# CAVE2 Comparison Of 1st/3rd User Perspectives In Virtual Motor Rehabilitation Tasks

by

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To my grand aunt Chelita, a stroke survivor, and my mom, the beautiful soul that stands by her side

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| | |
|---|---|
| 1PP | First-person perspective |
| 3PP | Third-person perspective |
| ADL | Activities of daily living |
| CAVE | Cave Automatic Virtual Environment |
| POV | Point of view |
| FOV | Field of view |
| NUI | Natural User Interface |
| UIC | University of Illinois at Chicago |
| VR | Virtual Reality |

## SUMMARY

Stroke is the leading cause of severe longstanding impairments in the US. Besides facing economic issues, stroke survivors are required to attend to rehabilitation therapies to deal with physical and cognitive disabilities that reduce their quality of life. In this context, virtual rehabilitation appears as an additional support to traditional treatments by taking advantage of virtual reality. However, researchers do not agree on which of virtual reality aspects are more relevant for specific therapies. One of those aspects is the user perspective; how a patient see a virtual environment but we do not know which is more beneficial. Rehabilitation applications mostly use first-person perspective or third-person perspective but rarely offer both; thus, a comparison between them is difficult to achieve.

We performed a user study (N=30) in the CAVE2 environment with RehabJim, a virtual rehabilitation game for upper limbs recovery developed at the Electronic Visualization Laboratory (EVL). Our analysis compared the effect of the user perspective, training modes, and two target sizes on user performance, the degree of immersion and body movements. Results suggested an effect of the training mode factor, and a smaller effect of the user perspective on time required to finish a task, hand movements, and movement corrections. User perspective had the main effect on head movements, but subjects felt the same immersion level under both user perspectives.

# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation

Each year stroke generates a tremendous impact on health and economics around the world. According to the American Heart Association (AHA) Statistical Update (3), since 2013, only in the US stroke is 2013 the fifth primary cause of casualties with an average of one person every 40 seconds. Additionally, there are around 795,000 incidences of new or recurrent stroke yearly. Ten percent of those cases targets the population between 18 to 50 years old. The economic impact between 2011 and 2012 for stroke was $ 33 billion; costs divided approximately in 60% of direct costs, including hospital staff, facilities, prescriptions and others, and 40% of indirect costs from lost future productivity. Globally the situation is not better; stroke accounts for 11.8 % of the casualties worldwide, making it the second-leading global cause just behind ischemic heart disease. Data for 2010 estimated 11.6 million incidences of ischemic stroke and 5.3 million for hemorrhagic stroke.

According to a survey of the US Census Bureau(3), strokes are now the primary cause of severe longstanding impairments in the US. Survivors usually suffer from physical and cognitive impediments and spent an average of $7,318 annually in rehabilitation services (3). Paresis is a common physical condition among survivors where damage caused by stroke provokes a partial paralysis in one leg or one arm (mono paresis) or one arm and one leg (hemiparesis). These impairments have a severe effect on the patients activities of daily living (ADL) as most likely the patient will require the constant help of a third person. Therefore, physical rehabilitation is essential to help “functional performance of ADL through the acquisition of new motor skills and recovery or compensation of lost motor skills” (4).

Motor rehabilitation tasks aim to transfer the dexterity acquired in therapy to daily activities. Moreover, several factors like the type of work, tasks order, and type of feedback have an impact on the effectiveness of a particular treatment. Under these conditions, virtual reality appears as a promising and convenient way to deliver rehabilitation practices as it allows an experience controlled by several variables. VR technologies allow creating virtual environments with practical tasks that mimic real-world therapies. However, VR setups offer more control over the work settings  task order, difficulty, and environmental elements  than traditional treatments. Sophisticated multisensory feedback complements the real-world elements by controlling color, illumination, temporal and spatial distortions, movements, special effects and others. These available ranges of possibilities augment the probabilities of providing the right neural feedback (5).

Several studies have evaluated the efficacy of virtual rehabilitation over traditional therapies or no interventions. In 2015, Cochrane published the review “Virtual Reality for Stroke Rehabilitation”(6) (evidence up to November 2013). The scope included evaluations of 37 trials with a total of 1019 subjects on “upper limbs, gait and balance, global motor function, cognitive function, activity limitation and quality of life” (6). Conclusions suggested that the same dose of conventional therapy and virtual rehabilitation is favorable for upper limbs recovery and

ADL. Though, researchers did not find evidence of improvements in grip force, walking speed or global motor function. Also, the review could not identify the most favorable characteristics of VR for rehabilitation and whether the recovery effects would continue in the long-term.

The unclear aspects of VR that contribute more upper limbs rehabilitation motivate the comparison of the first-person (1PP) and third-person (3PP) user perspectives in *VR virtual rehabilitation serious games*. Each perspective has its particular characteristics and influence in different ways the user performance, upper limbs movement, and degree of immersion. Only one preliminary study (N = 10) (7) with the RehabJim application have evaluated a virtual rehabilitation game for upper limbs recovery in a CAVE2 environment. In this research, we overcome limitations of this first preliminary study such as calibration, interpupillary distance, and limited sample population to provide an exhaustive assessment of the impact of user perspectives on performance, immersion, and body movements using an updated version of the RehabJim application.

## 1.2 Goals

The primary goal of this research was to compare the first-person perspective (1PP) with the third-person perspective (3PP) under the following factors: user performance, the degree of immersion, and upper limbs and head movements. We also evaluated the effect of different training *modes* and separate objects sizes. We expect that the updated done to the application will minimize the effect of latent variables on the user study comparisons.

User performance includes the task completion time and the score, represented as the number of objects caught during an exercise. The degree of immersion refers to the feeling of being into a game. Finally, the movements domain analyzes hand and head movements, and the errors made during the reaching tasks.

We had 30 user study sessions in the CAVE2 environment where the subjects performed twelve exercises that combine the user perspective, training modes, and target sizes factors. We expect that the results from this thesis can give us insight into the design and technical considerations for virtual rehabilitation applications under each perspective. Furthermore, with our user study, we want to provide a baseline for future evaluations of virtual rehabilitation games inside the CAVE2 environment.

## 1.3 Thesis Organization

Chapter 2 introduces the background concepts about virtual reality and virtual rehabilitation. Then, Chapter 3 describes relevant work done comparing user perspectives; designing applications for motor and cognitive rehabilitation, and evaluations of CAVE-like environments in the rehabilitation domain. Chapter 4 outlines the details of RehabJim and the work done for its latest release. Next, Chapter 5 describe the methods for the user study and the statistical approach taken. Chapter 6 presents the results, and we discuss them in Chapter 7. Finally, Chapter 8 wraps up the content and provides the future research direction.

# CHAPTER 2

# BACKGROUND

## 2.1 Virtual Reality and Immersion

Jaron Lainer coined the term Virtual Reality (VR) in the late eighties. Since then, Virtual Reality and Virtual Environments were terms used to refer to the same concept. Sometimes the attempts to define the terms tried to justify the need for using a particular technology; which led to arguments in favor and against the real need of it (8). Bryson defined it only based on VRs cognitive effects: "Virtual Reality is the use of computer technology to create the effect of an interactive three-dimensional world in which the objects have a sense of spatial presence"(8).

Even though Lainer avoided the term immersion in his definition, people in this domain consider it as a fundamental element for VR (9). Immersion itself is also a concept with a nonstandard definition; commonly we understand immersion as the feeling of being surrounded. Research based on the experiences of gamers (10) defines immersion as the state when the user gets a complete involvement with a digital game. Impressions that we can feel while reading a novel, enjoying a play or watching a movie. Though, these last ones do not require computer graphics or complex hardware (9).

Further studies have found that players were able to identify different levels of immersion(10). The first tier is *engagement* where a player just spends time and effort playing. Then we feel *engrossment* where the emotional and attention factors come into the player - game relationship. The last level of immersion, coined as *total immersion*, introduced the sense of presence. The associated user study suggested that immersion requires attention, feedback, and thinking; it is influenced by social presence but not necessarily by spatial presence.

Another study (11) identifies the concepts of *diegetic immersion* and *intra-diegetic* or *situated immersion*. The former defines the immersion into playing the video game (acting upon the game space), while the latter requires the manifestation of the previous one and adds the sense of being in the game space as a spatial and narrated space (acting within the game space). Additionally, the game space does not require a visual representation or conventional spatial resemblance, being a major obstacle establishing a relationship between the player and the game that avoids always noticing the external and internal game interface. These two studies presented a different number of sub levels, but we can see an overlap between them. The message is that a player can experience increasing levels of immersion while playing a game.

## 2.2 First and Third Person Perspectives

Computer games present different player perspectives modes. On the one hand, the first-person perspective (view) lets the user experience the virtual environment through the character's eyes; "the camera always looks wherever the player is looking" (12). The experience mimics more closely people's daily living reality. On the other hand, the third-person perspective allows the camera to focus on the game character. The problem of invalid camera positions such as a player standing close to walls, can be solved with complex camera positioning. Without regarding the position of the camera, a third-person view allows a wider spatial view of the surrounding elements and a full body view. Hence, instant feedback on body movements.

Differences between user perspectives are not only related to the camera position. Researchers suggested different influence in perception and cognitive mapping of a virtual environment (13). A third-person view provides an indirect interaction were the gamer acts as a puppeteer and perceives a scaled view of the avatar. The first-person one gives a direct manipulation and a 1:1 scale mapping.

## 2.3 Motor and Cognitive Impairments

A stroke may produce motor and cognitive impairments in a person. The International Classification of Functioning, Disability, and Health (ICF)(14) classifies these motor impairments in impairments of the body function or impairments of the body structure. These motor problems cause deviation in the ability of control the joint mobility, loss of muscle power and tone, and produce involuntary movements. Additionally, they can alter the structures related to movements in the nervous system(15). Problems are not independent and may appear simultaneously.

A cognitive impairment accounts for deficits of multiples independent domains. Problems appear in focusing on a task or switching attention to a new one; planning, organizing and controlling thoughts and actions; executing visuospatial tasks as visual search, drawing or constructing; remembering and identifying visual and verbal information; and using an meaningful and well disposed language(16). Survivors may also exhibit slowness of information processing.

Stroke rehabilitation relies on the neuroplastic nature of the brain. Neural plasticity stands for the brain ability to create new connections and to compensate for damaged cells(17); which allows learning and re-learning to happen(5). However, the mechanisms in which neural plasticity works are different across patients, including complex processes as restitution, substitution, and compensation. Thus, identifying the appropriate mechanisms under motor recovery activities would suggest the most effective type of exercise, duration, and goals (17). Rehabilitation therapies do not guarantee a complete recovery for each patient. Therefore, the therapies mainly center in helping patients to improve their quality of life both physically and psychologically.

*Stroke motor rehabilitation activities* mainly focuses on motor learning, the ability to learn a new behavior through skilled practice. Motor learning activities demand a considerable amount of repetitions to generate changes in neural organizations and produce changes in motor patterns(5). Motivation is fundamental to maximize the possibilities of a successful recovery. Patients that do not improvements in the short-term may be willing to quit. Additionally, the time spent on tasks and the necessary effort also plays against them. Therapists can rely on setting short-term goals and continuously show the patient their progress to keep them engaged with the therapy realistic goals. A set of interviews with 32 stroke professionals (18) summarized an understanding of the causes of motivation. Half of the professionals believed that personality factors cause patients motivation. Almost everyone considered clinical factors to be another reason; especially, they identified a correlation with increasing age and decreased motivation. Some specialists mentioned how the family had an effect on the patient; overprotection or high expectations affected negatively. The experts also identified factors in the rehabilitation environment as group treatment to be positive for patients. Finally, only a quarter of the caregivers identified their behavior as a relevant factor.

Traditional rehabilitation methods include several strategies (17):

**CIMT** Constrained Induced Movement Therapy forces the patient to use an impaired limb in functionality oriented tasks while the nonparetic limb is physically constrained (19). Studies have shown that patients have improved upper limbs functions over time. The exercises usually require the extension of the wrist, thumbs, and fingers.

**BWSTT** Body-Weighted Supported Treadmill Training focuses on lower limbs rehabilitation. Patients walk on a treadmill while a device supports their weight.

**Robot Training** Mechanically assisted therapy.

**Action Observation** Patients observe actions in another person. Observation may trigger learning, imitation and training effects.

**Mirror Therapy** Patient observes a reflection of the intact limb as it were the affected one (19).

**Virtual Reality** Immersive computer applications that provide real-time multi-sensory feedback.

**BCI** Brain Computer Interface or Noninvasive Brain Stimulation provides feedback to the brain for modulating its activity. Potential risks of this approach include seizures and headaches due to an inappropriate dosage(19).

**Motor Imagery** Patient mentally executes repetitions of simulated movements without any physical activity.(19).

## 2.4 Virtual Rehabilitation

Virtual Rehabilitation uses virtual reality to overcome limitations of traditional rehabilitation therapies. The created virtual environment (VE) provides fewer physical limitations to perform recovery tasks. Furthermore, VR configurations give the chance to monitor the user actions, provides personalized guidelines and multi-sensory feedback which may not be possible in the real world(5). A correct configuration of the interactions may encourage the achievement of a successful therapy.

Several studies have analyzed the impact of VR on neural circuits. For instance, visual information as feedback for errors in movements positively influence motor cortical areas during the process of learning the skill. Furthermore, the sense of immersion plus the broad range of sensory manipulations: color, brightness, location, audio input, temporal and spatial distortions, movements playback and others maximize the possibility of providing the accurate feedback for neural reorganization(5). Levac and Sveistrup(4) summarized the attributes of virtual reality and aligned them with the four primary motor learning variables: Practice, Augmented Feedback, Observational Learning, and Motivation. They suggested that variables required for inducing neuroplasticity are endemic characteristics of virtual reality systems.

**Practice** More practice will ameliorate the learning experience. However, the intensity of the training is essential in early stages of the recovery process. VR allows the configuration and adaptability of these tasks depending on the user condition. VR set-ups also recreate ecologically valid environments which include task-specific challenges that may not be possible in the real world. For instance, teaching how to use a wheelchair in the streets.

Engagement is another important factor of the practice experience. VR promotes meaningful tasks which provide a context for an optimal cognitive and motor effort to enjoy the given task.

**Augmented Feedback** Augmented feedback consist of additional information provided beside the usual body feedback, such as auditory, visual or tactile feedback. Examples include the representation of movement kinematics, game scores, the number of attempts, auditory feedback for successful efforts or contact feedback provided by haptics. Augmented feedback can also help to focus the user on the essential elements of the environment.

**Observational Learning** The mirror neuron system is a mechanism to provide feedback about movement patterns and the consequences of them that contribute to motor learning. By observing their image interacting with virtual objects, patients can understand the accuracy of their movements and their location inside the virtual environment. VR set-ups can also provide virtual teachers to demonstrate how to do the right actions, or augment the effects of learning by exaggerating movement features. The evidence of these interactions as their pair in physical environment is not conclusive.

**Motivation** As emphasized in the last section, motivation is fundamental to engage a patient in a continuous and repetitive practice. Motivation may be particularly important for children as it helps them focus on the tasks. Another hypothesis for the success of motivation in VR may be related to the use of trending technology and the gaming features. Individualization is also an important factor as allow a personalize treatment and adaptive stimuli. Other causes for motivation include competition against other patients or virtual players and the level of cognitive effort on each task. Motivation is also a fundamental factor when trying to transfer the rehabilitation tasks to the patients home. Thus, expecting them to perform the tasks without having the therapy environment as a motivational factor.

Evaluations of virtual rehabilitation applications have proved the benefits of virtual reality in the rehabilitation field. An assessment of 37 virtual rehabilitation papers for stroke(6) suggested a positive outcome on improving the upper limb function when used as a complement of traditional therapies. However, researchers are required to identify the specific characteristics of virtual reality that induce better outcomes.

# CHAPTER 3

# RELATED WORK

## 3.1 Effects of First vs Third Person Perspectives

During the late nineties, the game industry debated about the survival of the classic 1PP after the successful debut of Toby Gard and Paul Douglas' Tomb Raider. A closer analysis (12) allowed to understand that each viewpoint has an impact on the game design and emotional attachment with the game. The comparison in this study between John Carmack and John Romeros Doom and Tomb Raider (12) showed that a 1PP focused more action mechanics like aiming and shooting. 3PP demonstrated a positive impact on user navigation, exploration and puzzle solving, and enjoying the characters "cool moves". Even though the report did not present a user study, the analysis indicated the possible effects of the viewpoints on the player immersion: viewing the characters movements could emphasize the external control of the character and the personality distance between the player and the given role. While in a 1PP, the player-centered view may make the players believe that they are truly there.

Whether the user perspective affects the level of immersion is still an open question. Although game designers have argued positively for the 1PP because of its deeper sense of immersion(12), few user studies addressed the problem. Denisova and Cairns (20) subjectively evaluated the level of immersion of forty players using the IEQ questionnaire (21) as an overall result, and further divided the analysis into five domains: real world dissociation, challenge, emotional involvement, control, and cognitive involvement. The experiment required the subjects to play the RPG game Skyrim for fifteen minutes. Users under evaluation belonged to one of two groups: twenty playing in 1PP and twenty in 3PP. Results suggested that a 1PP provided higher levels of total immersion; real world dissociation, challenge, and cognitive involvement. Additionally, no difference was found between the scores of emotional involvement and controls aspects. Researchers suggested an association between the player perception in 1PP and the sense of challenge and cognitive effort; the restricted field of view constraints the understanding of the surrounding objects and the ability to see the players situation within the environment. Thus, the player in !PP perceives a greater challenge which leads to more cognitive activity. Results may explain why more experienced players prefer the first-person perspective.

Researchers have contrasted user views with the feeling of engagement and affective appraisal (22). Authors defined engagement as "the state of mind where a person can experience the environment directly, without mediation or distraction," and indicated the need for a sense of space within the virtual environment to develop it. Their definition of engagement is closely related to the definition of total immersion provided by Brown and Cainers(10). The experiment used 22 volunteers (randomly assigned to 1PP or 3PP) that searched for five objects for eight minutes in the game SECOND LIFE under a defined perspective and then filled a questionnaire. Results showed no significant difference on the effective appraisal variable between the two perspectives. However, the environment evoked more attention and was more enjoyable in 3PP. Additionally, with 3PP, the users found more objects and had a better sense of control. No other factor of engagement besides control had a significant difference between perspectives.

Physical tools are also a factor in the level of presence - the deepest level of immersion. An evaluation of two Nintendo Wii games (23) under 1PP and 3PP, and alternating the use of tools for tasks found more sense of presence when using an instrument for both perspectives. Though, there was no significant difference between views with or without tools.

The use of a distinct perspective does not only affect the level of immersion. Tidoni et al.(24) evaluated how the visual system understands observed body movements from 1PP and 3PP. Participants used an HMD to observe the movements of an avatar's hand while reaching an obstacle for either user perspective. Results indicated that the perspective and motor dexterity affected how a subject understood observed body movements; the 1PP gave more hand ownership, perceived control, and did not overestimate the perceived body movements.

Artificial Reality (ARt) experiences are applications that capture the body movements through a camera device and project the image on 2D screens. However, the cameras can map the hands in a 3D virtual environment. Pares and Altimira (13) argued that ARt rehabilitation applications rely blindly on 3PP (camera placed in front of the subject), neglecting the exploration of benefits brought by the 1PP (camera placed behind the subject). They evaluated a ball game and a game about athletics under the two user perspectives. Results for the ball game found significant differences between views; 1PP gave a lower sense of control. Besides, users were less active. Conversely, there were no significant differences for the athletics game.

Finally, the work done by Rottigni(7) presented conclusions on performance variables but did not evaluate the level of immersion in RehabJim in either perspective. His findings showed a user's preference for 3PP as it was easier to use and to understand. Besides, he reported that user interpreted the depth perception better in 3PP.

### 3.2 Measuring Immersion

The concept of immersion has different interpretations among researchers and gamers. We can describe it as a cognitive experience that arises while playing digital games. The level of immersion depends on the degree of involvement with different aspects of the game, and in the deeper level seems to deviate the player's attention towards the virtual world(25). Measuring immersion with a questionnaire is highly dependent on the players understanding of this concept. Jennett et al.(21) found that besides using questionnaires to obtain a subjective measure of immersion, objectives tasks like task completion and eye movements are also valid. The development of their questionnaire, called immersive experience questionnaire (IEQ), combined concepts of flow, cognitive absorption, and presence. Other questionnaires for immersion include the Igroup Presence Questionnaire (IPQ) (26) and Witmer's Presence Questionnaire (27).

Jennett et al. (21) performed three experiments to evaluate the use of the IEQ survey and their hypothesis about the levels of immersion(21). Experiment 1 focused on measuring the effect of a *return* to the real environment. Experiment 2 consisted of non-intrusive methods to measure eyes movements and their relationship with the level of immersion while clicking objects. Finally, Experiment 3 analyzed the factor of speed in a clicking activity after surprising results of Experiment 2 suggested higher levels of immersion in a non-immersive task. The interesting finding suggests that personality factors are likely important bolster the level of immersion besides game elements. The resulting questionnaire (IEQ) had six sections: "basic attention, temporal dissociation, temporal transportation, challenge, emotional involvement, and enjoyment"(21).

We used the IEQ questionnaire to evaluate the user level of immersion in the CAVE2 environment while performing the reaching tasks under different user perspectives. Although the questionnaire results are subjective, we believe that the immersion can have a positive effect on the player's motivation to finish a rehabilitation task. Thus, we want to obtain a first insight of immersion in a CAVE2 environment.

### 3.3 Applications for Motor Rehabilitation

VividGroup's Gesture Xtreme (GX) VR System(28) consists of a camera-based system that projects the image of the user to a screen, and based on tracking devices allows interactions with a virtual environment. The experience tracks specific or all body parts, avoids the use of intrusive elements and shows a reflection of the user body (third-person view), not an avatar. However, the scenarios are 2D and only provides visual and auditory feedback. Kizoni et al. (28) adapted its use as an rehabilitation application with four games: *Birds and Balls*, *Soccer*, *Snowboard* and *Sharkbait*. Pilot results were made with stroke patients, patients with neural system problems and young adults with cerebral palsy. More recent version of the system are now commercially offered. For instance, the GestureTek Health VR system has business cases in six rehabilitation institutes(29).

Similar Natural User Interface (NUI) approaches in 3PP replace web cameras with Kinect sensors. REMOVIEM(30), a low cost system, focused on patients with multiple sclerosis. Users performed lateral movement of trunk and arms while interacting with virtual balls. Da Gama et al. (31) presented a guidance and movement correction application that encouraged the user to perform therapeutic movements. Latif et al.(32) used the Kinect camera projection to allow an image of the patient body to interact with colorful circles, but also added a level where a basic skeleton representation replaced the user body.

NUI approaches in 1PP include applications for children with brain damage (cerebral-palsy), and patients with stroke. Yamaguchi et al.(33) categorized arm movement patterns strategies made by children; MIRA(34), another application for cerebral-palsy, provided catching, following, moving and grasping activities, while SVRS(35) presented reaching objects challenges. Applications for stroke include UMBRELLA(36), a projective tabletop system with exercises focused on fingers flexion, wrist flexion and extension, tapping, and grasping; and a virtual Nine Hole Peg Test for assessment of finger functions(37).

Researchers have evaluated the usability of commercial Kinect games such as Kinect Sports Table Tennis and Bowling(38). Occupational therapist thought that the games were not suitable for patients as shoulder flexion and extension movements could be more intensive than necessary.

Other approaches incorporate robotic support. Neurorehabilitation Training Toolkit (NTT)(39) placed two handles with unique visual markers on a desk, while a robot provided aided 2D movements to control a glider in a virtual environment. Data collected through a pilot study would be used for adjusting the level of robotic help. The BrightArm Duo system(40) hold the patient's forearms onto two grasp sensing devices placed on a table top. Reaching and grasping movements allow the interaction with Unity3D games in 1PP.

Electronic gloves like CyberGlove$^{TM}$ and CyberGrasp$^{TM}$ provide more accurate information of hand joints angles and even tactile feedback. Patel et al.(41) used these gloves in a feasibility study on post-acute patients. The first-person applications included a mirror task and reaching objects task in 1PP. Fluet et al.(42) also used these devices to test an 85 years old subject on a virtual piano simulator, a hammer simulator and an adapted version of Pong. Standen et al.(43) used custom built gloves and proposed a low cost system with four games: a space race, a car race, a target shooting challenge and a balloon popping.

Virtual rehabilitation applications also implement conventional strategies. We found mirror therapies applications (44)(41)(45), and constrained-induced movement therapies (46). The literature for motor rehabilitation applications is varied; applications combine natural user interfaces, robotic support and wearable devices to provide a non-intrusive experience. Game mechanics and game design are exploited to create a sense of flow and to offer different methods to induce neuroplasticity. Applications rely on 1PP or 3PP to do a task but rarely offer both perspectives. Therefore, finding which perspective is more beneficial is a difficult task.

### 3.4 Cognitive Rehabilitation

Virtual rehabilitation normally focuses on motor training tasks, but recently cognitive training in VR have aroused more attention. Researchers based this interest on the assumed interdependence between cognitive and motor training. Thus, by combining them, they may create more efficient rehabilitation tools(47).

Cognitive rehabilitation expands over several domains. Reh@bTask, a rehabilitation tool that adapts the Toulouse Pieron (TP) task, focuses on specific attention and memory training.

Reh@bTask uses a tabletop surface and an augmented reality haptic to provide interaction. Also, the game provides up to 120 levels of difficulty which is calculated based on the number of targets, distractors, allowed time and type of stimulus and adapts to the patient specific conditions. An evaluation of the tool showed improvements in the cognitive domain but not greater improvements in the motor domain as compared to a control group. Additionally, neutral and positive stimuli have been reported to perform better than negative stimuli(48).

Attention disorders are frequent cognitive deficit after stroke. Llorens et al.(49) hypothesized that competition could have positive effects in attention. Even though competitive strategies have been reported to increase motivation and intensity, they were not applied before to stroke rehabilitation.

### 3.5 CAVE in Virtual Rehabilitation & Related Areas

Researchers have analyzed the use of CAVE environments in virtual reality exposure therapy (VRET). A study (N=34) on the effectiveness of treatments using an HMD (low sense of presence) versus a CAVE (high sense of presence) for acrophobia (fear of heights) (50). Participants completed three sessions that included one hour of exposure to the environment. Results showed no differences in effectiveness between both mediums; CAVE gave higher levels of presence, and there was no correlation between presence and anxiety. Moreover, the authors questioned the use of VR as the application did not elicit anxiety on ten patients.

Another study evaluated the human empathy towards avatars of known and unknown people expressing pain (51). Participants (N=42) were engaged in a virtual conversation with avatars showing moderate and intense pain. Results reported users feeling empathy for known and unknown avatars, but higher empathy for the formed one. Also, measures of skin conduction were higher during the pain reactions. Although our work did not incorporate emotional elements, these results allow us to question whether emotional factors can positively influence the effectiveness of virtual treatments.

CAVE environments have also targeted treatments. 'Lost in the City' proposed a VE for teaching social skills to children with autism (52). The scenario simulated a street environment where the children could learn skills to deal with traffic lights, cars, and other street elements. Another research presented an initial design for treating rheumatoid arthritis(53).

Finally, the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago has two serious games for virtual rehabilitation in the CAVE2 environment. First, CAVEChef(7) offered an attempt at lower limbs rehabilitation. A kitchen environment set the interactive area where the user mimics activities of daily living, such as moving ingredients and instruments around the scene, which require walking around. Then, RehabJim(7) is an upper-limb rehabilitation game centered on reaching objects. We present a user study based on this last application. We provide a detailed description of RehabJim in the next chapter.

# CHAPTER 4

# IMPLEMENTATION

## 4.1 RehabJim Overview

RehabJim is a virtual rehabilitation game that focuses on upper limbs tasks. It relies on aspects of VR to provide an engaging, immersive and motivating environment for patients. RehabJim leverages the open space provided in the CAVE2 environment, the Vicon Bonita IR cameras and the Kinect v2 sensor to offer a non-intrusive experience. A patient just needs to wear 3D tracking glasses to start interacting with the objects in the environment. RehabJim's novelty is allowing the user to play in 1PP (Figure 1) or 3PP (Figure 2).

The primary objective is to reach virtual objects, represented as textured-spheres, that appear, one at a time, at less than one arm-length from the patient's chest. The hands, tracked by the Kinect v2 sensor, trigger interactions with the spheres when the two objects collide in the virtual environment. The application provides feedback for these interactions as special effects for objects disappearing; sounds effects for objects appearing or disappearing; and visual information showing the available time to perform an action and number of objects caught. The main characteristic of the game is the possibility of performing the tasks in 1PP and 3PP, an option not commonly used among rehabilitation applications. Most applications rely either on only one user perspective.


Figure 1: RehabJim in the first-person perspective

The game art uses a low polygon design with cartoon styles. The patient's avatar is a simplification of a human body, while a cartoon-styled skeleton represents the therapist. Figure 3 shows the base 3D models used in the application. The avatar replicates the body movements based on the Kinect tracking data. However, the head position is determined by the tracking glasses position. A PS3 Wand Controller or Speech Recognition allow the patient or therapist to interact with the system settings.

The game offers three training types and a tutorial. *Progressive Training* places objects progressively farther from the user, *Custom Training* read the object positions from an XML file, and *Random Objects* locates the objects 70 cm away from the user on a constrained surface of a

Figure 2: RehabJim in the third-person perspective

sphere. The experiments done in this research used the *Random Objects* Training. Additionally, the objects appear in an area always visible from the 1PP.

Within each training type, the patient can experience three different training modes:

**Normal** besides the descriptions given above, no alterations or feedback are added to the user movements or virtual objects.

**Distorted** The patient movements are flipped. For instance, the right arm controls the left arm movement and vice versa.

**Trajectory** The hand's movement leave a white trail showing the recent movement paths. Additionally, the application shows a straight red line between the closest hand to the target and the target's position. The application does not force the user to follow the given path.

Each training exercise shows a configurable number of spheres as targets, which appear for at most 8 seconds, and can be performed in any combination of training modes. Currently, RehabJim only has one background scene representing an open nature area.

Originally the avatar had no transparency; thus, it occluded objects that appeared in front of it in 3PP. We added a transparent material to avoid this problem. Also, we updated the texture of the targets from a basic color material to a wool-like red texture to improve the contrast with the environment. Objects in the scene suffered updates in rotation and calibration to avoid problems in positioning when changing the position of the Kinect sensor. Additionally, we changed the camera manipulation for changing between perspectives. The first release always placed the camera at the center of the CAVE2 and translated forward or backward all the elements in the scene when changing user views. We preferred to only apply modifications in the camera position while leaving all the other elements in the scene untouched. These last change gave us more understandable tracking logs and simplified the calibration procedure. Finally, we added the possibility of choosing the object sizes for each exercise.

## 4.2 CAVE2 - A Large Scale Virtual Reality Environment

CAVE2 is a cylindrical VR environment composed of seventy-two displays arranged in eighteen columns that create a view of 320 degrees with a resolution of 36 Megapixels per eye (54). An arrangement of fourteen Vicon IR cameras over the displays track the position of retroreflective markers, including position and orientation. A pair of tracking glasses, PS3 wand controllers, and XBox controllers have markers attached to them. For the purpose of this implementation, we use the tracking glasses to represent the patient and a PS3 wand controller to access to the application menu and calibration options.

The CAVE2 environment has a total walkable area of approximately 34 square meters. However, the application is designed to keep the patient in the center of the environment which defines the origin of the coordinate system in the virtual environment. Even though the objects displayed in RehabJim appeared about the patients position, the center of the CAVE2 is the most convenient place for the exercise due to the constraints imposed by the Kinect V2 sensor used. The environment also offers an arrangement of twenty speakers and two subwoofers (54) mounted at the top and bottom of the columns. The capability of providing stereo 3D is taken into account in RehabJim to enhance the sense of immersion and provide audio feedback for the user actions.

The environment supports the development of applications on Linux and Windows. For Linux, the applications should be developed using the omegalib middleware(55), a wrapper over OpenGL, OpenSceneGraph and Vtk applications. Omegalib applications can use python or C++ programming languages. For Windows, CAVE2 supports applications developed in the Unity3D game engine using the getReal3D(56) plug-in. The plug-in, developed by Machdyne, is responsible for correctly displaying a scene on each of the 72 screens. getReal3D currently supports up to Unity3D 5.5, but RehabJim used Unity3D 5.2.3.

### 4.3 Data Gathering

Kinect V2 (Kinect for XBox One) is a natural user interface device capable of tracking twenty-five joints per person and at most six skeletons in a single scene(57). The improvements in its hardware in relation with its antecessor allows a higher depth fidelity, getting data at a frequency of 30Hz from objects in a range of 0.5 to 4.5 meters in front of it, and in a field of view of 70 x 60.

We aimed to develop a non-intrusive virtual rehabilitation application. Thus, the Kinect sensor fit our requirements and we were able to keep the amount of wearable tracking devices on the user to only the tracking glasses. The Omicron SDK provided the interface to obtain motion capture (mo-cap) data in the Unity application. The first version of RehabJim captured data for hands, elbows, shoulders, hips, knees and ankles to locate the position of the Generic Boy


Figure 3: Generic Boy and Generic avatar used to represent the patient and therapist respectively. Avatars created for Unity by BITGEM(1)

and Generic Skeleton avatars. The former representing the patient while the latter representing the therapist.

We updated the RehabJim application to also account for the data of the hand tips, thumbs, wrists, neck, spine-shoulder, spine-mid, spine-base and feet in addition to the already captured data. The head position was provided by the head tracker data processed by the Vicon Bonita cameras. The addition of the new data allowed a better display of bones rotations in the avatar making the movements more realistic though their cartoonish style. Specifically, the rotation values for the forearm gameobject calculated with the elbow and hand positions were replaced by calculations between the wrist and elbow. In a similar way, the hand rotations are now

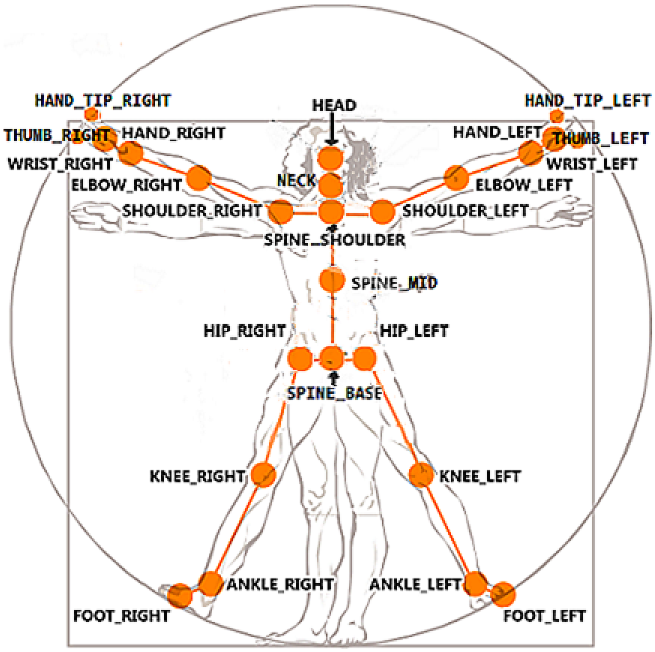


Figure 4: All possible joint data provided by the Kinect for XBox One sensor. RehabJim stores the listed data points except for the head. The Vicon Bonita cameras provide the head position and rotation. Image from Microsoft's website(2)

calculated by using the hand tip - hand positions. It is important to mention that the Omicron SDK(58) update for July 2016 did not provide information about joints rotations.

### 4.4 Environment Calibration

Acquiring precise tracking data was a major project concern. The precision depended on two main components: Vicon cameras calibration and Kinect V2 calibration. We calibrated the VICON cameras following the manufacturer's recommended procedure. First, we fed each of the fourteen cameras with movement data by moving a long piece of metal with attached reflective trackers in front of them. Then we proceeded to locate the center of the CAVE2 environment by place a metal tracker on the floor with a 90 degrees orientation between the front and the lateral screen.

Originally, the Kinect V2 location was under the central CAVE2 screen column, only a 22 - 27 cm from the floor. That position reduced the Kinect field of view in approximately half and produced a bounciness effect on the hands when the users extended their arms in front of them. To minimize these tracking problems, we decided to relocate it to follow Microsofts recommendations: the device should be at least 60 cm and at most 180 cm from the floor. Thus, we placed the Kinect on a tripod at 73 cm from the floor and 19 cm in front of the lower screen. The depth sensor was aligned to be approximately at the displays horizontal midpoint. Then we manually rotated the device and tripod to make it form a parallel coordinate system with the floor.

All the alignments made were crucial as we required to perform translations between the positions of in the Kinects coordinate system, whose origin stands at the location of the depth sensor, and Unitys coordinate system, defined at the CAVE2 center point. We validated the calibration of the environment by rendering the calibration scene in RehabJim.

A tripod carefully placed a 15 cm diameter styrofoam sphere at three different locations inside the CAVE2. At each site, the center of the object approximately matched the position of its virtual representation. A user using the tracking glasses proceed to walk around the tripod and evaluated if the styrofoam sphere completely occluded the virtual sphere rendered on the

Figure 5: In front, tripod with 15 cm diameter Styrofoam sphere used to calibrate the environment. Behind, Kinect sensor reallocated to meet Microsoft's requirements.

screens. The initial results suggested that the scene was rotated. After rotating the CAVE2 center by about five degrees, the scene looked more adjusted to reality. Further evaluation of the sphere occlusion suggested that there is 0.5 - 1.0 cm displacement between the styrofoam sphere and the virtual sphere. However, we believe that this calibration error would not have any considerable impact in the user study as the avatars hand colliders are bigger than an average hand size. Therefore, the size reduces the chances of failing to touch the object.

To adjust the scene rendering to each particular subject, we also consider inputting their inter-pupil distance measurement at the beginning of each exercise. The scene calibration and measurement of the inter-pupil distance overcome the assumptions made by Rottigni(7) during his user study.

## 4.5 Calibration Scene

During the environment calibration we aimed to align the Z-axis from the Kinect and Unity, represented by the direction from the CAVE2 to the middle display; and the X axis which should be parallel between the two systems. We realized that we would not be able to obtain acceptable data points if we did not make translation corrections to the positions by code. We created a calibration option that allowed to reposition the avatar in the X, Y and Z axis and store the calibration values in a configuration file. Stored values represent the offset between the CAVE2 center and the position of the center of the Kinect depth camera. We used the following steps to obtain accurate offset values:

1. Place a user in the center of the CAVE2 and enter to calibration mode.
2. Using the 3PP, update the Y axis offset such that the avatar is standing on the floor. Use the hands positions to validate that the height of the person is correct.
3. Using the 1PP, update the Z axis offset such that the projection of the arms when extending them horizontally to the side displays is correctly aligned (nodes 9 and 29).
4. Using the 1PP, update the X axis offset such that the projection of the arms when extending them horizontally to the front display is correctly aligned (node 19).

This simple procedure allows a fast repositioning of the Kinect in the CAVE2, saving a considerable time of manual and hard coded calibration of the device. We further notice that the instrument could be calibrated to account for possible rotations in the Kinect coordinate system. However, we did not implement the procedure as the tripod positioning and calibration scene obtained accurate values at the CAVE2 center. Future requirements as allowing the patient to walk around the scene would certainly required to account for coordinate system rotations.

## 4.6 Summary

We updated the CAVE2 application RehabJim. Calibration improvements, objects rotations, and scaling give a more accurate tracking and representation of the patient movement. Changes in camera positions manage the transition between 1PP and 3PP in a direct way. Avatar transparency avoids targets occlusion in 3PP while targets textures give more contrast with the environment. We added some control to the difficulty by providing the selection of different object sizes. The new approach for placing objects in the scene guarantee that the object will always be inside the FOV in 1PP. Finally, we update the log module to give more joints data and performance information per patient.

# CHAPTER 5

# METHODS

## 5.1 Environment Constraints

Given RehabJim's object reaching nature, a primary design concern was choosing the location to place the objects within the virtual environment. A 3PP does not impose any constraint, we could opt to place the object anywhere, and the patient would always see them. However, a 1PP imposes restrictions in the field of view inside the CAVE2. In the 1PP, the vertical field of view only displays the image seen over the user's shoulders to approximately thirty degrees up. Analogously, the users would only see their hand and forearms within a shoulder flexion range of 90 - 120 degrees. The horizontal field of view did not have any problem; the user just required to make a head rotation to see more than 180 degrees of screen space.

Therefore, the 1PP did not allow freedom to place the objects anywhere; they would require being inside the field of view to allow the patient object interaction. Due to our interest in comparing the perspectives under the same conditions, we had to constrain the possible space for the objects to appear in both perspectives, by default, restricting the shoulder flexion in both settings.

The objects appeared at a random position 70 cm away from the joint between the subject shoulders ("shoulder-spine" in Kinect's jargon) and within the screen constraints described above for each experiment.

## 5.2 Participants

The Institutional Review Board (IRB) approved the user study under the Protocol # 2016-0332. We initiated the recruitment using the mailing list for undergraduate and graduate students from the Engineering Department at UIC and pasting posters around the UIC East Campus. We wanted to obtain subjects mainly new to virtual reality technologies but did not limit our scope by leaving out experienced users.

Thirty students (8 women and 22 men), aged 18-32 (M=24.57 years, SD=3.57) from the University of Illinois at Chicago (UIC) volunteered to participate and completed all the required exercises. Almost all the participants were affiliated with the departments of the UIC College of Engineering. Their experience with virtual reality technologies was diverse; eight of them were new to VR, fifteen of them had little experience with commercial headsets (Oculus, HTC Vive, Google Cardboard), and seven of them had major experience with VR devices including the CAVE2 environment. Ten of the subjects used either glasses or contact lenses, but no one declared to have stereoscopic vision problems or other eyes condition. The average distance from the pupil to the nose was 3.1 cm (SD=0.33), and the average height was 173.8 cm (MIN=155, MAX=193, SD=9.34). Figure 6 shows the ethnic race distribution for the participants of the user study.

Besides this sample population, we had three more subjects whose data was removed. The first two due to a bug in the object positioning algorithm, and the last one for not following the instructions during the training session. The bug in the algorithm allowed the objects to appear outside the field of view of the screen in the first-person perspective, thus, increasing the

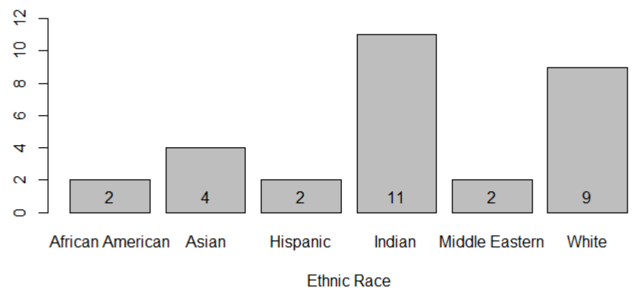


Figure 6: Ethnic race distribution of the subjects that successfully completed the exercises in the pilot user study

completion time even though the subjects could have been skillful enough to catch the object faster.

### 5.3 Apparatus

We performed the user studies in the CAVE2 environment at the Electronic Visualization Laboratory (EVL). We used the Vicon™ Bonita infrared cameras and the Kinect™ for Xbox One™ as the tracking systems. The former tracked the head through retroreflective markers on the 3D glasses, and the latter gathered data from the rest human joints. The application saved the resulting data in the CAVE2 Master Node computer in JSON format(59).

Other materials used include a Panasonic Lumix™ wide-angle video camera for video recording each session and the SUNWIN™ Pupillary Distance Ruler to measure the subject's inter-pupil distance. At the end of each session, we provided two questionnaires, one per user perspective.

| Package | Functions |
|---|---|
| forecast(62) | Box-Cox(63) lamba and data transformation |
| car(64) | Levene's test(65) for homogeneity of variance |
| nortest(66) | Lilliefors (Kolmogorov-Smirnov) test (67) for normality |
| R Stats | Shapiro-Wilk test (68) for normality |
| moments(69) | Kurtosis, Skewness |
| ez(70) | ANOVA for repeated measures |
| ARTool(71) | Nonparametric ANOVA for repeated measures |

TABLE I: R packages used in the statistical analysis

For post-processing the data we used Python scripts. The data analysis was done with two statistical software: G*Power(60) (v 3.1.9.2) for the power analysis and R(61) for the remaining statistical tests. Table I lists the R packages used for the statistical calculations.

## 5.4 Procedure

The facilitator in charge of all the user studies hosted each user at a time. Besides assuring that each session followed the required protocol, he responded to any questions and video-recorded each session using a wide-angle camera.

At the beginning of the meeting, the user read and gave consent to the Informed Consent and Media Consent forms required by the IRB protocol. The facilitator told each user that the study aimed to analyze differences in performance metrics, movement kinematics and immersion levels in a reaching objects tasks. After gathering demographic data and the inter-pupil distance value, the facilitator updated the parameter in the CAVE2 application launcher. Later, he proceeded to describe the CAVE2 environment technical details, typical domains of application and started a short demonstration of the RehabJim game perspectives and training modes. Then the subject performed two rounds of exercises combining the two user views and the three training modes. If required, the facilitator gave more time to make sure that the subjects were confident about their adaptation to the environment. No user manifested any motion sickness problem with the VR settings. Before starting the exercises, the facilitator described the experiment guidelines:

- The subject should place their arms fully extended next to their bodies. After reaching an object, they should return their arms to the initial position.
- At any moment, the subject can require to take a break or stop the user study session. The user study session would be resumed after the user consent.
- The subject will start using a perspective assigned randomly.

Table II shows all the available exercises. A whole session consisted on twelve exercises that combined the 1PP and 3PP, the three training modes (normal, distorted and trajectory) and two ball size (15 cm diameter and 10 cm diameter). Additionally, each exercises showed twenty objects.

At the end, the subjects filled two survey. One consisted of a set of adapted questions from the IEQ questionnaire(21) for 1PP, while the other one had the same set of questions but for 3PP. The facilitator instructed the subject to start filling the surveys in the same order they experienced the perspectives during the session.

| Exercise | Abbreviation |
|---|---|
| 1PP Normal Mode - Object 15 cm | 1n15 |
| 1PP Distorted Mode - Object 15 cm | 1d15 |
| 1PP Trajectory Mode - Object 15 cm | 1t15 |
| 1PP Normal Mode - Object 10 cm | 1n10 |
| 1PP Distorted Mode - Object 10 cm | 1d10 |
| 1PP Trajectory Mode - Object 10 cm | 1t10 |
| 3PP Normal Mode - Object 15 cm | 1n15 |
| 3PP Distorted Mode - Object 15 cm | 1d15 |
| 3PP Trajectory Mode - Object 15 cm | 1t15 |
| 3PP Normal Mode - Object 10 cm | 1n10 |
| 3PP Distorted Mode - Object 10 cm | 1d10 |
| 3PP Trajectory Mode - Object 10 cm | 1t10 |

TABLE II: Exercises used during user study.

### 5.5 Hypothesis

We focused our main analysis in the performance metrics given by the *Completion Time*, *Number of objects reached*, and the subjective metric of *Immersion Level* provided by the environment. The completion time is the total time required to touch an virtual object under a specific treatment condition; it accounts for sum of the reaction time and movement time. The number of objects reached represents the user score after finishing capturing the objects in an exercise. The immersion level is a subjective metric gathered by a questionnaire.

Previous work by Rottigni(7) (N=10) suggested that there is a difference in the average completion times for a given task under different perspectives. Specifically, tasks done using the 3PP required less time to be completed than the ones in 1PP. Also, there were no suggested differences between scores in any of the treatment conditions. Building on that point, we present the following main hypothesis:

**Hypothesis 1** The completion time for an exercise in 1PP and 3PP are equal.

**Hypothesis 2** The number of objects reached is the same under any training mode in 1PP and 3PP.

For the level of immersion, we believed that a 1PP would create a more immersive experience as it could be understood as an extension of the human body.

**Hypothesis 3** The immersion level in 1PP is the equal to the immersion level in 3PP.

Rottigni also presented a metric called *Object Position Detection Errors*, which represented the movement corrections that a user needed to do to catch an object. The authors calculated this metric manually through the observation of video recordings. Each attempt to capture an object was qualified between three levels depending on the deviation from a natural movement. Rottigni's results showed that there were significantly more errors in the 1PP on the normal mode (p-value=0.0036), and in trajectory mode (p-value=0.0092). From this previous work we present the following hypothesis:

**Hypothesis 4** The number of movement corrections in 1PP and 3PP are equal.

Our secondary analysis focuses on the body movement under each user perspective. We compare measurements of head, hands and movement straightness. We used an index of sinuosity to calculate the movement straightness. Archambault(72) defines it as an index of deviation from a straight line connecting the start position and the endpoint. This measure of trajectory shape is a ratio between the total movement made by the hand and the straight line connecting both points at the beginning of the movement (an ideal movement would have a value of 1).

We hypothesize that the body movements are different under the different user perspectives. Thus, we expect to reject the following hypothesis:

**Hypothesis 5** The distance traveled by the primary hand is equal on each user perspective.

**Hypothesis 6** The distance traveled by the head is equal on each user perspective.

### 5.6 Statistical Approach

Our pilot experiment focused on finding differences in population means for the dependent variables under specific treatment conditions. These conditions were the result of the combination of three categorical (nominal) factors: ($k_1$) Perspective (First-Person, Third-Person), ($k_2$) Training Mode (Normal, Distorted, Trajectory) and ($k_3$) Target (Big Sphere, Small Sphere). Individual factors or an interaction between may be responsible for differences in sample means. However, as each subject was exposed to all these treatment conditions in twelve distinct exercises, they may also be a responsible factor. We ended with a balanced design with repeated measured within-subjects.

A two-way ANOVA test with replications can analyze the data, but variations within subjects would be treated as an error. Also, it would not account for the repeated measures. Instead, we selected a two-way (multi-factor) ANOVA with a within-subject design to attribute differences to dissimilarities among subjects. Statistically, the within-subjects test improves the power, by providing more samples, and reduces the error variance(73). Additionally, it saved time as each subject provided twelve samples.

Similarly to a two-way ANOVA, the within-subjects design has assumptions about the data. We checked the data for normality using the Lilliefors (Kolmogorov-Smirnov) normality test. We also used the more conservative Shapiro-Wilk test but guided our analysis based on the previous Lilliefors test. The within-subjects design violates the independence of errors assumption of the ANOVA; thus it uses the Sphericity assumption. We checked the sphericity assumption using the Mauchly's test. If the data violated the Sphericity assumption, we arranged the F statistic by adjusting the degrees of freedom using the Greenhouse-Geisser correction, and the more conservative Huynh-Feldt correction. Researchers have criticized the Mauchly's test for failing to report accurate values for small samples and being over-detecting in large samples (74); thus, we contrasted the results with the corrected values.

For data not normally distributed, we evaluated if transformation functions as the logarithm function, square root function or Box-Cox(63) function could rearrange the normality. If so, we proceeded with the ANOVA within-subjects test with the transformed data. However, we reported means and standard deviation as non-transformed data for readability.

Otherwise, for non normally distributed data, we used Wobbrock's Aligned Rank Transform (ART) test(75) for repeated measures. We did not use the Scheirer-Ray-Hare, a nonparametric analogous of the two-way ANOVA (76), because we did not find recommended posthoc analysis methods.

We performed posthoc analysis for statistically significant results ($p<0.05$) obtained only from the ANOVA test and the ART test. For the parametric ANOVA, we chose the pairwise comparison with the Holm-Bonferroni adjustment. For the nonparametric ART, we further analyzed significant differences using a cross-factor contrast test named *differences of differences* which is suggested by ART's authors (71) for interactions, and pairwise comparison for independent factors.

The level of immersion did not require a multi-factor ANOVA because we just compared the perspective factor. In this scenario, we used a one-way ANOVA or the Kruskal-Wallis test depending on the violation of the ANOVA assumptions. We used the same methods described above for checking the normality, and we further checked for homogeneous variances using the Levene's test.

### 5.6.1 Power Analysis

The design of the pilot experiment exposed each subject to twelve different exercises in one session. Thus, we assume that each subject provides twelve samples; each for every treatment condition.

We performed a Power Analysis to estimate the number of samples required in the pilot experiment. Given that we did not have previous data to estimate the effect size, we chose to use the conventions small ($f = 0.10$), medium (*0.25*), and large ($f = 0.40$) proposed by Cohen(77). We set $\alpha$=.05, power 1-β= .90, and number of groups = 12 ($k_1$x$k_2$x$k_3$).

Within G*Power(60), we used the *A priori* power analysis for the *ANOVA: Fixed effects, special, main effects and interactions* statistical test. We estimated the sample size for the independent factors $k_1$,$k_2$ and$k_3$, and for the interaction between them. From the different sample size pools we selected the highest number with the assumption that at most we would get 30 subjects.

To obtain a power of 0.95 and a small effect size, we would require to have 1548 samples or approximately 129 subjects. However, a medium effect size would only require 251 samples or 21 subjects. Figure Figure 7 plots an estimation of the total sample size required for obtaining a given Power. We ended obtaining 30 subjects for the pilot user study.

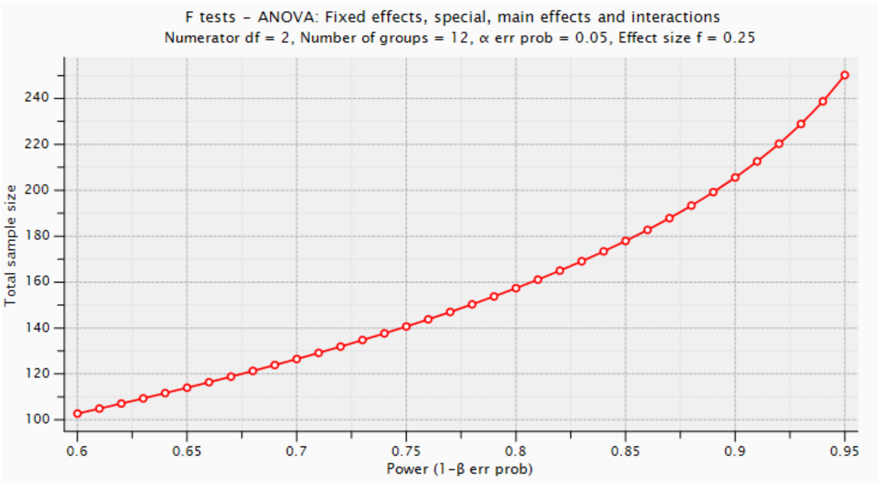


Figure 7: Power vs Total Sample Size

### 5.6.2 Assumptions and Threats to Validity

Confounding variables as fatigue and practice can affect a within-subject design. On the one hand, fatigue, either physical or mental can have adverse effects on the performance of the last exercises. However, the practice can produce a training effect due to adaptation and recognition of patterns in the activities, which could reduce the completion time required to finish a task and increase the quality of the movements. To minimize the effects this internal validity, we randomized the starting perspective for each subject; however, the exercises per perspective had a defined order. Not performing a total randomization of the exercises is a drawback of the experiment design but we assumed the values to wash out. Additionally, we regularly asked the subjects to take a break if required to minimize the fatigue. In average, each subject spent 25 minutes per session inside the CAVE2.

We assume that the results of this pilot user study are generalizable to a population of young adults. By having a reduced number of subjects with experience with the CAVE2 environment, we aim to generalize the results to people with almost non-experience with virtual reality. We can not assume that we can extend the results to the older adults, which is the biggest population of stroke patients.

Furthermore, we assume that the environment conditions were constrained to avoid the subjects from distractions from the real world. The controls included reducing the background noise and adjusting the lighting conditions. Changes in temperature were not under our control.

# CHAPTER 6

# RESULTS

For each dependent variable, we started by presenting a plot that superimposes a violin plot and a point plot. The violin plot compares side by side the histograms for the values of the factor on the X axis, and displays with dotted lines the quartiles. Meanwhile, the point plot marks the mean value for the distribution and shows a confidence interval around that point. For contrasting purposes, we have used two colors for the each variable, one for the violin distribution and the other for the line connecting means. Later, we contrasted the insights obtained from the plots with the results of the statistical tests.

## 6.1 Completion Time

Completion Time stands for the total time required to finish each exercise under a particular treatment condition. Based on the previous results obtained by Rottigni(7), we hypothesize that "*H1: Completion Time in 1PP == Completion Time in 3PP*".

We plotted interaction plots superimposed on violin plots to observe the effect of two factors and the interaction between them, and get first insights on the non-transformed data. Interaction plot in Figure 8 showed an effect of the perspective under the distorted, and a smaller effect on the trajectory mode. Also, it suggested an apparent effect of the *mode* factor in the distorted mode. Lines crossing between the distorted mode and normal modes indicated an effect of the

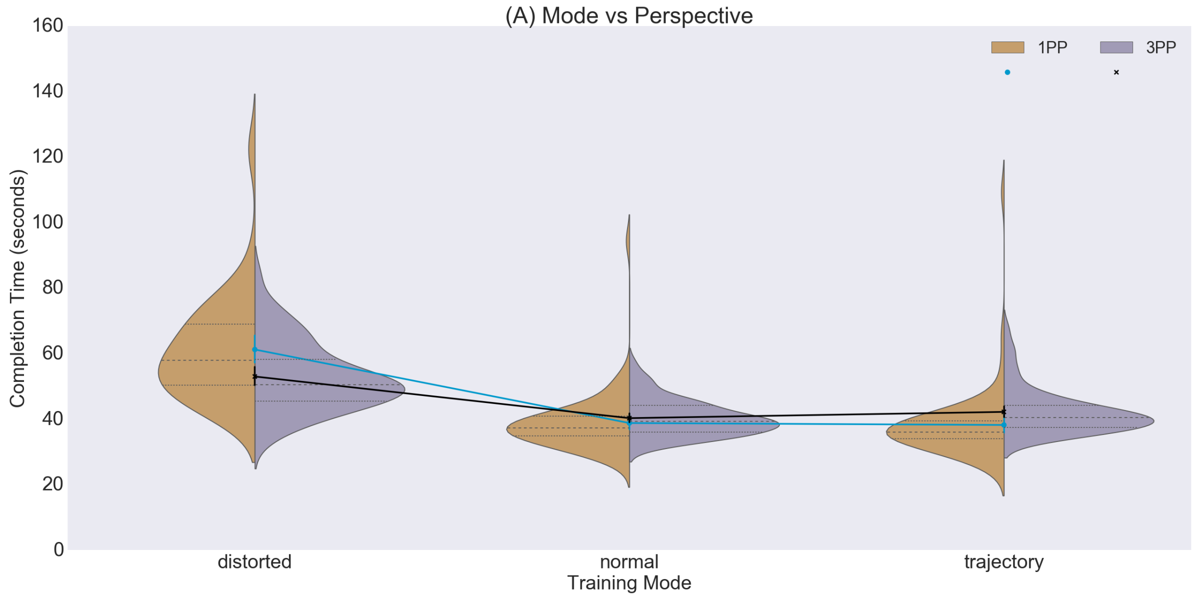


Figure 8: Mode vs Perspective on Completion Time

interaction perspective - mode; interaction effect that is less obvious between normal mode and trajectory mode where we can see "alligator jaws".

Interaction plot in Figure 9 did not suggest any effect caused by the perspective factor, ball size factor nor the interaction between both. Even though the lines seems to be not parallel, the confidence intervals suggested that the difference was not significant. Finally, the plot in Figure 10 indicated only an effect of the mode, which probably is not significant between the normal and the trajectory modes.

We checked the data for normality after transforming the data using the Box-Cox function and obtained a p-value = .094 after applying the Lilliefors test and a p-value = .044 with the Shapiro-Wilk test. This last value indicated that the data did not follow a normal distribution.

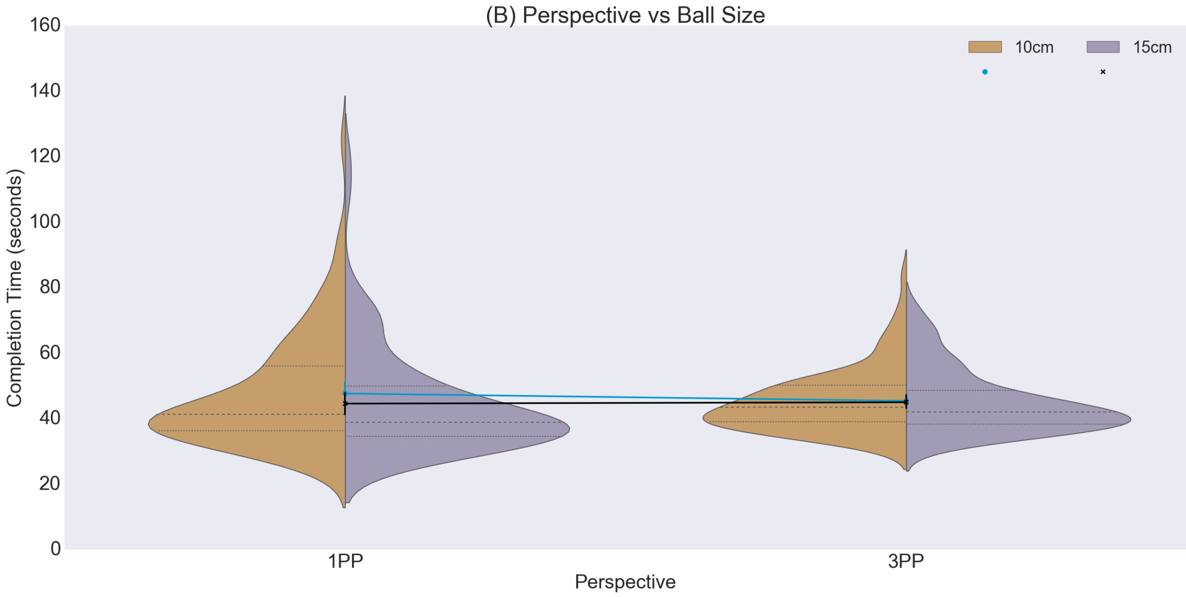


Figure 9: Perspective vs Ball Size on Completion Time

However, we decided to follow the Lilliefors test value and proceed with a parametric approach. We also obtained a skewness of -0.046 and a kurtosis of -0.205.

Completion Time data were analyzed using a ANOVA with within-subjects factor of perspective, mode and ball size. The two-way ANOVA test reported significant values for perspective ($F_{1,29}$=7.491, $p$ = .01, $\eta^2$ = .019), mode ($F_{2,58}$=200.368, $p$ = .0, $\eta^2$ = .461) , ball size ($F_{1,29}$=10.947, $p$ = 0.003, $\eta^2$ = .013), perspective:mode ($F_{2,58}$=39.66, $p$ = .0, $\eta^2$ = .085), and perspective:ball size ($F_{1,29}$=6.759, $p$ = .015, $\eta^2$ = .007). The Mauchly's test indicated that the data did not violate the sphericity assumption. Moreover, the sphericity correction values for supported the results. From our initial insight, we reject the interaction between the mode and the ball size, but support the other suggested effects.

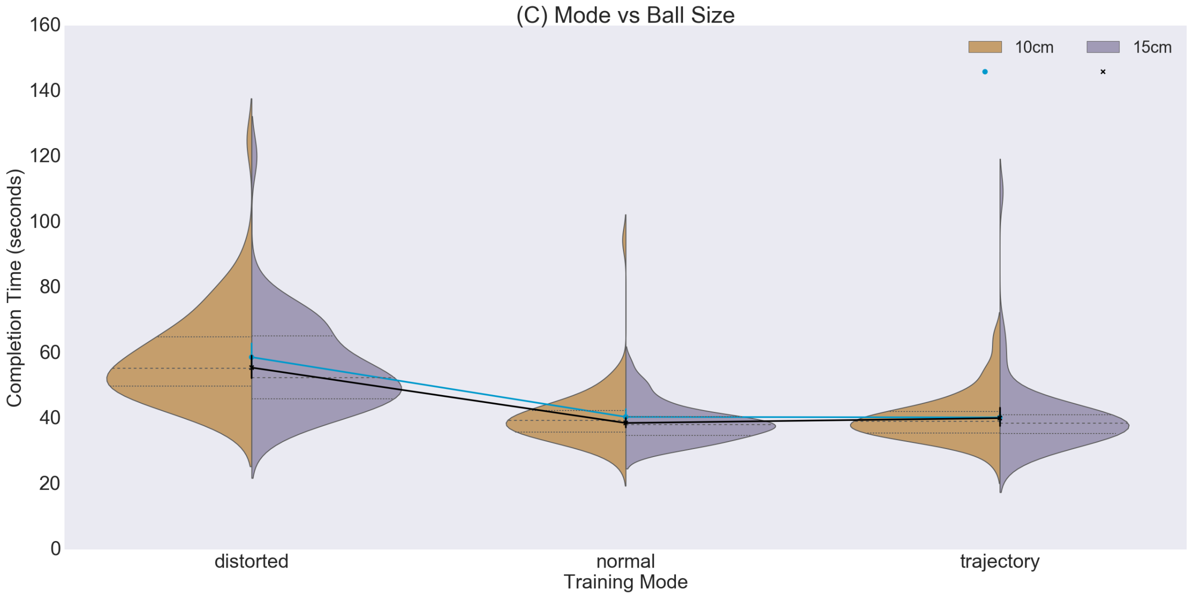


Figure 10: Mode vs Ball Size on Completion Time

A posthoc analysis using the Holm-Bonferroni pairwise comparisons suggest that the distorted training mode was the main responsible for taking more time for the tasks the be completed. By changing only the Mode, there was no significant difference in completion time between the normal and the trajectory options. The main effect for the Mode explained approximately 46.1% of changes in variance. Perspective factor alone had a small effect ($\eta^2 = 0.021$), and it was the only **not** significant for exercises in normal mode with smaller objects. In 1PP, tasks under trajectory mode required less time than in 3PP; but in distorted mode, tasks required more time.

Interaction Perspective - Mode accounted for the second major effect ($\eta^2 = .085$). Exercises in the distorted mode were always slower than any other activities not involving this mode.

Also, there were two differences in tasks not using the distorted mode: the exercise 3-n-15 was slower than 1-t-15 (p-value=0.0070) and, 3-t-15 was slower than 1-n-15 (p-value<0.0001). In both cases, the 1PP was faster.

Changes in the object size claimed the third biggest effect ($\eta^2 = .013$). However, the posthoc analysis did not report any significant comparison when only changing the ball size. Finally, the interaction between perspective and ball size suggested that trajectory exercises were faster in 1PP, but did not have a consistent winner on the other two modes.

In summary, from the six combinations of mode and ball size, changes in perspectives had a significant impact on the completion time except for the exercise in normal mode with smaller objects. We have evidence to reject the hypothesis 1; the completion times are different between perspectives. However, the perspective does not account for the biggest effect on the variance in time.

## 6.2 Immersion Level

Immersion level was calculated as the summation from questions 1 to 30 in the questionnaire. Questions 6, 8, 9, 10, 17 and 19 look for negative answers; thus, their scores were inverted. The data, transformed with the Box-Cox function, passed the Lilliefors test (p-value = .1192) and the Levene's test (p-value=.766). The kurtosis was -0.52 and the skewness -0.33. The summation of scores from the questionnaire for immersion level was analyzed using a one-way ANOVA. We obtained non-significant differences for the immersion level under the two perspectives ($F_{1,58} = 0.59$, p-value=.445).

| **Mauchly's Test of Sphericity** | | | | |
|---|---|---|---|---|
| **Effect** | **Mauchly's W** | **Sig.** | **Greenhouse-Geisser $\epsilon$** | **Huynh-Feldt $\epsilon$** |
| Mode | 0.9653835 | .6107 | 0.9665417 | 1.034335 |
| Perspective:Mode | 0.9856896 | .8172 | 0.9858915 | 1.057293 |
| Mode:Ball Size | 0.9842254 | .8004 | 0.9844704 | 1.055605 |
| Perspective:Mode:Ball Size | 0.9937285 | .9157 | 0.9937676 | 1.066657 |

| **Test of Within-Subjects Effects for Completion Time** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | | **DFn** | **DFd** | **F** | **Sig.** | $\eta^2$ |
| Perspective | Sphericity Assumed | 1 | 29 | 7.49 | **.0100** | .021 |
| Mode | Sphericity Assumed | 2 | 58 | 200.37 | **<.0001** | .461 |
| | Greenhouse-Geisser | 1.93 | 56.06 | — | **<.0001** | — |
| | Huynh-Feidt | 2.07 | 59.99 | — | **<.0001** | — |
| Ball Size | Sphericity Assumed | 1 | 29 | 10.95 | **.0030** | .013 |
| Perspective:Mode | Sphericity Assumed | 2 | 58 | 39.66 | **<.0001** | .085 |
| | Greenhouse-Geisser | 1.97 | 57.18 | — | **<.0001** | — |
| | Huynh-Feidt | 2.1 | 61.3 | — | **<.0001** | — |
| Perspective:Ball Size | Sphericity Assumed | 1 | 29 | 6.759 | **.0150** | .007 |
| Mode:Ball Size | Sphericity Assumed | 2 | 58 | 0.31 | .7360 | <.0001 |
| | Greenhouse-Geisser | 1.97 | 57.10 | — | .732 | — |
| | Huynh-Feidt | 2.1 | 61.23 | — | .736 | — |
| Perspective:Mode: Ball Size | Sphericity Assumed | 2 | 58 | 1.024 | .3660 | .001 |
| | Greenhouse-Geisser | 1.99 | 57.64 | — | .3650 | — |
| | Huynh-Feidt | 2.1 | 61.87 | — | .3650 | — |

| **Holm-Bonferroni Pairwise Comparison** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.d.10 | 3.d.10 | 1.n.10 | 3.n.10 | 1.t.10 | 3.t.10 | 1.d.15 | 3.d.15 | 1.n.15 | 3.n.15 | 1.t.15 |
| 3.d.10 | **.0002** | – | – | – | – | – | – | – | – | – | – |
| 1.n.10 | **<.0001** | **<.0001** | – | – | – | – | – | – | – | – | – |
| 3.n.10 | **<.0001** | **<.0001** | 1.00 | – | – | – | – | – | – | – | – |
| 1.t.10 | **<.0001** | **<.0001** | .8250 | .4250 | – | – | – | – | – | – | – |
| 3.t.10 | **<.0001** | **<.0001** | .4250 | .4250 | .0440 | – | – | – | – | – | – |
| 1.d.15 | .2000 | .3850 | **<.0001** | **<.0001** | **<.0001** | **<.0001** | – | – | – | – | – |
| 3.d.15 | **<.0001** | .5880 | **<.0001** | **<.0001** | **<.0001** | **<.0001** | **.0160** | – | – | – | – |
| 1.n.15 | **<.0001** | **<.0001** | .1520 | **.0030** | 1.00 | **.0003** | **<.0001** | **<.0001** | – | – | – |
| 3.n.15 | **<.0001** | **<.0001** | 1.00 | 1.00 | .4250 | .3210 | **<.0001** | **<.0001** | **.0090** | – | – |
| 1.t.15 | **<.0001** | **<.0001** | .2000 | **.0130** | .4250 | **.0003** | **<.0001** | **<.0001** | 1.00 | **.0070** | – |
| 3.t.15 | **<.0001** | **<.0001** | 0.425 | 0.425 | 0.157 | 1.00 | **<.0001** | **<.0001** | **<.0001** | 0.083 | **<.0001** |

TABLE III: Statistical Results for the **Completion Time**

We also observed the results for the domains that conform the immersion value: "attention, temporal dissociation, transportation, challenge, emotional involvement, and enjoyment"(21). Neither of them provided significant statistical differences in their means after performing one-way ANOVA tests. Table IV reports the mean and standard deviation per domain, experiment and user perspective. Additionally, we aimed to get an idea of the preferred user perspective with question 29: "How much would you say you enjoyed playing the game under this perspective?"(21). 1PP obtained an average of 4.21 (SD=0.83), while third-person perspective got on average 3.86 (SD=0.93). The Kruskal-Wallis test did not report significant differences between user preferences ($\chi^2$=2.72, p-value = 0.0989). In conclusion, we do not have enough evidence to suggest a different in the immersion level cause by the user perspective; thus, we did not reject hypothesis 3.

| | First Person | | Third Person | |
|---|---|---|---|---|
| *Domains* | M | SD | M | SD |
| Attention | 4.59 | 0.82 | 4.52 | 0.80 |
| Temporal Dissociation | 3.65 | 1.29 | 3.54 | 1.32 |
| Transportation | 3.88 | 1.13 | 3.67 | 1.12 |
| Challenge | 3.77 | 1.31 | 3.97 | 1.29 |
| Emotional Involvement | 3.40 | 1.46 | 3.25 | 1.44 |
| Enjoyment | 3.69 | 1.20 | 3.68 | 1.16 |
| Total | 3.81 | 1.28 | 3.72 | 1.27 |

TABLE IV: Mean and standard deviation for the immersion level and domains per user perspective

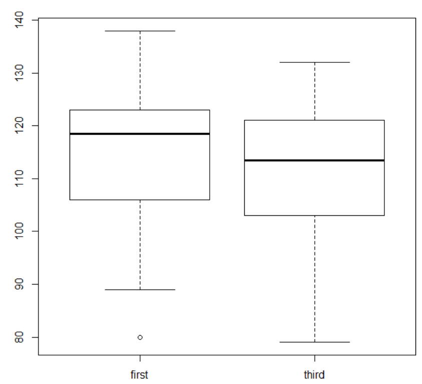


Figure 11: Level of Immersion between user perspectives

### 6.3 Movement Corrections

We defined a movement correction as the hand trajectories that create angle smaller than ninety degrees between three consecutive segments. These actions represent situations when the subject's movement diverse from normal arm movement. Also, the movements only count the errors made with the hand that caught the target. We evaluated the hypothesis 4: the number of movement corrections made in 1PP is the same as in 3PP.

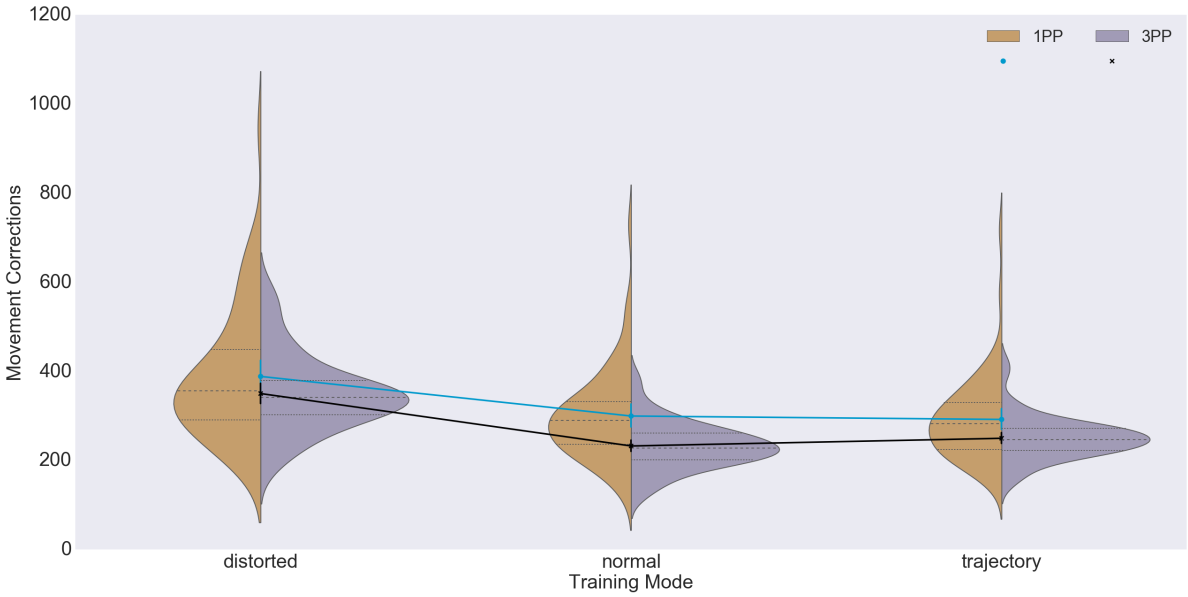


Figure 12: Mode vs Perspective on Movement Corrections

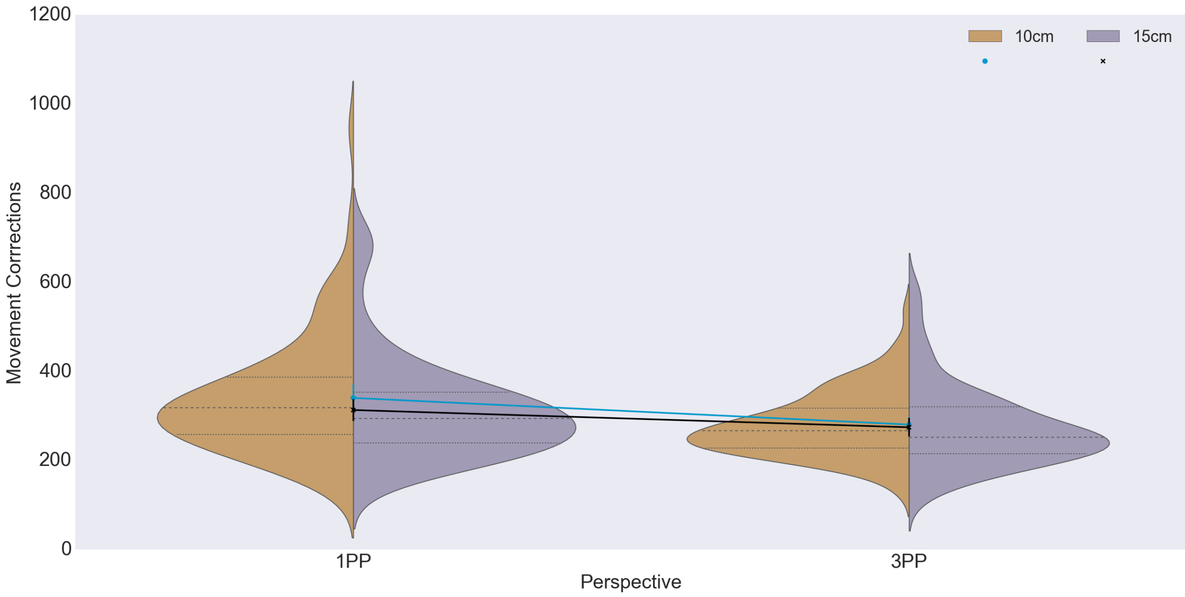


Figure 13: Perspective vs Ball Size on Movement Corrections

Plot in Figure 12 suggested effects caused by the perspective under the normal and training modes; an effect by the mode factor and possibly an effect from the interaction of these two factors. Plot in Figure 13 did not suggest any effect as the confidence intervals overlapped. Finally, plot in Figure 14 suggested an effect of the mode factor.

We checked the data for normality and obtained a normal distribution after a logarithmic transformation (Lilliefors p-value=.0583). The Shapiro-Wilk test did not support the normality (p-value=0.002), but again we referred to the Lilliefors test result. The skewness was 0.43, and the kurtosis was 0.34.

The Mauchly's test indicated that the data did not violate the assumption of sphericity (Table V). A multi-factor ANOVA within-subjects gave significant results for the perspective

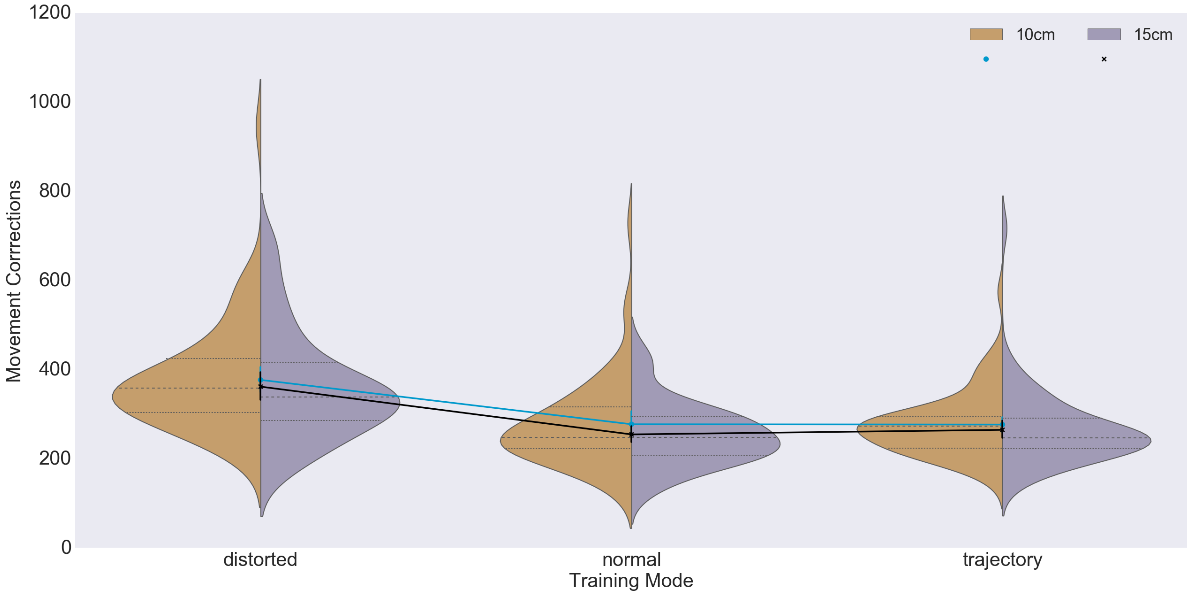


Figure 14: Mode vs Ball Size on Movement Corrections

($F_{1,29} = 15.79$, p-value=.0004, $\eta^2 = .065$), the mode ($F_{2,58} = 128.35$, p-value<.0001, $\eta^2 = .28$), the ball size ($F_{1,29} = 9.65$, p-value=.0042, $\eta^2 = .012$) and the interaction between perspective and mode ($F_{2,58} = 6.58$, p-value=.0026, $\eta^2 = .001$).

The Holm-Bonferroni posthoc analysis suggested that changes only in the mode factor are significant when comparing the normal or trajectory mode against the distorted mode. Thus, the distorted mode explains 28% of the effect in movement errors and provokes the subject to make more errors. Changes between the perspective factor are only significant in normal mode. Subjects under 3PP committed significantly fewer errors than in 1PP. The perspective factor explains 6.5% of the error variance. As opposed to these two individual factors, the posthoc analysis did not report significant differences between ball sizes. Finally, the interaction perspective - mode had more effects on exercises with bigger objects.

In conclusion, we reject the hypothesis 4, the movement errors differ under each perspective, but we emphasize that the perspective is not the main effect of this variance. Most of it is explained by the use of the distorted mode.

## 6.4 Primary Hand Movement

The primary hand refers to the hand used to catch an object. In a case of failure, it is the closest hand to the object. We hypothesized (Hypothesis 5) that the total meters traveled by the primary hand are the same in 1PP and 3PP.

The plot in Figure 15 shows an effect of the mode factor, perspective and an interaction of both. However, differences in perspective were only apparent under the distorted mode. The plot in Figure 16 did not suggest any effects between the perspective and the ball size factors. Finally, plot in Figure 17 showed an effect of the mode between the distorted mode against the normal and trajectory ones.

We checked the data distribution for normality and did not pass the Lilliefors test ($p < 0.0001$). Thus, we evaluated the data using the Aligned Rank Test. We obtained significant values for the mode factor ($F_{2,319}$=168.39, p-value<.0001, $\eta^2 = .192$) and for the interaction between the perspective and the mode ($F_{2,319}$=25.63, p-value<.0001, $\eta^2 = .027$).

We performed a posthoc analysis using a pairwise comparison with a Holm-Bonferroni adjustment for independent factors, and differences of differences for interaction contrasts. The results suggested that the distorted mode generated the main effect in variance for the

| Mauchly's Test of Sphericity | | | | |
|---|---|---|---|---|
| **Effect** | **Mauchly's W** | **Sig.** | **Greenhouse-Geisser $\epsilon$** | **Huynh-Feldt $\epsilon$** |
| Mode | 0.8309968 | .0749 | 0.8554297 | 0.9037621 |
| Perspective:Mode | 0.8866718 | .1856 | 0.8982077 | 0.9537799 |
| Mode:Ball Size | 0.9326465 | .3767 | 0.9368967 | 0.9992883 |
| Perspective:Mode:Ball Size | 0.9552863 | .5271 | 0.9572000 | 1.0232744 |

| Test of Within-Subjects Effects for Movement Corrections | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | | **DFn** | **DFd** | **F** | **Sig.** | $\eta^2$ |
| Perspective | Sphericity Assumed | 1 | 29 | 15.79 | **.0004** | .065 |
| Mode | Sphericity Assumed | 2 | 58 | 128.35 | **<.0001** | .280 |
| | Greenhouse-Geisser | 1.71 | 49.61 | — | **<.0001** | — |
| | Huynh-Feidt | 1.81 | 52.42 | — | **<.0001** | — |
| Ball Size | Sphericity Assumed | 1 | 29 | 9.65 | **.0042** | .012 |
| Perspective:Mode | Sphericity Assumed | 2 | 58 | 6.58 | **.0026** | .015 |
| | Greenhouse-Geisser | 1.80 | 52.10 | — | **.0038** | — |
| | Huynh-Feidt | 1.91 | 55.32 | — | **.0031** | — |
| Perspective:Ball Size | Sphericity Assumed | 1 | 29 | 0.72 | .4046 | .001 |
| Mode:Ball Size | Sphericity Assumed | 2 | 58 | 0.57 | .5661 | .001 |
| | Greenhouse-Geisser | 1.87 | 54.34 | — | .5555 | — |
| | Huynh-Feidt | 2.00 | 57.96 | — | .5660 | — |
| Perspective:Mode: Ball Size | Sphericity Assumed | 2 | 58 | 0.06 | .9378 | <.001 |
| | Greenhouse-Geisser | 1.91 | 55.52 | — | .9316 | — |
| | Huynh-Feidt | 2.05 | 59.35 | — | .9378 | — |

| Holm-Bonferroni Pairwise Comparison | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.d.10 | 3.d.10 | 1.n.10 | 3.n.10 | 1.t.10 | 3.t.10 | 1.d.15 | 3.d.15 | 1.n.15 | 3.n.15 | 1.t.15 |
| 3.d.10 | 1.00 | – | – | – | – | – | – | – | – | – | – |
| 1.n.10 | **.0048** | .0971 | – | – | – | – | – | – | – | – | – |
| 3.n.10 | **<.0001** | **<.0001** | **.0407** | – | – | – | – | – | – | – | – |
| 1.t.10 | **.0002** | **.0124** | 1.00 | .0534 | – | – | – | – | – | – | – |
| 3.t.10 | **<.0001** | **<.0001** | .2037 | .7134 | .3104 | – | – | – | – | – | – |
| 1.d.15 | 1.00 | 1.00 | **.0311** | **<.0001** | **.0086** | **<.0001** | – | – | – | – | – |
| 3.d.15 | 1.00 | 1.00 | .2037 | **<.0001** | .0747 | **<.0001** | 1.00 | – | – | – | – |
| 1.n.15 | **<.0001** | **<.0001** | .7934 | .3104 | 1.00 | 1.00 | **<.0001** | **.0001** | – | – | – |
| 3.n.15 | **<.0001** | **<.0001** | **.0004** | 1.00 | **.0012** | .3298 | **<.0001** | **<.0001** | **.0036** | – | – |
| 1.t.15 | **<.0001** | **<.0001** | .6568 | .3964 | .7880 | 1.00 | **<.0001** | **.0004** | 1.00 | **.0016** | – |
| 3.t.15 | **<.0001** | **<.0001** | **.0118** | 1.00 | **.0057** | 1.00 | **<.0001** | **<.0001** | .0768 | .8170 | .0580 |

TABLE V: Statistical Results for **Movement Corrections** of the primary hand mode factor. For the interaction between perspective and mode, the distorted mode again produced the main effects. In both cases, any exercise using the distorted mode generated longer trajectories in the hand movements.

Given the effect of the interaction between perspective and mode, we can reject the hypothesis 5, though the effect of changes in perspective individually is inexistent. Therefore, primary hand movements are different on each user perspective.

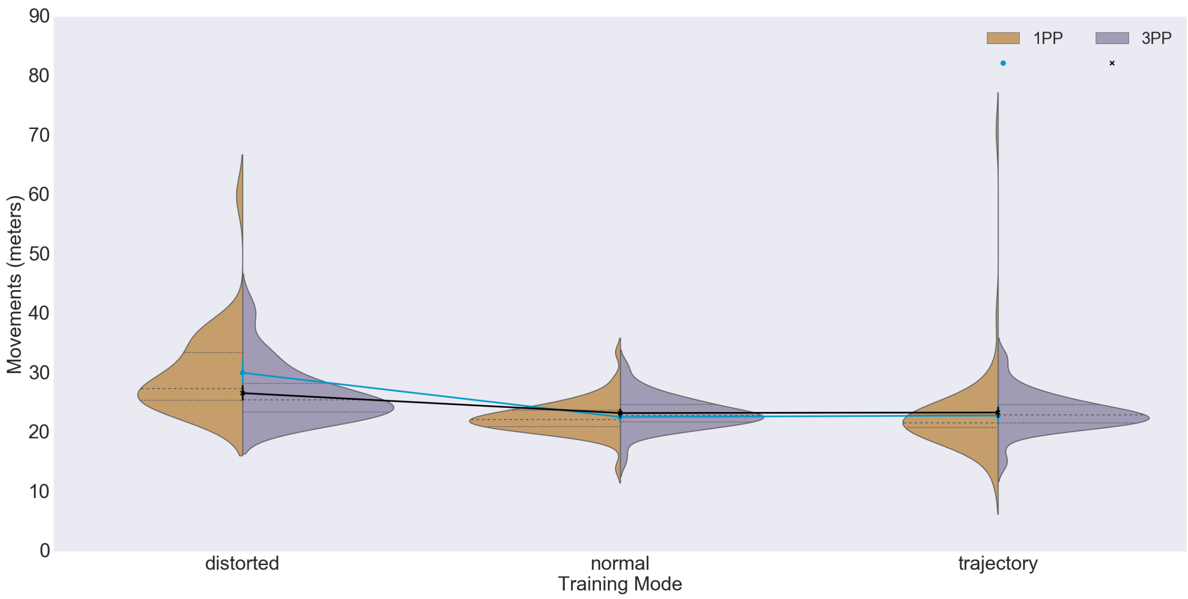


Figure 15: Mode vs Perspective on Primary Hand Movement

| Test of Within-Subjects Effects for Primary Hand Movements | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | | **DFn** | **DFd** | **F** | **Sig.** | $\eta^2$ |
| Perspective | Aligned Rank Test | 1 | 319 | 1.97 | .1612 | .004 |
| Mode | Aligned Rank Test | 2 | 319 | 168.39 | **<.0001** | .192 |
| Ball Size | Aligned Rank Test | 1 | 319 | 0.006 | .9392 | .001 |
| Perspective:Mode | Aligned Rank Test | 2 | 319 | 25.63 | **<.0001** | .027 |
| Perspective:Ball Size | Aligned Rank Test | 1 | 319 | 0.57 | .4504 | <.001 |
| Mode:Ball Size | Aligned Rank Test | 1 | 319 | 0.16 | .8480 | .0007 |
| Perspective:Mode: Ball Size | Aligned Rank Test | 2 | 319 | 0.15 | .8577 | .0006 |

| Posthoc Analysis with Holm-Bonferroni Adjustment | |
|---|---|
| **Contrast** | **Sig.** |
| d - n | **<.0001** |
| d - t | **<.0001** |
| n - t | .5249 |
| 1-3 : d-n | **<.0001** |
| 1-3 : d-t | **<.0001** |
| 1-3 : n-t | .2229 |

TABLE VI: Statistical results for **Primary Hand Movements**

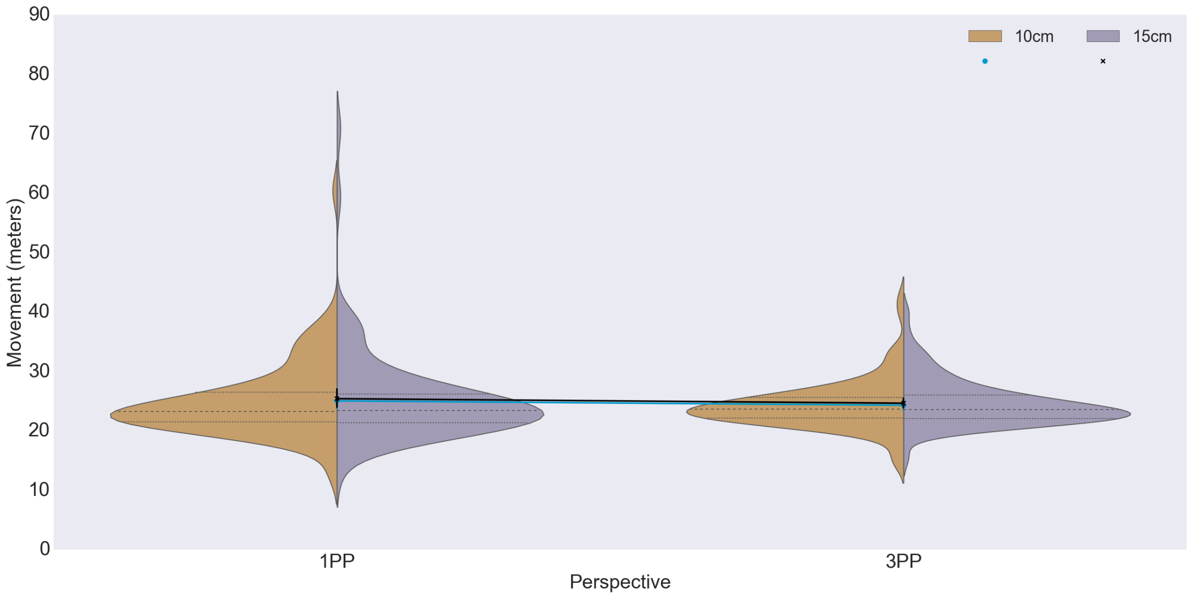


Figure 16: Perspective vs Ball Size on Primary Hand Movement

### 6.5 Head Movement

We hypothesized that the distance traveled by the user's head would be the same under the two user perspectives. The first insight from the plots suggested an effect of the perspective (Figure 18), and possibly a smaller effect due to the training mode (Figure 18).

We checked the data for normality, and it passed the Lilliefors test (p-value=0.064) and the Shapiro-Wilk test (p-value=0.09). The transformed distribution (Box-cox) had a skewness of -0.171 and a kurtosis of 0.2. Also, we validated that the data did not violate the assumption of sphericity (Table VII). The results from the multi-factor ANOVA with within-subjects design

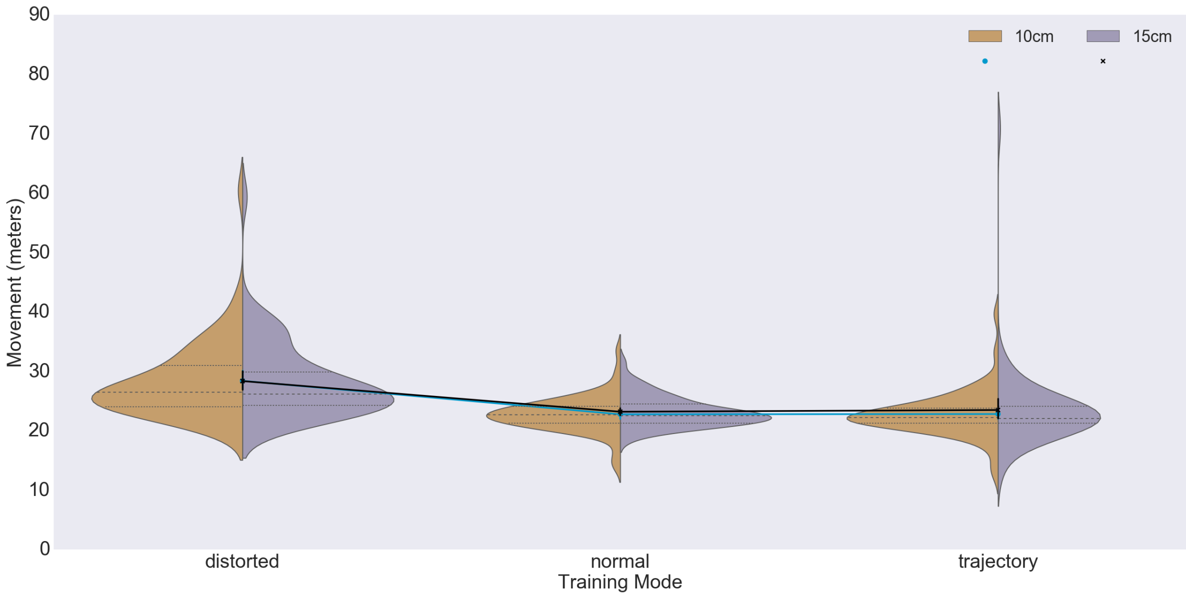


Figure 17: Mode vs Ball Size on Primary Hand Movement

obtained significant results for the perspective factor ($F_{1,29}$=159.24, p-value<.0001, $\eta^2$=.302), and the mode factor ($F_{2,58}$=19.41, p-value<.0001, $\eta^2$=.047).

The posthoc analysis pairwise analysis with Holm-Bonferroni adjustment showed that 1PP always requires more head movements than 3PP. Moreover, the mode factor is only significant in first-person between the distorted mode and the trajectory mode, being the distorted mode the one that required more movements. On the other hand, the 3PP had significant differences in the mode factor only between the distorted and normal modes; the normal mode required fewer head movements. We reject the hypothesis 6, different amount of head movements are needed under each user perspective. Also, this is the only case where the primary factor is due to the changes in perspective.

| Mauchly's Test of Sphericity | | | | |
|---|---|---|---|---|
| **Effect** | **Mauchly's W** | **Sig.** | **Greenhouse-Geisser $\epsilon$** | **Huynh-Feldt $\epsilon$** |
| Mode | 0.9025575 | .238 | 0.9112095 | 0.9690445 |
| Perspective:Mode | 0.9240848 | .331 | 0.9294412 | 0.9904985 |
| Mode:Ball Size | 0.9987509 | .983 | 0.9987525 | 1.0725888 |
| Perspective:Mode:Ball Size | 0.9980143 | .973 | 0.9980182 | 1.0717148 |

| Test of Within-Subjects Effects for Head Movements | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | | **DFn** | **DFd** | **F** | **Sig.** | $\eta^2$ |
| Perspective | Sphericity Assumed | 1 | 29 | 159.24 | **<.0001** | .302 |
| Mode | Sphericity Assumed | 2 | 58 | 19.41 | **<.0001** | .047 |
| | Greenhouse-Geisser | 1.82 | 52.85 | — | **<.0001** | — |
| | Huynh-Feidt | 1.94 | 56.20 | — | **<.0001** | — |
| Ball Size | Sphericity Assumed | 1 | 29 | 1.46 | .237 | .001 |
| Perspective:Mode | Sphericity Assumed | 2 | 58 | 2.82 | .068 | .005 |
| | Greenhouse-Geisser | 1.86 | 53.91 | — | .072 | — |
| | Huynh-Feidt | 1.98 | 57.45 | — | .069 | — |
| Perspective:Ball Size | Sphericity Assumed | 1 | 29 | 1.71 | .201 | .002 |
| Mode:Ball Size | Sphericity Assumed | 2 | 58 | 0.311 | .734 | .000 |
| | Greenhouse-Geisser | 2.00 | 57.93 | — | .733 | — |
| | Huynh-Feidt | 2.15 | 62.21 | — | .734 | — |
| Perspective:Mode: Ball Size | Sphericity Assumed | 2 | 58 | 0.31 | .734 | .000 |
| | Greenhouse-Geisser | 2.00 | 57.89 | — | .733 | — |
| | Huynh-Feidt | 2.14 | 62.16 | — | .734 | — |

| Holm-Bonferroni Pairwise Comparison | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.d.10 | 3.d.10 | 1.n.10 | 3.n.10 | 1.t.10 | 3.t.10 | 1.d.15 | 3.d.15 | 1.n.15 | 3.n.15 | 1.t.15 |
| 3.d.10 | **<.0001** | – | – | – | – | – | – | – | – | – | – |
| 1.n.10 | .1187 | **<.0001** | – | – | – | – | – | – | – | – | – |
| 3.n.10 | **<.0001** | **.0191** | **<.0001** | – | – | – | – | – | – | – | – |
| 1.t.10 | **.0111** | **.0013** | 1.00 | **<.0001** | – | – | – | – | – | – | – |
| 3.t.10 | **<.0001** | .2854 | **<.0001** | 1.00 | **<.0001** | – | – | – | – | – | – |
| 1.d.15 | 1.00 | **<.0001** | 1.00 | **<.0001** | .1573 | **<.0001** | – | – | – | – | – |
| 3.d.15 | **<.0001** | 1.00 | **<.0001** | **.0169** | **.0003** | .4318 | **<.0001** | – | – | – | – |
| 1.n.15 | .1021 | **.0042** | 1.00 | **<.0001** | 1.00 | **<.0001** | .5177 | .0002 | – | – | – |
| 3.n.15 | **<.0001** | **.0495** | **<.0001** | 1.00 | **<.0001** | 1.00 | **<.0001** | .0081 | **<.0001** | – | – |
| 1.t.15 | **.0094** | **.0033** | .4858 | **<.0001** | 1.00 | **<.0001** | **.0061** | **.0026** | 1.00 | **<.0001** | – |
| 3.t.15 | **<.0001** | 1.00 | **<.0001** | 1.00 | **<.0001** | 1.00 | **<.0001** | .9941 | **<.0001** | .5250 | **.0001** |

TABLE VII: Statistical Results for **Head Movements**

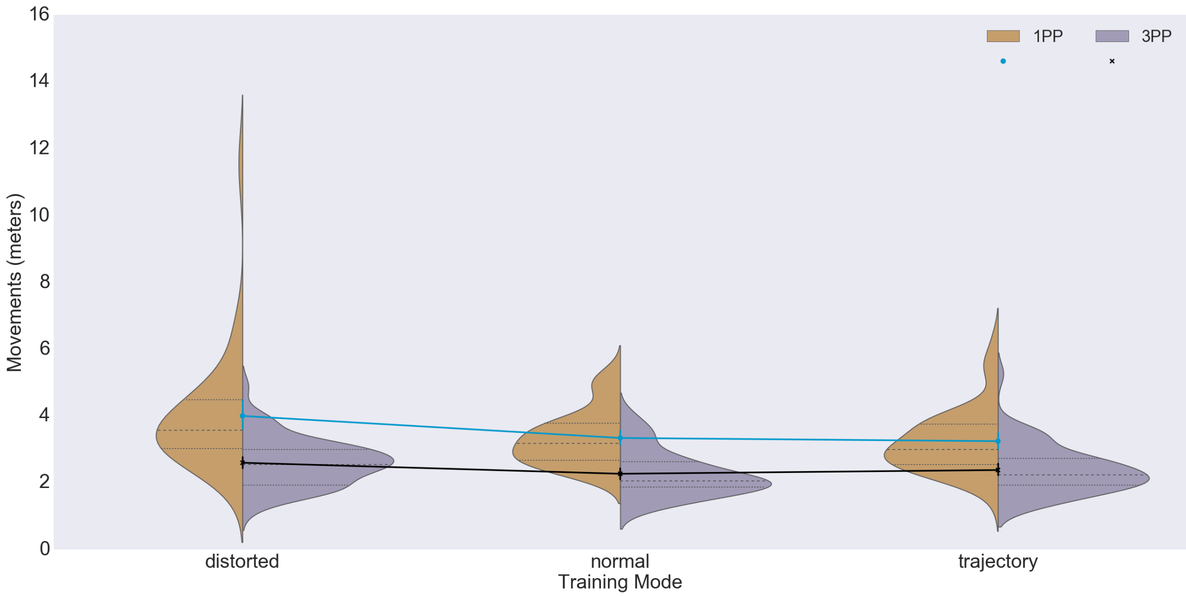


Figure 18: Mode vs Perspective on Head Movement

## 6.6 Number of Objects Caught

We represented the exercise score as the number of objects caught after 20 chances to get an object. Results showed a distribution entirely skewed to the right (M=19.66, MED=20, MIN=9, MAX=20). The plot in Figure 21 showed an effect of the interaction perspective - mode on the results in distorted mode. Then, the plot in Figure 23 suggested a small effect of the object size. Finally, the plot in Figure 22 suggested an effect of the mode. Also, scores obtained by some subjects deviate from the distribution being nine the minimum number of objects caught.

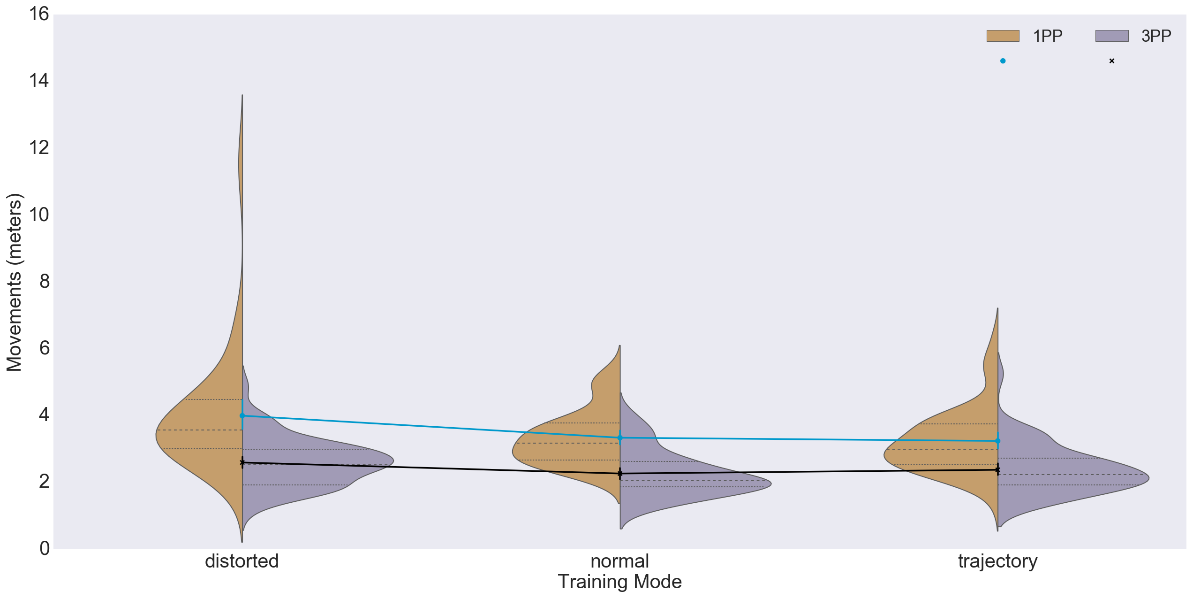


Figure 19: Perspective vs Ball Size on Head Movement

The data did not pass the normality tests; thus, we analyzed the results of the nonparametric Aligned Ranked Test ANOVA. The results got significant results for all the factors and interactions except for the interaction Mode - Ball Size Table VIII. The posthoc analysis, using pairwise comparisons for independent factors and differences of differences for interactions, indicated that the distorted mode is the common factor across exercises that causes the subjects to lose objects. Differences due to the distorted mode gave us evidence to reject the hypothesis 2; the number of objects reached is not the same under the same training modes in 1PP and 3PP perspectives.

| **Test of Within-Subjects Effects for Number Objects Reached** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | | **DFn** | **DFd** | **F** | **Sig.** | $\eta^2$ |
| Perspective | Aligned Rank Test | 1 | 319 | 86.4 | **<.0001** | .023 |
| Mode | Aligned Rank Test | 2 | 319 | 37.07 | **<.0001** | .052 |
| Ball Size | Aligned Rank Test | 1 | 319 | 30.7 | **<.0001** | <.001 |
| Perspective:Mode | Aligned Rank Test | 2 | 319 | 31.20 | **<.0001** | .015 |
| Perspective:Ball Size | Aligned Rank Test | 1 | 319 | 14.51 | **.0002** | .002 |
| Mode:Ball Size | Aligned Rank Test | 1 | 319 | 1.90 | .1513 | .004 |
| Perspective:Mode: Ball Size | Aligned Rank Test | 2 | 319 | 3.25 | **.04** | .001 |

| **Posthoc Analysis with Holm-Bonferroni Adjustment** | |
|---|---|
| **Contrast** | **Sig.** |
| 1 - 3 | **<.0001** |
| d - n | **<.0001** |
| d - t | **<.0001** |
| n - t | .0579 |
| 10 - 15 | **<.0001** |
| 1-3 : d-n | **<.0001** |
| 1-3 : d-t | **<.0001** |
| 1-3 : n-t | .6364 |
| 1-3 : 10-15 | **.0001** |
| 1-3 : d-n : 10-15 | **.0475** |
| 1-3 : d-t : 10-15 | .1088 |
| 1-3 : n-t : 10-15 | .6252 |

TABLE VIII: Statistical Results for **Number of Objects Reached**

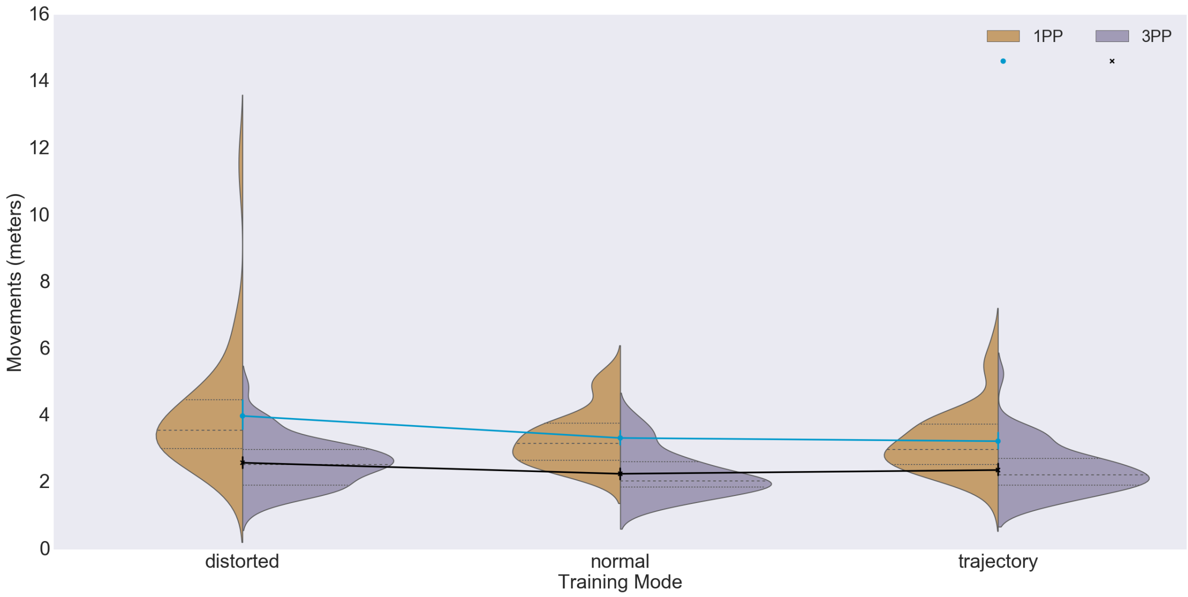


Figure 20: Mode vs Ball Size on Head Movement

## 6.7 Movement Straightness

The approach to obtain the movement straightness differs from the one used for obtained the results described in the preceding sections. We analyzed not the whole exercise but every of the twenty attempts per exercise. We calculated the movement straightness (sinuosity) as the ratio between the distance traveled by the hand and the straight line between the object and the closest hand. Results showed an average sinuosity of 1.47 and a median of 1.25.

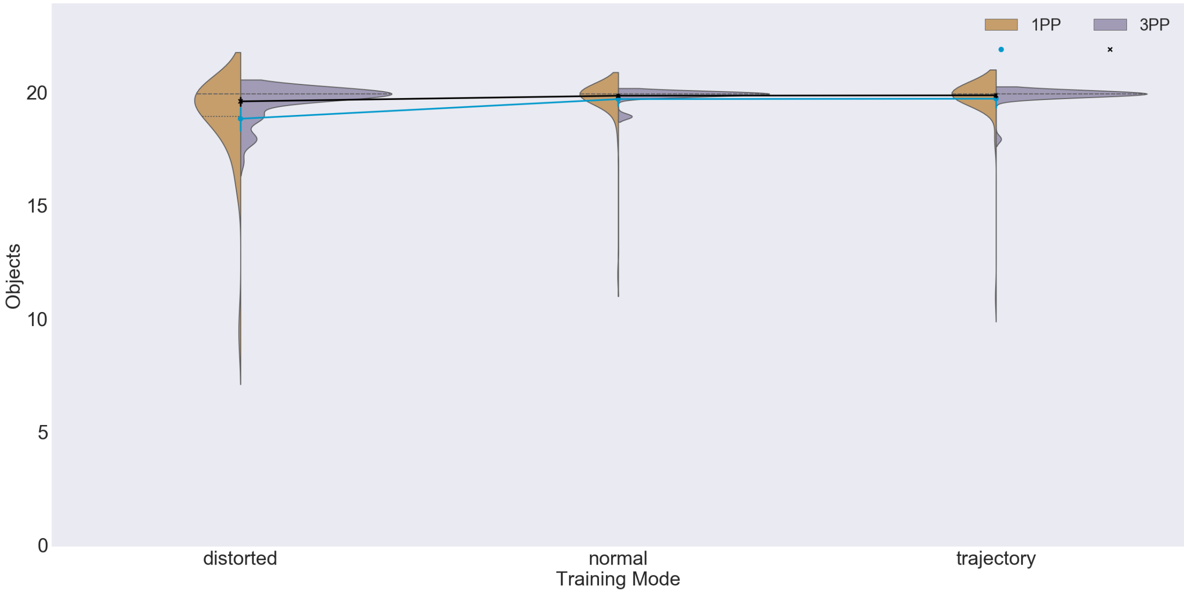


Figure 21: Mode vs Perspective on Number of Objects

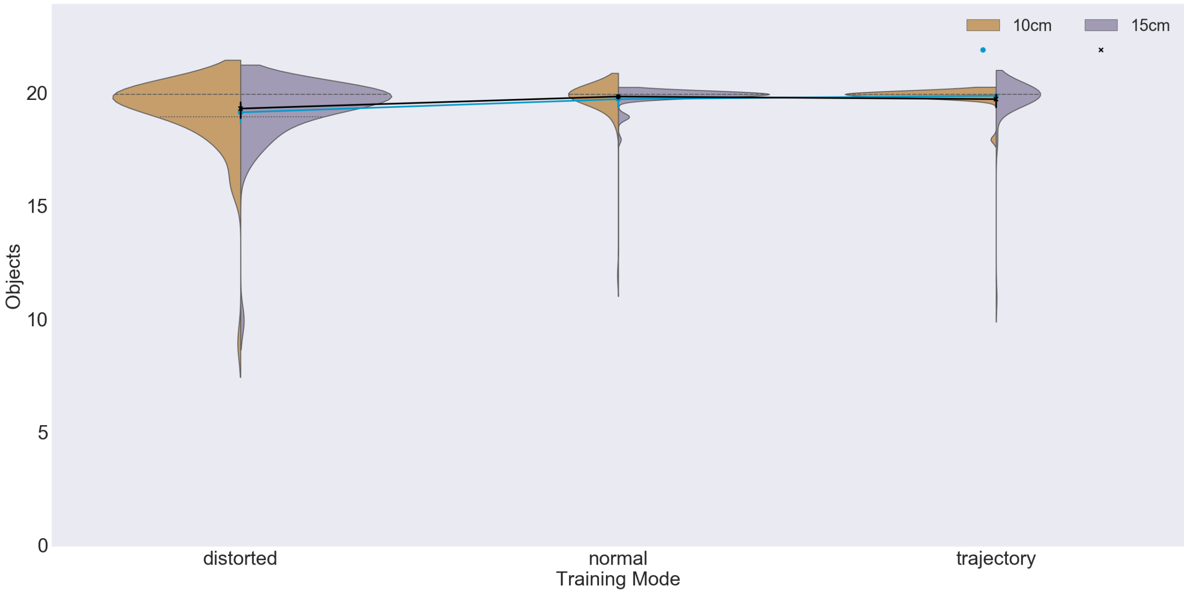


Figure 22: Perspective vs Ball Size on Number of Objects

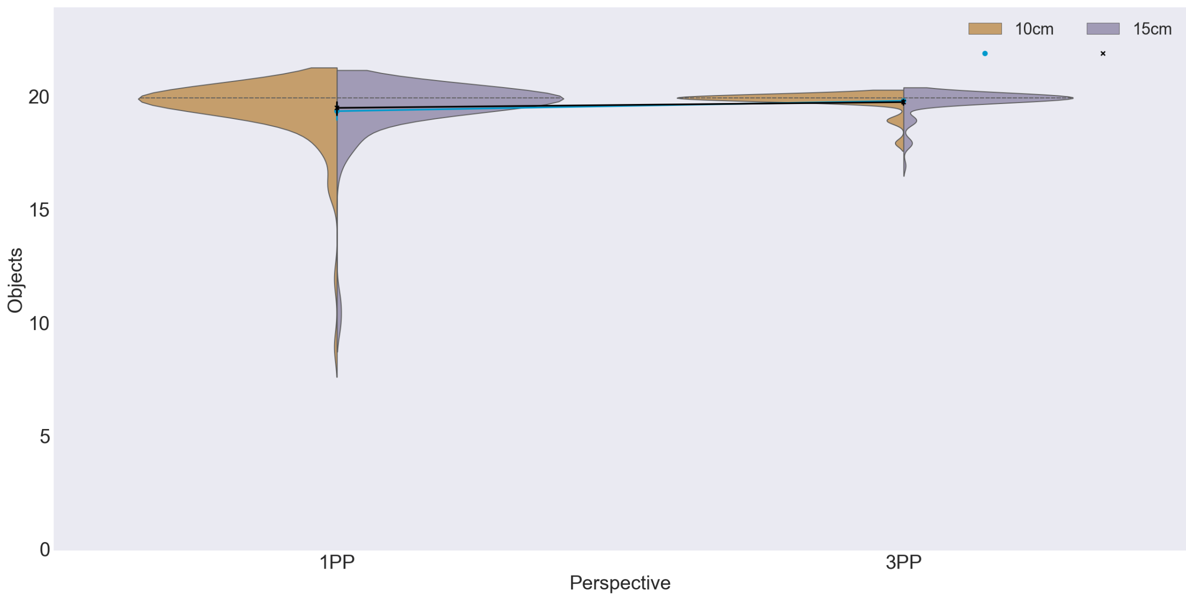


Figure 23: Mode vs Ball Size on Number of Objects

# CHAPTER 7

# DISCUSSION

## 7.1 Completion Time

Completion time for the reaching exercises was slower in both perspectives under the distorted training mode. Although the subjects experienced two rounds of practice, the distorted mode requires more cognitive effort which we consider a good alternative to complement motor rehabilitation. We thought that the 3PP would help users to adapt easier to the distorted mode as they can see the full movement on the screen. However, subjects manifested that the adaptation to the distorted mode was more straightforward (M=3.7) in the 1PP than in 3PP (M=3.61).

Although we obtained most significant results in completion time due to the training mode, the results in changes of perspectives were interesting. Changes in user perspectives were statistically significant for all the combination of training modes and ball sizes except for exercises in normal mode with smaller objects. However, the p-value for the exercise in the trajectory mode with smaller objects (p-value = 0.044) is close the $\alpha$ threshold. There is a discrepancy between these results and the results with bigger objects which have smaller p-values. We believe that this is a learning effect. Exercises with smaller objects were the last exercises on each user perspective. Thus, the user may have learned the movement patterns for that perspective while working with smaller objects.

The subjects performed better on the distorted mode in 3PP than in 1PP. We think that by watching the movements in the avatar, the user realized faster that there was a mistake in the action. Although, the performance results were flipped for the other two modes. In general, the subjects obtained faster completion times in 1PP than in 3PP for trajectory and normal modes. We believe that the 1PP gives a better adjustment as the person perceives it as an extension of their body. Also, it avoided depth perception problems that appeared in 3PP.

Changes in the object size alone were not statistically significant. We considered this option as a way to add a control to the difficulty, but we are required to make finer arrangements to the hand models. However, the interaction between perspective and ball size suggested that the setups add more difficulty for some exercises. The avatar's hands, represented as cubes, are bigger than the average hand size. Thus, they make it easier to collide with the objects in the scene and also absorb any screen configuration error in the CAVE2 environment.

In comparison to Rottigni(7), we can not support the hypothesis that 3PP led to less completion time as we were only able to witness this in distorted mode. Also, we believe that the improvements in the latest version of RehabJim gave us more confidence in our results. Our calibration requires less time to setup, and though it still requires a manual rotation, it speeds up the environment setup. Also, by adding more joints to reflect the rotations in the arms, we believe that the hand and forearms movements look more natural than before, implying a more accurate result in collisions. Moreover, our arrangement for placing objects into the screen space reduced the chance of having longer completion times just because the object was out of range.

Similarities in the median for the number of objects caught is concerning. Results suggest that eight seconds is more than enough to grab an object; the actual average for reaching the object was 2.28 seconds (SD=1.1). Thus, we can adjust the difficulty by carefully manipulating the given time per object.

### 7.2 Immersion

Results from the immersion questionnaires did not show significant differences between both user perspectives. Therefore, we can not reject the Hypothesis 3: The immersion level in the 1PP is the same as the immersion level in 3PP. Also, there are not significant differences either on any of the immersion domains analyzed between perspectives. Even though in average more people preferred 1PP, the result is not statistically significant. We believe that the game difficulty has considerable influence on these results.

Our sample population consisted of young adults who perceived the game to be easy in both perspectives (1PP: M=2.04, SD=0.92; 3PP: M=2.21, SD=0.92). The small value in perceived difficulty could potentially break the flow after repeated sessions. Even though this may not be generalized to older adults, we believe that the game needs more elements to increase its attractiveness. On the other hand, the CAVE2 environment gained positive reactions from the participants without virtual reality experience. Some participants also suggested making more use of the area inside the environment.

We also believe that the low difficulty level in the exercises has an effect on the idea of immersion. As described in the literature (47), more cognitive-intensive tasks can gather more attention. It is a limitation of this study to not compare the immersion between training modes and just focus the analysis on user perspectives.

Surprisingly, we did not receive much feedback related to the avatar. We believed that most of the users would not accept the cartoon-styled avatar, but no one criticized the design or asked for a more accurate human shape.

Up to our knowledge, our comparison between user perspectives is the first study made in a CAVE2 environment for the topic of immersion. Similar work evaluating games under two perspectives found the 1PP to be more immersive (20), or no difference in the computer experience (22), but differences in performance or sense of control.

### 7.3 Body Movements

Subjects performed different movement patterns in the distorted mode. On the one hand, in normal and trajectory modes, they mainly aimed for the object following a geodesic curve. They usually incurred in movement corrections, but in general, the movement was direct. On the other hand, in the distorted mode, some subjects explored the space from the frontal plane towards the sagittal plane. Other subjects, who adapted easier to the distortion, avoided this movement pattern and aimed directly at the target.

Changes in mode mainly explained the variances in movement errors, and differences in the primary hand movement, but the perspective explained the differences in head movements. We expected this effect on the head movement as the user is required to explore 180 degrees of screen space to find the object. Even though we did not present the differences in rotation, we observed a notorious difference between perspectives. In 1PP, the users had to rotate their head if the object was in the periphery.

Subjects also performed movements with the secondary hand while trying to get an object. We perceived this behavior mostly on distorted mode when the subjects figured out they were making a mistake, and in other modes when they initially planned to get an object with one hand but in the process decided to use the other hand. Our results for movement errors did not account for the secondary hand movement.

### 7.4 Depth Perception

Subjects manifested problems with depth perception with objects to the sides and closer to the frontal plane in 3PP. Even though Rottigni(7) manifested that the shadows helped with this issue, we did not receive much feedback related to the use of shadows. A subject explained that shadows were helpful as a secondary resource, and it would not be the first option to understand depth. Moreover, the shadows were affected by the transparency of the object, making them lighter. Also, Rottigni's experiment did not place object to the sides; the objects always appeared 30 cm in front of the subject, and there was no need to use peripheral vision.

Similarly to the results from Debarba et al.(78), objects in 3PP did not help with the precision; we believe that the objects look too small to perceive a change in the object size for objects that are further away. Even though we updated the objects texture and obtained better contrast with the environment, 3PP lacked visual cues to help reduce the depth perception error. By adding more elements to the background scene, we may be able to create an environment with more visual elements to create a 3D context. Two subjects believed that the 3PP was rendered in 2D, one subject felt that the trajectories somehow helped to understand perspective, and one subject felt that the objects in 3PP appeared behind his frontal plane. This last comment does not go along with the technical implementation as we did not place any object behind the frontal plane but reveals a severe limitation in perception in the scene.

Problems with depth perception in 3PP are mostly related to the stereoscopic parallax in CAVE environments. A new study(79) demonstrated that the distance estimation in CAVE-like environments depends on the distance to the screen and the stereoscopic parallax of the target. Distance from targets near the screen (zero-parallax) are easier to understand than objects far into the scene (positive parallax); misperceptions for objects that are further away can get up to 50%. However, the understanding of depth may be different for moving objects. Salamin et al. (80) indicated that a 3PP gives a better evaluation of distances and anticipation of objects, but the authors obtained the results using an HMD. An evaluation is necessary to contrast if the effect also applies to CAVE-like environments.

Another attempt to deal with depth perception is to change the geometry of the target. Powell(81) found that using spheres in upper limb tasks takes longer time than geometries like an apple or an icosahedron, which provide more visual cues.

## 7.5 Outliers

Outliers were not familiar; only two subjects incur in these situations. One of them for only one exercise, thus, we believe that the subject was able to adapt better after that first trial. The second user gave interesting insights. The subject had difficulties in both perspectives but got worst times in 1PP. Although the subject declared not to have any stereoscopic problem, an observation of the movements suggested that there was an obvious problem detecting depth under both views. We accounted these results for our calculations and realized that we need to provide more visual cues.

## 7.6 Trajectory Mode

The impact of the trajectory mode in the first-person view is affected by the smaller FOV. The posthoc analysis suggested that there is not a difference between both of the normal and the trajectory modes; pragmatically, both conditions can be considered as the same exercise. Surprisingly, subjects thought the trajectory mode was more helpful in 1PP (M=3.5, SD=1.33) than in 3PP (M=3.2, SD=1.47). None of them followed the suggested straight line rigorously, mainly because their movements followed a geodesic curve in 3D. Two subjects felt the trajectories to be distractive.

## 7.7 Movement Fidelity

We expanded the range FOV of the tracking area by placing the Kinect higher. The new position alleviated the flickering problem with the hands. Additionally, adding tracking joints corrected the rotations between elbow & shoulder, elbow & wrist and, hand & wrist. However, approximately one-third of the participants manifested a problem with how the application handled the movements in 1PP. The observations included misalignment between their body and the arm rendered, a delay in the movement or flickering movements.

We believe that these issues are related to the calibration methods and the Kinect's fidelity. Also, the Kinect specifications state a sampling frequency of 30 Hz. However, the application did not record the samples at a uniform rate. We overlooked the synchronization with the different layers in the application; thus, further interpolation and sample rate adjustments are required to analyze speed profiles and reaction time.

## 7.8 Related Issues

Physical issues included fatigue and eyes convergence. Two subjects manifested fatigue problems after complete the exercises, especially for standing at the same spot and focusing on the same area during the whole time. One subject had difficulties in focusing the spheres in 1PP. Also, one subject felt the visual effects to be too bright and hard on the eyes.

Three people pointed problems with the tracking glasses. Two of them found it difficult to see objects in the periphery as the lenses focused forward. The other subject felt that wearing the glasses on top of his glasses was uncomfortable, mainly because they kept sliding down.

# CHAPTER 8

# CONCLUSIONS

We presented a user study results comparing the effect of the user perspective on user performance, the level of immersion and upper body movements, using an updated version of the RehabJim application in the CAVE2 environment. Also, we analyzed the effect of different types of exercises and object sized on the dependent variables. Our contribution included a report of the level of the effect of the independent factors (perspective, mode, ball size) and the effect of the interactions between them. We hope to provide a baseline for future user studies performed in the CAVE2 environment.

Exercises done in *distorted* are significantly different than the *normal* and *trajectory* modes, due to the added cognitive effort. Distorted mode had more influence on user performance variables, hand movements, and movement corrections. However, we can not conclude if the subjects considered this mode to be more engaging or frustrating. In 1PP, tasks in distorted mode took longer to complete than in 3PP. However, in trajectory mode, tasks in 1PP took less time to complete. Then, the level of immersion was the same under both user perspectives, possibly influenced by the simplicity and lack of adaptive difficulty. Next, the 1PP required more head movements as it explored a wider area. Finally, 3PP had better scores though the median was the max score.

We speculate that the variability in the results of the two perspectives is beneficial as we can not directly discard the usage of any of them. 1PP had a limited field of view but allows mechanics that test location and reaction while giving a better sense of depth perception. Conversely, 3PP gives better movement feedback, provides a wider field of view, and takes more advantage of trajectory effects, but makes depth perception more challenging. The literature commonly prefers to use either of them but not both; thus, we believe that by alternating the perspectives, the application has the potential to provide wider possibilities of task-oriented exercises.

## 8.1 Future Work

Results obtained from the user study gave us valuable lessons and suggested possible improvements research directions. Adjusting the difficulty of RehabJim is one of the most concerning issues. We would like to add various mechanics to set the difficulty such as as an adaptive completion time, show more objects on the scene, distractors or require to move objects around specific targets.

Dealing with the depth perception error in third-person perspective is another important issue. We can implement several possible solutions like changing the geometric shape of the targets, adding more contextual elements to the virtual environment, and work with better scene illumination.

The nonuniform sampling required further data processing to obtain a better understanding of the variations in speed, and whether we can identify differences in the reaction time. Besides, we plan to provide a better interface between the Kinect and the CAVE2 environment to minimize sampling problems.

Also, we want to use the collected data to create estimated geodesic trajectories; customizing the avatar and provide more background scenarios. From the visualization standpoint, we would like to explore which visualizations are more useful to the domain expert. Finally, we want to update the calibration methods to account for the Kinect rotations about the CAVE2 axis.

**APPENDICES**

# Appendix A

# QUESTIONNAIRE

IEQ Questionnaire Questions(21)

1. “To what extent did the game hold your attention?”
2. “To what extent did you feel you were focused on the game?”
3. “How much effort did you put into playing the game?”
4. “Did you feel that you were trying you best?”
5. “To what extent did you lose track of time?”
6. “To what extent did you feel consciously aware of being in the real world whilst playing?”
7. “To what extent did you forget about your everyday concerns?”
8. “To what extent were you aware of yourself in your surroundings?”
9. “To what extent did you notice events taking place around you?”
10. “Did you feel the urge at any point to stop playing and see what was happening around you?”
11. “To what extent did you feel that you were interacting with the game environment?”
12. “To what extent did you feel as though you were separated from your real-world environment?”

## Appendix A (Continued)

13. "To what extent did you feel that the game was something you were experiencing, rather than something you were just doing?"
14. "To what extent was your sense of being in the game environment stronger than your sense of being in the real world?"
15. "To what extent did you feel as though you were moving through the game according to you own will?"
16. "To what extent did you find the game challenging?"
17. "Were there any times during the game in which you just wanted to give up?"
18. "To what extent did you feel motivated while playing?"
19. "To what extent did you find the game easy?"
20. "To what extent did you feel like you were making progress towards the end of the game?"
21. "How well do you think you performed in the game?"
22. "To what extent did you feel emotionally attached to the game?"
23. "To what extent were you interested in seeing how the games events would progress?"
24. "How much did you want to win the game?"
25. "Were you in suspense about whether or not you would win or lose the game?"
26. "At any point did you find yourself become so involved that you wanted to speak to the game directly?"
27. "To what extent did you enjoy the graphics and the imagery?"

## Appendix A (Continued)

28. "How much would you say you enjoyed playing the game under this perspective?"

29. "When interrupted, were you disappointed that the game was over?"

30. "Would you like to play the game again?"

Open questions:

1. Please describe any difficulties or problems you faced during the exercises.

2. Please provide any additional feedback that could help us improve the design and ease of use of the application.

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# VITA

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Education

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Professional Experience

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