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A Study of Human Balance and Coordination Using a Head Mounted Display

This paper investigates the hypothesis that men and women perform differently in virtual environments in terms of balance and coordination during surprise events. It reports on an experiment in human subject balance and coordination using an HTC Vive head-mounted display (HMD) to create a virtual environment. For the experiment, 30 male and 30 female subjects of college age were asked to navigate along a clear path in a virtual world using a controller with their dominant hand and asked to balance a virtual ball on a virtual plate using the other controller in the nondominant hand. The test subjects moved along a clearly marked path, with three surprise obstacles occurring: a large rock landing near the path, an explosion near the path, and a flock of birds coming across the path. Data included six degrees-of-freedom (DOF) trajectories for the head and both hands, as well as data gathered by the computer system on ball location and velocity, plate location and velocity, and ball status. Likert scale questionnaires were answered by the test subjects relative to video game experience, sense of presence, and ease of managing the ball movement. Statistics showed that the male students dropped the ball less frequently at $p = 0.0254$ and $p = 0.0036$. In contrast, female students were aware of their performance with correlation levels of 0.632 and 0.588. [DOI: 10.1115/1.4050788]

Keywords: virtual reality, virtual environments, balance and coordination, human computer interfaces/interactions, virtual and augmented reality environments

1 Introduction

Virtual reality (VR) is not a new technology; the use of stereoscopic vision for the generation of virtual environments has existed for about four decades. There are studies to improve VR technology, such as the cave automatic virtual environments, holograms, and head-mounted displays (HMDs). These technologies have made great progress through development of both software and hardware. Considering application areas, there have been several studies to adapt VR to entertainment and for training in different disciplines such as manufacture [1], emergency reaction situations [2], medicine [3], and undergraduate and graduate learning methods [4]. However, there is a significant lack of research for human reaction and behavior while human subjects are in a virtual environment. There are few studies on how VR stimuli work on human beings, if there are similitudes or differences for reaction by men and women, or if the subjects follow a determined pattern with their body under given stimulus. Although this research was published at the CIE 2020 conference [5], there is otherwise a lack of published research in the analysis of human behavior related to balance and coordination when immersed in a virtual environment, and this fact provides motivation for this study.

A concept that is shared in all VR systems is the presence in a virtual environment. The meaning of this concept is related to *presence* with respect to the real-world experiences, and how deeply involved the user feels in the virtual environment [6]. Usoh et al. completed an investigation in which the most common method to analyze the presence in a virtual environment is by giving a questionnaire to the tested subjects, but they consider that it is necessary to generate a like real-life experience to verify the performance of the virtual environment with respect to presence [6]. Also, Slater et al. mention in an investigation with a tri-dimensional chess experiment, how the self-perception in the virtual environment is important. With this approach they define the virtual body, which is both part of the perceived environment, and represents the being that is doing the perceiving [7]. Presence in virtual environments is an important concept to consider, and it requires one to include the design of the virtual environment and how it is evaluated (e.g., questionnaires, a comparison between real-life and VR experiments, or both).

This paper investigates the difference between females and males in terms of coordination and balance in a virtual environment during surprise events. The motivation for this work is to better understand balance and coordination of human subjects in very dangerous environments such as military operations which is not only important but crucial. All the experiments are conducted with a HMD, which is the HTC Vive model. The purpose of this research effort is to measure and compare the human response to stimuli in a virtual environment, more specifically the dominant and nondominant hand trajectories are measured with time as the subject balances an object while advancing along a virtual trail where

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unknown obstacles suddenly appear in the test subject's way. The overall objective is to measure and compare trajectories from male and female subjects, to learn from human balance response, and with this information understand how humans respond to virtual environment stimuli, by using the HTC Vive. This knowledge has implications with regard to the presence in virtual environments and can be confirmed within the experiment with a survey. So, the principle focus for this research is that it is possible to differentiate male and female subjects when they are balancing an object while they go on a virtual environment trail with obstacles using a statistical trajectory analysis, and a survey to confirm the presence is also used. The main contribution of this research is to show there are differences between male and female subjects when they are balancing an object while they go through a virtual environment trail with obstacles using a statistical trajectory analysis.

This paper is organized by sections. Section 1 explains the problem, gives a background, and sets the objectives. Section 2 contains a literature review, and the experimental methods are provided n Section. 3. In Sec. 4, the data are examined. For Sec. 5, the data from Sec. 4 are analyzed and discussed. This is followed by statistical analysis in Sec. 6, and for Sec. 7, the conclusions from the experiment are outlined.

2 Review of the Literature

Virtual Environments are computer simulations, which create a world that appears to our senses in much the same way that we perceive the real or "physical" world [8]. This virtual reality experience provides synthetic or artificial stimuli to one or more of the user's senses. Normally the most common substitution is the visual stimuli, and commonly supported by the aural (hearing) stimuli. On a second level, it is also common to use skin-sensation and force feedback (with special instruments) and this is referred to as haptic sense. Some of the less frequently used stimuli are vestibular (balance), olfaction (smell), and gustation (taste). It is important to consider that all the senses could be recreated with virtual stimuli, but some are harder to recreate than others. Also, it is important to consider the importance of the specific sense at the moment to recreate the stimuli for the different senses [8].

For the HMD, the technologies to reproduce the virtual reality environment with all its respective stimuli are reliant on the following technologies [9]:

(1) Real-time 3D computer graphics
(2) Wide-angle stereoscopic displays
(3) Viewer (head) tracking
(4) Hand and gesture tracking
(5) Binaural sound
(6) Haptic feedback
(7) Voice input/output

From these technologies, the most relevant are the *real-time 3D computer graphics, wide-angle stereoscopic displays, viewer (head) tracking*, which are mandatory, the *hand tracking and the binaural sound* are desirable, and the *haptic feedback* and *voice input/output* are technologies which are still in development and are not fundamental [9]. Thanks to the advance in technology, it is possible to create virtual environments where the user can be immersed in them with all the possible stimuli.

An important area for study is the replication and motion visualization from the human body. This kind of research helps to understand how the body is designed while developing a user interface, where biomechanics scientists can observe and learn with a more dynamic system [10]. Engineers and scientists work on new techniques to develop virtual environments where it is possible to observe and manipulate different components from the human body.

One of the most significant points in biomechanics is the creation and validation of equipment to help humans in physical activities. The use of this special equipment with VR recreates specific activities as with a simulator. These kinds of simulators help to learn new activities with an interactive virtual environment. An example of these activities is swimming. Swimming is an activity that requires several pieces of equipment to simulate the complete environment, and the haptic feedback is more complex than most other activities [11]. Based on the research from Guo, a physical model achieved the goal of improving swimming instruction by using VR technology.

Other important uses where biomechanics and VR work together are rehabilitation training. Ranky et al. designed a virtual reality augmented cycling kit (VRACK). This system is based on a stationary bike, with novel handle bars based on hydraulic pressure sensors and innovative pedals that monitor lower extremity kinetics and kinematics [12]. The subject rides in a virtual environment where the communication system is used to monitor the pedal forces, handlebar forces (both hands are separate), and the heart rate while the subject is immersed in the virtual environment. The VRACK design focuses on helping people with riding asymmetry. By the use of quantitative measures and a dynamic and safe environment, it is possible to help people with rehabilitation [12].

The use of special equipment analysis also involves vehicle handling, including responses to drive a car [13], or how a pilot reacts under different circumstances in a VR flight simulator [14]. This vein of research usually includes mixed evaluation of the human response under virtual environments, considering body and eye tracking, binaural sound, and the controllers (e.g., steering wheel, pedals, joystick).

Oberhauser and Dreyer used equipment that can simulate an Immersive Virtual World to Simulator Research. It is possible to observe in the same figure, fidelity, flexibility and cost change. While the cost and fidelity of the research increase with the advanced equipment, the flexibility for other kinds of projects decreases [13]. This fidelity can also be observed in Eduave and Valencia's research, where the test subjects tried a standard driving simulation using a 27 in. LCD monitor and an immersive driving simulation using the Oculus Rift CV1 virtual reality headset. Even when both experiments were simulations with the driving equipment, there is a significant difference with the use of (2D) and an HMD (3D VR) [15].

An example to consider is the work by Choiri et al. [15], which recreates a stadium with humanoid models to simulate a sprint race, and this simulation has the goal of improving the sprinter's concentration for real competitions. For athletes to achieve good results, athletes must have agility and ability in their area of competition, but they also require strong mental conditioning. Choiri et al. assert that the results of the most successful athletes are influenced by mental factors and the ability of athletes to master their psychological state. One of the elements that affect the psychological state is concentration. Their investigation focuses on creating a training process to help athletes improve their concentration using VR technology.

Human locomotion in virtual environments is important. Walking comparisons between a natural walking experience and the perception of walking motion in a virtual environment is a research area that Nilsson et al. studied [16]. Their investigation considers different field of views and relate it with the walking experience. They found that there exists a range of visualization where the subjects feel more natural with walking locomotion [16].

For training of snowboard activity, Hament et al. located the board with a constant pitch angle, which is a small downward angle similar to that found in a beginner's bunny slope. Their platform had two degrees of freedom, which are roll and yaw, and it was possible to acquire the x value from the software. The yaw and roll values come from accelerometer and gyroscope data from an HTC Vive controller and IR sensors are plotted with the resulting lateral acceleration rendered in the virtual environment [17]. Their data help the understanding of human balance and reaction when the subject is immersed in a virtual environment for snowboarding.

Mallaro et al. investigated a comparison between an HMD and a CAVE, where the responses of humans are studied on an interactive pedestrian simulator [18]. For this experiment, a group of persons has to "physically cross a one-lane virtual road with continuous traffic traveling from left to right." The car traffic pattern has random gaps between cars, and the subjects have to watch and cross to the other side when they think the gap between cars is long enough [18]. Mallaro et al. focuses on two main aspects of road crossing: gap selection and movement timing. The gap selection is divided into factors: number of gaps seen, and the mean gap size taken at the moment to cross. For the movement timing there are four factors: standing position from the roadway, timing of entry, road crossing time, and time to spare [18].

One of the most common uses for VR technology is videogames and entertainment. Lee et al. worked with a data glove, which is compared against the Vive controller. The data glove has bending sensors to examine which finger is bent or not, and the "MPU6050 6-axis sensor" to detect the rotation and movement of the hand [19]. To verify the reaction of the subject, they play a game two times (one with the Vive controller and one with the Data Glove), in which the subject has three different situations (each of 1 min), where they have to use different configurations that they select with the corresponding controller.

Body motion and tracking has several study areas, but the most common applied is related to the optical motion capture technologies. Tobon defines motion capture by its own name: motion is the act of physical changing location, and capture is taken into possession, to seize, or to acquire. Therefore, motion capture is the acquisition of movement [20]. To digitize motion and have the opportunity to analyze it or work with it, there are several techniques, which combine the use of hardware and software to capture movement. Some of the most common motion capture systems are

- Infrared tracking
- Optical motion tracking
- Magnetic motion capture
- Mechanical motion capture

The purpose from the motion capture depends on the use of the device. One purpose can be to animate characters for movies [21]. It can be also be used to better understand the kinematics and biomechanics of the human body, like O'Brien et al. who mentions in an investigation where the joints and body measurements are analyzed [22]. Mortimer et al. investigates how to use the capture of motion to teleoperate the dynamic of user interfaces for robotics [23]. One of the most important areas to use body tracking and motion capture is in VR systems, where the body tracking helps the engineers to design and observe mock ups in a CAVE [24], or it can help a user to select certain activities by the hand gestures while he or she is immersed in a virtual environment [25].

Most of the consoles or devices that use body motion tracking include own integral system. This is the case of the HTC Vive, Oculus Rift, or Kinect. There exist other products in the market, such as Vicon, which is typically used in CAVE systems.

In the case of the HTC Vive (VR system used in this investigation), the system has two lighthouses (tracking base stations), which cover a 360 deg play area, have wireless syncing, fits standard threaded mounting points, and cover a room-scale of $6'6'' \times 5'$ minimal room size to a $16'4''$ maximum between base stations [26]. The headset and controllers have several sensors inside them captured by the lighthouses. These lighthouses are two small cubes that emit light and scan the room vertically and horizontally. Every time the lighthouse emits the light, the sensors from the headset and the controllers are activated and the lighthouse measures the time that it takes to be activated. By calculating the position and orientation of the sensor when it was activated, the lighthouse is able to track the headset and controllers with six degrees of freedom (i.e., x, y, z, roll, pitch, and yaw) [27].

Slater et al. mentions that presence can be defined by the subjects as their sense of "being there," referring to the sensation of realism in a virtual environment [28]. This definition can be extended to the subject's experience in the virtual environment, than the real world where the experiment is taking place, and the user feels immersed in an actual place, instead of just watching images [28]. It is important to consider the perception and stimuli (e.g., aural, haptic, vestibular) from the environment, and the subject's existence in the actual virtual environment (the self-existence in a virtual environment is known with the name of Virtual Body). To feel more immersed in a virtual environment, it is possible to add different feedback actuators, but some are harder to create than others, and it is important to consider which are the most significant for the experiment. In addition, it is also important to consider the laws of physics (e.g., gravity, objects collisions), and the possibility of virtual actuators responding to the subject [28].

Virtual reality presence is an important aspect to consider for VR investigations. Barfield et al. mention that the performance and presence have a strong relationship, and it is necessary to research effects to define how to measure presence and what are its limits [29]. There are few methods to measure presence. The two most common are to create an experiment in VR and real life to compare results, and the other is to use a survey. Comparing experiments would be the most precise method to confirm the depth of the presence. The problem is that it is not always easy to replicate the experiment in real life (VR is very often used to investigate circumstances that are not easy to replicate or that are very dangerous or expensive). The option of the survey is easier to apply, but it does not have the reliability that an experiment comparison would have. For this investigation, a survey is applied to all the participants after the subject is reintegrated to the real environment, and this survey is compared with their paths in the virtual environment to confirm or refute how immersed they were at the moment in the virtual environment.

3 Procedure and Methodology

Virtual environments are a fundamental part of any VR project. What is desired is a virtual environment where the human subject is so immersed in the created environment that he or she believes the environment is real. The equipment used for this project is: a computer to create the program and save the corresponding data, a HMD to show the track and where the subject has visual stimuli, two controllers, one to navigate inside the virtual environment (with the dominant hand) and a second one to balance a virtual ball which is on a plate (with nondominant hand), tracking system, two boxes which track the HMD, the two controllers, and a set of headphones. The HMD, controllers and tracking system are the original system from HTC Vive.

Using the HTC Vive, this project studies human balance and coordination. This investigation measures the balance and coordination of the head, dominant hand, and nondominant hand, by tracking the hand in six degrees-of-freedom (DOF): x, y, z, pitch, roll, and yaw over time. The body tracking from each test subject draws three paths on the six dimensions where data is saved on the memory and is compared at evaluation. The subject navigates by moving the dominant hand on a track, and this track is on an open area which has curves and land relief. A screen capture of the track is shown in Fig. 1. With the nondominant hand, the subject balances a ball which is supported on a plate, as is shown in Fig. 2. Since the goal is to study the balance and coordination of the subject, on the track three unknown obstacles appear with the intent of generating a dramatic and strong stimuli, which are separated based on space along the test subject's path. These stimuli are:

(1) An explosion on the track
(2) Meteors coming from the left side
(3) Bird flock crossing through the path

These unknown obstacles for the subject are shown in Fig. 3, and they have the goal of generating an impact on the subject. It is expected that the subject should react with compensating motion. With this impact, it should be possible to observe whether there is a disturbance to the smooth path from the body tracking data caused by these stimuli. It is possible to observe three paths from

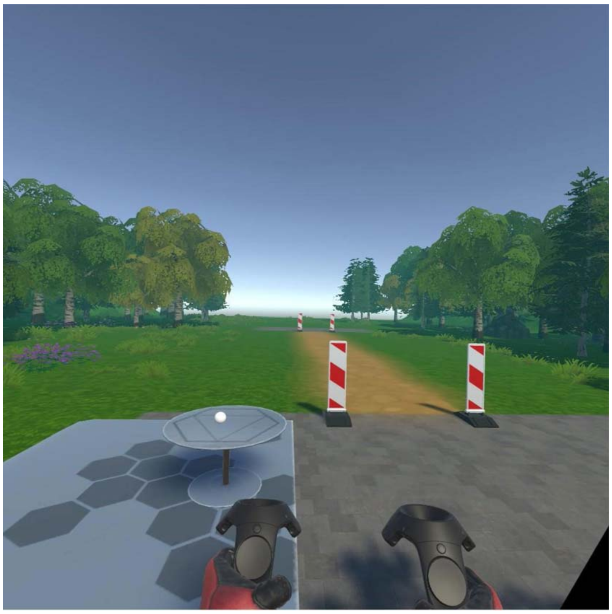

Fig. 1 Virtual environment

the body tracking, one from the HMD and two from controllers (one for each control). The results are statistically analyzed considering the six DOF on a 3D environment.

Since the purpose of this research effort is to measure and compare the human response to stimuli in a virtual environment, the experimental work is conducted in a virtual reality environment where an HTC Vive HMD system is used. The experimental methodology is as follows:

- Give the subject an approved consent form and questionnaire, and obtain a signed form.
- Determine dominant and nondominant hand.
- Give a VR tutorial to the subject.
- Test the subject on the virtual environment.
- The subject has time for reintegration to the daily activities.
- Provide a survey about the presence in the experiment.

These six steps represent the basic experimental methodology.

The research team provides a synopsis of the study to the test subject, requests that the test subject read and sign an informed consent form, and asks the subject to complete a brief questionnaire. To determine which control is used by each hand, it is necessary to use a survey. It is the Edinburgh Handedness Questionnaire and is formulated with questions in which the subject answers which hand they prefer to use for each activity (e.g., writing, using scissors, using a key to unlock a door), or if there is no preference at all. This configuration helps the user feel more natural from the moment they are immersed in the virtual environment. An orientation using the HTC Vive equipment is conducted, where the subject uses the system with all the equipment and learns how to use the hand-held wands to navigate in a virtual environment. This training is fundamental to preparing the subject. The central idea is to familiarize the subject with the equipment, but without letting the subject know the actual experiment. When the subject completes the tutorial, he or she knows how to manipulate the HTC Vive in the virtual environment, and he or she is capable of traveling on the virtual trail. This tutorial is provided in a different environment than the test track, and the subject is able to learn how to use the controllers, how to balance the ball on the plate, and how to reset the ball on the plate in case the ball falls to the floor.

Fig. 2 Ball on plate to balance

As with the tutorial, the test subject is then located in a scene in a virtual world while using the HTC Vive system equipment. The test subject navigates through the virtual environment where there is a marked trail with undisclosed obstacles. The undisclosed obstacles are: a rock coming unexpectedly in front of the subject, an explosion next to the trail, and flock of birds coming from one side. Based on position along the virtual world trail, obstacles are expected to create a disturbance on the subject's trajectory appear, forcing the test subject to balance the virtual ball on the plate controlled with the subject's nondominant hand. If the test subject puts his or her nondominant hand in a horizontal position, the virtual ball falls from the plate to the floor just like in real life, but the ball can be reset to the plate using the button from the dominant hand controller. For experimental expediency, the ball can be reset on the plate with the click on the controller, instead of grabbing it from the floor. This avoids having the subject stop every time the ball falls. This utility facilitates the completion of the experiment.

The use of VR for a prolongated time can make the eyes tired or alter other human senses. For this reason, it is important to have a reintegration time to the real world. After the test, the test subject sits quietly and regains their real-world perspective for around 10–15 min. After the subject reintegration, he or she is asked to respond to a survey. This survey focuses on measuring the VR presence, which means how immersed the subject felt in the virtual environment similar to Slater et al. [28].

After saving all the data from the degrees of freedom (x, y, z, roll, pitch, yaw) over the time, it is necessary to organize and analyze it. The information from all the participants is saved in different folders, to avoid any kind of confusion with the information. And there is a master file with the collected data from all the participants. This data is separated by male and female, and it contains data for statistical analysis.

To compare the balance and coordination from both genders, this research focused on the time to complete the track, the time it took to reset the ball (if the ball was dropped), the effective balancing time during the experiment, how many times the subject dropped the ball, the ball speed and the survey score. These variables were analyzed by contingency tables, t-test, correlation and phase planes. The next section of the paper provides explanation on the parameters, variables and methods used for this investigation.

4 Experimental Data

In this case, the environment is controlled and the data from the headset and controllers are collected. The environment exists as a path in a forest that is 190 m long with 8 curves and a width of 4 m. An important fact from the path is that the virtual environment works with a left-hand system. The plate that is used to balance the ball has a diameter of 0.31 m (31 cm) and the ball has a diameter of 0.03 m (3 cm).

Every time a subject participates in the experiment a new file is created with the information from the subject. This information has data as values from the different variables that the subject gathered

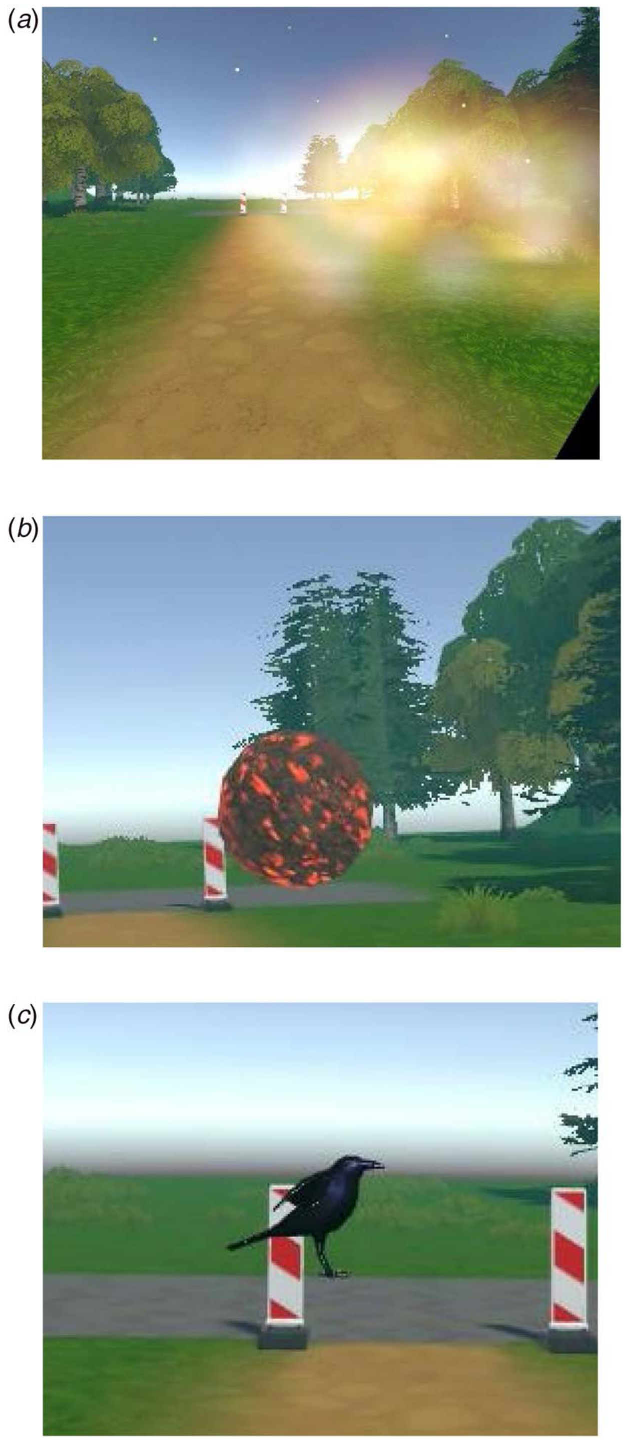

Fig. 3 Stimuli: (*a*) explosion, (*b*) meteors, and (*c*) birds

along the path. These variables are the track time, how many times the ball and/or the plate were dropped, at what time the events happened, the ball displacement on the plate, and the position on the six degrees of freedom (DOF) from the headset and the controllers (both right and left). From these variables it is possible to get some indirect variables such as the time to reset the ball, the effective balancing time of the ball, the ball speed, the delta between the controllers and the headset, and the speed of the headset and the controllers. With the mark in the specific events it is possible to analyze periods of time around specific events.

This paper is focused on the study of the human balance and coordination when a subject is in a virtual environment. Some variables were shown to be insignificant: whereas, others had a significant relevance in the study. The variables with significance are:

- Time to complete the path (track time)
- Time to reset the ball
- Effective time balancing the ball (balancing time)
- How many times the ball is dropped (ball drop)
- Ball speed
- Survey score

5 Data Analysis Techniques

Using the information contained in the variables mentioned above, this research effort looks for significant differences between the performance of male and female subjects using statistical methods. The methods used in this study are the contingency table (with chi-square), the *t*-test and the correlation between variables. A variable that is also considered with the data collected from the experiment is the presence from the subjects (evaluated with a survey), which is potentially related to the other variables by a relationship between the presence and the balance and coordination from the different subjects.

The first statistical method used is contingency tables. The variable containing the number of times the ball was dropped as converted to a categorical variable with three levels: low drops, neutral drops, or high drops. Lyman and Longnecker mention that contingency tables are tabulations arranged in cross, and their function is to test for comparing proportions [30]. Thus, the contingency table analysis is used to determine if the proportion of each category of drops is the same for male and female subjects.

The second statistical method used is two-sample *t*-tests. Five variables (track time, time to reset the ball, balancing time, ball drop, and ball speed) were separately investigated to determine if the mean value for each variable is the same for male and female subjects.

The third statistical method utilized is correlation analysis. The correlation between survey responses (presence survey, gamer survey, and difficult to balance survey) and the quantitative variables: track time, time to reset the ball, balancing time, ball drop, and ball speed were studied.

As another means of analysis, Beuter et al. mention that the phase plane is an analysis method for dynamic systems, where the variables are plotted against their time derivatives. [31]. In their study, Beuter et al. used the phase plane because it contains the complete information about the dynamics of the studied motion, based on the displacement and velocity [31]. The phase plane helps to create a model for an object's movement, and it is visually easy to detect if there are any disturbances from the original pattern. The displacement is represented with X and the velocity with $\dot{X}$. This method had been used to represent the movement shape of different objects or body parts as in the research from Beuter et al., where they studied and modeled the motion of a leg [31].

There were a total of 71 students who participated as test subjects: 35 male students and 36 female students. From the 35 male students there were 5 outliers, and thus there were 30 effective subjects for the research. From a total of 36 female subjects, there were six outliers, which made an effective subject population of 30 from the female students.

Data from the experiments is available in Gracia De Luna's thesis [32]. These data show the score from the presence survey, the score for a video game familiarity survey (Likert scale 1–7), the score for the difficulty balancing the ball, the time in the track in seconds, the average time that it took the subjects to reset the ball when it was dropped, the effective balancing time, the number of times the ball was dropped, and the ball speed shown in meters per second.

6 Results From Analysis

For this paper, analyses are made with the statistical methods and variables mentioned in Sec. 4. The statistical techniques used for

Table 1 Drop ball contingency table

	Female	Male		Female	Male
Observed			Expected		
Low drops	12	22	Low drops	17	17
Neutral drops	14	5	Neutral drops	9.5	9.5
High drops	4	3	High drops	3.5	3.5
Test					
Low drops	1.470588	1.470588			
Neutral drops	2.131579	2.131579			
High drops	0.071429	0.071429			
		p value			
		0.025385			

analysis in this paper are contingency tables, *t*-tests, and correlation analysis.

6.1 Contingency Table (Chi-Square). To determine if the number of dropped balls is equal for both genders, a contingency table was constructed as Table 1. The level of performance is a categorical variable, Drop Ball, which is based on how many times the subjects dropped the ball on the complete track. There are three levels depending on how many times the ball was dropped on the route, which are high, medium and low. These levels are based on the maximum times that a subject had dropped the ball (i.e., 23 times), splitting the time from 0 to 6 for low dropping, from 7 to 14 for medium dropping and from 15 and more for high dropping. Table 1 is composed of three sub-tables that display the working calculations of the chi-squared test used to determine if the performance of ball drop is independent of gender. The first sub-table contains the observed observations, ball drop versus gender. The second sub-table calculates the expected value for a hypothesis that the level of ball drop performance is independent of gender and the third sub-table displays the values of the Chi-squared test statistic for each cell in the table. Note Table 1 contains the *p*-value for the test of hypothesis that level of performance is independent of gender.

The analysis shown in Table 1 was for participants completing the path with no distracting events. A second scenario analyzed was focused on the three events (i.e., the explosion, the meteors and the bird flock). In the contingency table for this scenario, Table 2, there are three levels (i.e., no dropping, low dropping and high dropping), where no dropping is when the subject did not drop the ball in any event, and the low and high dropping are separated when the subject drops 1 time for low dropping and 2 or more times for high dropping. The composition of Table 2 is identical to that of Table 1.

Table 2 Drop ball contingency table for surprise events

	Female	Male			
Observed			Expected		
No drop	6	18	No drop	12	12
Low drop	13	4	Low drop	8.5	8.5
High drop	11	8	High drop	9.5	9.5
Test					
No drop	3	3			
Low drop	2.382353	2.382353			
High drop	0.236842	0.236842			
		p-value			
		0.003628			

6.2 T-Test. Five quantitative variables measuring participants' performance were collected. A two-sample t-test assuming equal variance was utilized to determine if the mean performance for male and female participants was the same for each quantitative variable. The results for each *t*-test are provided in Secs. 6.2.1–6.2.5.

6.2.1 Track Time. This test compares the total track time of the male and female subjects. The mean value is compared considering the values from the experiment's subjects. For this analysis, the variances are assumed as equal, and the *p*-value is 0.958, which is not a significant difference between male and female subjects.

6.2.2 Time to Reset the Ball. This analysis is made to compare the average time for the subjects to reset the ball, and the data from the male and female subjects is analyzed with the *t* test method for independent variables. The variances were considered different and with a *p*-value of 0.325.

6.2.3 Balancing Time. This analysis considers the total track time of the subjects minus the total time to reset the ball, which considers only the time that the ball was balanced. In this *t* test, the variance is assumed equal for both variables, and the *p*-value for balancing the ball is 0.994.

6.2.4 Ball Drop. The number of times that the ball has been dropped in the experiment is one of the most important variables in this study. The mean value of the male and female subjects is compared with the *t* test. For both *t* tests, the variance is assumed to be the same for both variables. The *p*-value for dropping the ball in the complete path is 0.172 and the *p*-value for dropping the ball in the events is 0.013.

6.2.5 Ball Speed. For the ball speed, there are two scenarios where the average speed value is shown during the experiment and the delta (highest difference between speed values) speed of the ball on this same period. For this analysis, the variance is assumed as equal and has a *p*-value of 0.125. For the delta speed analysis, it is assumed that the variables have different variances and the test has a *p*-value of 0.601.

6.3 Correlation. Correlation analysis was attempted for multiple variables used in this study. The correlations were grouped by Presence Survey Score, Gamer Survey Score, Difficulty in Balancing the Ball Survey, and correlation between the various surveys. Table 3 displays the correlation coefficients for each gender. Correlation coefficients with a ρ-value greater than 0.5 are highlighted in bold.

For the phase plane, three plots for each subject (one for each event) were generated, where the 180 plots can be seen in Appendix D of Gracia De Luna's thesis [32].

Table 3 Summary of correlation tests

	Male	Female
Male and female presence correlation		
Track time	−0.246	−0.045
Balancing time	−0.216	−0.167
Ball drop	−0.204	−0.127
Average ball speed	−0.140	−0.093
Male and female video game correlation		
Track time	−0.170	−0.246
Balancing time	−0.208	−0.017
Ball drop	−0.020	−0.352
Average ball speed	0.004	−0.333
Male and female balance difficulty correlation		
Track time	−0.019	0.317
Balancing time	−0.109	0.127
Ball drop	0.200	**0.623**
Average ball speed	0.245	**0.588**
Male and female survey correlations		
Presence and gamer	0.071	−0.153
Presence and balance	0.140	0.121
Gamer and balance	0.135	−0.332

7 Conclusions

There were four different analysis methods used in this research. For that reason the conclusions are separated by the different methods explaining the result from each analysis, with the different variables that were studied. After the individual explanation from the contingency tables, the *t*-test, correlation and the phase planes, a general conclusion is made from the different tests. The research thesis is analyzed to affirm or reject that there is a difference by comparison between male and female subjects in virtual environments.

7.1 Contingency Table (Chi-Square). Table 4 summarizes the results from the analysis made with the contingency tables. It shows the *p*-value results and the observations from each case. The studied variables were the performance dropping the ball in the complete path and during the stimuli events.

There are a total of two contingency tables analyzing how many times the ball is dropped, one for the complete track and one focused on the stimuli events on the path. In both cases, male subjects have a better performance, dropping the ball less times on the path. When the events happen, this performance has a confidence level of 95%. Based on this data, it is shown in this research that male subjects have better balance and coordination in virtual environments. While analyzing the complete path and when there are different stimuli to distract the subject, in both cases the male subjects had better control of the ball as measured by the number of dropped balls.

7.2 T-Test. As a summary for the data obtained from the different *t*-tests, Table 5 shows the *p*-value and observations from the different analyzed variables. Each of the analyses were made comparing the performance between male and female subjects, where a

Table 4 Summary of contingency table

	p Value	Observation
Drop ball (complete path)	0.0253	Male subjects drop the ball less times having a better performance
Drop ball (during events)	0.0036	Male subjects drop the ball less times having a better performance

Table 5 Summary of *t* test

	p Value	Observations
Track time (s)	0.958	There is no significant difference between male and female subjects
Reset ball time	0.325	There is no significant difference between male and female subjects
Ball drop on the complete path (score)	0.172	There is no significant difference between male and female subjects
Ball drop during the events (score)	**0.013**	Male subjects drop the ball less during the stimuli events
Avg. ball speed (m/s)	0.125	There is no significant difference between male and female subjects
Delta ball speed (m/s)	0.601	There is no significant difference between male and female subjects

p-value lower than 0.05 represents a significant difference between the male and female subjects in the respective variable.

The *t* test was used between the male and female subjects, analyzing the track time, the time to reset the ball, the effective time balancing the ball in the path, how many times the ball was dropped (in the complete path and during the specific events), the average ball speed and the change in ball speed. Considering all variables, there was not a statistically significant difference in the complete path analysis. The variables with higher difference were the average ball speed and the times that the ball was dropped, but they had a *p* value of 0.125 and 0.172, respectively. However, there was a variable with a significant difference. This variable was the subject's performance of dropping the ball during the stimuli events, which had a *p* value of 0.013. The sum of all male subjects dropped the ball 21 times during these events, while the female subjects dropped the ball 44 times during the events. This shows that for this single variable, male subjects have a better performance when they balance and coordinate objects in virtual environments, even with distractions.

7.3 Correlation. The results from the correlation analysis are shown in Table 3. This table organizes the correlation in four areas, first the correlation from the presence against the performance variables, second between the videogames skills and the performance variables, third between the balance difficulty survey and the actual performance from the subjects, and last, a correlation among the three surveys. The correlation coefficients are shown for male and female subjects.

The correlation in this research studies the possible relationship between the presence, the subject's experience playing videogames, and the subject's balance feeling during the experiment against their performance. Subject's presence did not have a correlation with the performance from the subject, and the videogames experience did not have any relationship either. However, when the correlation from the subjects perception of the difficulty balancing was made, it was found that this feeling in the female subjects had a correlation with their performance dropping the ball and with the control on the ball speed that they had. The female correlation coefficient between the difficulty level and their performance was of 0.623, while the male coefficient was of 0.200 (For this study we look for a ±0.5 correlation or greater). There was a correlation coefficient of 0.588 for female subjects between their feeling balancing the ball and the average ball speed during the experiment, and the male subjects had a 0.245 coefficient in this same correlation.

Based on this correlation analysis, it is possible to say that female subjects have a better interpretation between the virtual environment and the feeling of control. This interpretation helps the female subjects to better understand the quality of their performance during the experiment. This occurred even when they dropped the ball more times.

7.4 General Conclusions. The objective is to learn and understand the human balance response in virtual environments. The thesis for this investigation is that it is possible to differentiate male and female subjects when they are balancing an object while they go in a virtual environment trail with obstacles using statistical analysis. Based on the different statistical analyses, it is possible to differentiate male and female subjects when they balance an object while they go through a path in a virtual environment for a few select variables, only. However, the research team looked hard at much data, and this analysis resulted in only limited statistically supported differences. Therefore, it is reasonable to conclude that there are few differences between the virtual world behavior of men and women test subjects.

The variable which had an actual difference between the male and female subjects was dropping the ball in which the male subjects had a better performance over the female subjects. Both contingency tables of ball dropping show that the male subjects have a performance of low dropping of the ball, while female subjects have a medium performance. And, with the *t* test analysis, male subjects have a significantly better performance dropping the ball fewer times during the distraction events that happened in the experiment. The correlation analysis shows that female subjects better understood their level of performance, even when they had dropped the ball more times. The female feeling of success or poor performance with the experiment was more strongly related to their actual performance, while the male subjects had not developed this feeling.

A limitation of this study is that it does not provide design guidelines for creating balance or coordination during events in a virtual environment. The thesis from this research is affirmed for a few select variables because it proved possible to differentiate male and female subjects when they balance an object while they go through a path in a virtual environment. This was shown with the performance of dropping the ball during the experiment, where male subjects dropped the ball fewer times. It was also found that female subjects had a better interpretation of their performance in virtual environments, which is a skill that male subjects did not have. These two points summarize the conclusions for this paper.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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