-194.84696*	45.10516	.001	-306.6815	-83.0124
	Normal	VRCon	70.04417	45.10516	.283	-41.7904	181.8787
		VRBroom	194.84696*	45.10516	.001	83.0124	306.6815
Games-Howell	VRCon	VRBroom	124.80279*	42.61565	.026	14.5031	235.1025
		Normal	-70.04417	50.06570	.362	-197.8222	57.7339
	VRBroom	VRCon	-124.80279*	42.61565	.026	-235.1025	-14.5031
		Normal	-194.84696*	42.19903	.001	-303.9780	-85.7159
	Normal	VRCon	70.04417	50.06570	.362	-57.7339	197.8222
		VRBroom	194.84696*	42.19903	.001	85.7159	303.9780

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

Hand Distance

	group	N	Subset for alpha = 0.05	
			1	2
Tukey HSD[a]	VRBroom	10	424.9217	
	VRCon	10		549.7245
	Normal	10		619.7687
	Sig.		1.000	.283

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Univariate Analysis of Variance

Between-Subjects Factors

		Value Label	N
group	1	VRCon	10
	2	VRBroom	10
	3	Normal	10

Tests of Between-Subjects Effects

Dependent Variable: Hand Distance

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	194824.201[a]	2	97412.101	9.576	.001	.415
Intercept	8473862.560	1	8473862.560	833.027	.000	.969
group	194824.201	2	97412.101	9.576	.001	.415
Error	274654.194	27	10172.378			
Total	8943340.955	30				
Corrected Total	469478.395	29				

a. R Squared = .415 (Adjusted R Squared = .372)