A THERAPEUTIC EVALUATION
OF A CREATIVE REACHING GAME
IN IMMERSIVE VIRTUAL REALITY

by

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ABSTRACT

Virtual Reality (VR) has several applications beyond entertainment, e.g., architectural planning, surgical procedure assistance, and physical therapy. These implications are important and require the most accuracy for users, especially when their healthcare is involved. Users can lose accuracy immersed in a virtual environment (VE) from inaccurate depth perception. Often, people underestimate distant objects and overestimate close objects in VR, which concerns software developers and healthcare providers. VR Therapy systems also rely on information from VR hand controllers, which do not fully capture the movement from the rest of the limb. While VR games have shown much potential for rehabilitation, research on creative virtual therapy is still growing. Considering many possibilities for therapeutic interventions in VR, my goal is to create activities with an appropriate balance between the intensity level of therapy intervention with enjoyment and entertainment. I will also capture the limb's movement both from the arm and hands with a non-invasive elbow sleeve sensor. I propose a creative line art drawing game in an immersive VR environment as a tool for both upper extremity therapy and vision therapy using enjoyable multi-dimensional reaching tasks.

To examine the validity of the proposed virtual therapy system, I conducted two preliminary human-subjects experiments: a mixed design varying the drawing content (Easy vs. Hard; a between-subjects factor) and the user’s position (Seated vs.

Standing; a within-subjects factor) on 16 non-clinical participants; and a within-subjects design varying the drawing content dimension (2D vs. 3D) and the content's orientation (Vertical vs. Horizontal) on 12 non-clinical participants.

My results of the first experiment (SUI 2021) show that the change of drawing content objectively influenced participants' drawing performance, e.g., the completion time and the number of mistakes, while they did not feel the difference in the difficulty level between the contents subjectively. Interestingly, participants reported more enjoyment from drawing the Hard Chicken content than the Easy Fish content and more substantial body stretches in the Seated setting than the Standing setting.

The results of the second experiment (submitted to ACM/IEEE CHASE 2023) show that for all levels, there was no significant difference between subjective easiness, comfortability, and enjoyment and between objective measures for task completion time and the number of mistakes. This finding suggests that all versions are at the same therapeutic intensity level, with no model being more prone to longer time or more mistakes and are all usable/feasible. This leads to the customization of therapy to the user with any of these configurations and orientations while keeping the same level of intensity; for example, if a patient has restricted lower limb mobility and requires to be seated, they can use the horizontal orientation interchangeably. However, there was significance with elbow resistance change, which shows how data collection from just the hands and not throughout the arm is insufficient for VR rehabilitation, particularly for the upper extremities. There is a need to improve depth perception, visual cues, and reaching capabilities in VEs, especially for 3D objects.

INTRODUCTION

Musculoskeletal injury is one of the leading causes of disability in most developed countries, and approximately 1.71 billion people have musculoskeletal conditions worldwide [71]. According to the American Academy of Orthopedic Surgeons' report, an estimated 126.6 million Americans (approximately one in two Americans) live with a musculoskeletal condition [72]. With the increasing number of post-stroke survivors, who often have certain musculoskeletal conditions, such as upper extremity functional limitations, the need for more effective therapeutic methods and research is continuously growing [73]. Physical therapy (PT) is well-known for being effective in rehabilitation. However, low adherence to PT exercises among patients has been reported due to varied reasons, including lack of motivation, slow or invisible recovery progress, and absence of supervision and mental support.

To address these issues, VR has much potential as a tool that provides a more engaging PT experience with appealing visual effects and interactive sensory feedback [25,64,69]. Prior research has shown that VR is preferred in rehabilitation for several reasons, e.g., its portability for home-therapy, ability to attenuate pain, independence from external pressures and distractions, engaging game-like characteristics, and ability to simulate real-life tasks in an environment that is easier to measure and evaluate performance [5,44]. By transforming rehabilitation into an entertaining game

in VR, the intense, repetitive, task-oriented therapeutic exercises could become more engaging and enjoyable [25]. On the other hand, however, there are still questions that I need to explore for more effective and widely acceptable VR therapy; for example, how I can effectively control the perceived level of difficulty in different VR therapy interventions, i.e., customization of therapy intensity, and how the VR intervention settings can influence the user's (patient) therapy experience.

As VR gains popularity in therapy, developers must look at how being in a VE with a head-mounted display (HMD) affects depth perception. VR displays use visual cues to simulate a 3D environment in the brain, creating the impression of depth. We rely on multiple depth and visual cues because our perception of the world is multisensory [14]. However, humans have a tough time judging the depth of a scene, even in the real world; most people underestimate the distance of distant visual objects and overestimate the distance of near visual objects [50].

Many studies have been conducted to study issues in VR, depth perception, and distance misestimation [28,37,62]. Witmer and Sadowski [66] concluded that low-quality depth perception in VEs is the major problem that needs to be studied and improved. Another study showed that depth perception is insufficient in simple VEs and, even with simple manipulations, could not be improved [2]. The authors emphasize the need for future research to improve depth perception in a VE. Another simple, immersive VE that found inaccurate depth perception estimations warns researchers of how this negatively impacts future studies. Researchers who want to use VR systems in a cognitive experiment must take extra care, especially if the tasks

involve perception or navigation [53]. It is important to research how the brain processes different visual information and physiological depth cues, especially when putting humans in a new immersive environment. Studying depth cues and how they interact will improve the spatial representation of objects and will help VR developers understand how information is processed by users.

My thesis is a combination of two studies, the first of which was published in the ACM SUI Conference 2021 and addresses the need for a VR therapy application that integrates art therapy for upper extremity rehabilitation in a completely immersive environment. My second paper was submitted to IEEE/ACM CHASE Conference 2023 where I explore how to use the creative exergame for vision therapy by adding depth and different dimensions/orientations to the game and another mode of data collection. Figure 1 displays my proposed drawing exergame that was tested on healthy participants in preliminary studies to evaluate effectiveness and usability.

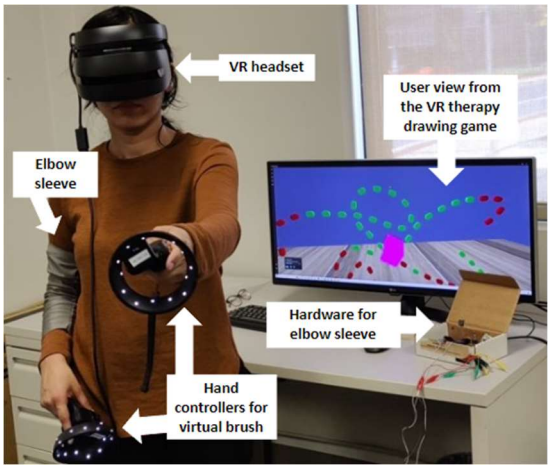


Figure 1 The immersive VR drawing game developed for my upper extremity and vision virtual therapy intervention

RELATED WORKS

In this section, I review some previous peer-reviewed work related to virtual therapy for physical rehabilitation and the user's body position impacts on the VR experience. I also cover some interactive drawing applications in immersive VR settings, which are related to the drawing intervention that I use for my own study. I also explored publications about where depth perception falls short in VR applications and how to measure/improve it effectively. I found the papers for my literature review through platforms such as Google Scholar, IEEE Xplore, and ACM Digital Library. Some of the keywords I used when looking for papers to research were "Applications of VR in Therapy," "Depth Perception in Virtual Reality," "Conventional Vision Therapy for Depth Perception," "Physical Therapy for Upper Limb Mobility," "Correlation of Reaching to Distance Estimation," and "Shortcomings of Depth Perception in Virtual Environments."

Virtual Therapy for Physical Rehabilitation

Despite the known effectiveness of PT interventions for rehabilitation, various limitations, including the time commitment, intensity of labor and resources, dependence on patient compliance, geographical availability of special facilities, and costs/insurance coverage, have been reported [25,41,61]. Virtual therapy has shown the potential to engage the patient and improve their therapy experience. Henderson et

al. [25] presented a therapy system with multiple VR game simulations to improve the hand function of post-stroke patients, resulting in the participants' enjoyment in the task. Other studies also showed VR treatments to be supplemental or interchangeable by conventional therapy. For example, Feng et al. [16] showed that virtual therapy could improve gait and balance in certain cases, e.g., Parkinson's patients saw an improved gait and balance after training with VR games. Kim et al. [34] also presented a study that showed VR treatments could lead to functional improvements in stroke patients, in both upper extremity function and visual perception. Together with haptic stimuli using data gloves in VR, multiple studies showed positive results for hand movement rehabilitation in post-stroke patients [5,30,58].

One of the biggest advantages of using VR for PT could be that it is portable; patients can take their therapy home to do it frequently at their convenience. Li et al. [45] developed a VR therapy home-based system (VRT-Home) for children with hemiplegic cerebral palsy to practice hemiplegic hand and arm movements. Their results showed that the system successfully targeted hand/arm movements of the hemiplegic upper extremity, especially reaching activities that involve the shoulder and elbow. Additionally, the child participants reported "[having] lots of fun" and "would like to take the games practice therapy activities home to play."

However, while the research addressed above showed that there are positive effects of VR intervention for physical rehabilitation, some research also stated that there is still limitation of the existing literature. Multiple reviews on the efficacy of

VR therapy concluded that the current evidence on the effectiveness of using VR in the rehabilitation of upper limb mobility in patients with stroke is still limited and I need more studies to support this effect while investigating different intervention types through rigorous studies [25,42,63].

Wearable Sensors for Virtual Therapy

Wearable sensors for VR based PT have become popular due to its accessibility and ability to monitor the quantity and quality of body movement. The data collected from wearable sleeves can help make rehabilitation treatment more effective. Brandão et al. [7] explore the feasibility of unsupervised physical therapy in a patient's home, particularly for patients with hemiparesis due to stroke. The patients were trained with IMU (inertial measurement unit) based VR, a system they could use in their homes without any supervision. Researchers found that the arm function of these patients improved significantly within six weeks of rehabilitative therapy sessions.

VR-based techniques have been used in healthcare to provide better rehabilitation options to patients with disabilities. But VR combined with wearable devices has made this experience of recovery more pleasant and valuable for patients [32]. VR provides patients with an immersive experience in a virtual world and gives them the capability to interact with virtual objects using motion sensors. This attribute makes VR-based rehabilitation a promising tool to promote active participation of patients in their therapy process and produce better motor recovery [33]. The data

collected from wearable sleeves while performing VR physiotherapy can be visualized by patients even if they do not have any technical knowledge, they can easily see their performance for each session [52].

In another study, Lee et al. [43] examine the integration of wearable sleeves in VR based physical therapy. In this study the data was collected from wearable sensors in a VR based goal-directed shoulder rehabilitation system to analyze task performance and improvement after each training session. The study was conducted on patients with frozen shoulders where they performed shoulder muscle strengthening, and core muscle strengthening exercises. While patients were performing exercise by interacting with the VR environment, the sensors were secured to their shoulders to measure the range of motion (ROM). The data collected from training sessions suggested that the usage of wearable sensors in a VR therapy can provide better information to offer customized individual training programs. Hence, it is suggested that wearable sensor-based home VR therapy with rehabilitative games is feasible and safe despite the lack of any supervision [67].

Effects of Body Position on Virtual Experience

One interesting research topic is to understand the effects of VR user's body position (or bodily involvement), specifically the seated or standing settings, on their experience and task performance in VR [70]. There have been multiple VR systems based on different user body configurations, including seated and standing [68], leaning while seated and standing [39], and walking in place [60]. Xu et al. used an

immersive VR (iVR) exergame to investigate how being standing vs. seated affects gameplay performance, intrinsic motivation, and motion sickness. Their results showed that compared to standing, being seated could result in higher exertion and provide higher value to players, could lead to participants feeling sicker in the iVR exergame, and could lead to participants missing more gestures in the exergame. This led to the recommendations that full-body gestures for seated exergames need to be designed carefully to help minimize the feeling of motion sickness and to provide more time to perform the gestures [68]. I will focus on a therapy game for upper-body mobility instead of a full body exercise game with different UX measures.

In the context of PT, gathering data on what body configuration allows for the best range of motion during a VR therapy could lead us to better application designs for patients. However, many prior studies only focused on a certain position configuration, e.g., VRT-Home was only used in the seated configuration for their child participants. Gao et al. explored how physical activity in VR experiences could reduce stress while promoting health and well-being in older adults [19]. Given that the most immersive VR setting applications are in a limited space, large-scale ground navigation is not the user's primary action. However, considering the PT context, which could benefit from different position configurations, it is important to investigate the effects of body position in the user’s therapy experience and performance.

Interactive Drawing in Virtual Environments

Among several distinct types of VR applications, interactive drawing is one of the most popular VR use cases. For example, an artistic VR game "Tilt Brush" allows users to change their virtual surroundings and sketch freely [74]. In a work by Laver et al. [42], users reported they enjoyed the virtual art interface, since it allowed them to create accurate drawings. Multiple drawing applications have been proposed while showing the effectiveness of drawing in a positive virtual experience. Nakagawa et al. [51] built a multi-user audiovisual system for interactive mixed reality experience, using an optical see-through head-mounted display (Microsoft HoloLens). In their system, users could draw virtual lines using their fingers while experiencing various visual expressions and audio effects according to the height of real space. Raffle et al. [56] also developed a system named "Jabberstamp," which is a visual and interactive tool to draw and record voices for children to support children's emergent literacy. Gerry [21] pointed out that this kind of drawing/painting activity in iVR environments could also promote empathy and creativity in remote multi-user settings.

For therapy applications, virtual art therapy, however, has yet to be further studied. In one of the earliest efforts in this research, McNiff [48] presented the "Virtual Art Therapy Studio" for use of VR drawing/painting art in therapy and highlighted its advantages for training and accessibility. Such advantages include creating bold and expansive gestures from simple movements, having more precision in a visually diverse way, having better accessibility with drawings easily sent to

colleagues all over the world simultaneously, and easing storage of images instead of physical file cabinets. Different uses of the virtual art studio have been shown to be an effective medium for art therapy, especially for physically challenged patients. However, McNiff did not consider how body position can affect the user's experience and the therapeutic applications, which I explore in my study.

Visual Cues and Depth Perception

Visual cues consist of proprioceptive cues (accommodation and convergence), binocular cues, monocular cues, and dynamic cues. Monocular cues involve the relative size of an object when perceiving distance; it is important that the object's size decreases when farther away and that there is information on the 3D space (floor, walls, ceiling, other objects, etc.). Other monocular cues that humans use in a natural environment are occlusion, relative size, cast shadows, shading, distance to horizon, texture gradient, and linear perspective [4]. Dynamic cues involve changing the position of an object and other visual cues depending on the user's position (translation or rotation). My VR game focuses on monocular cues and dynamic cues, with the virtual content having relative size, context in a space with floor and background, and the ability to change location/color depending on the user's motions.

A person's visual environment can be divided into three subspaces, each of which has a different distance perception: the personal space (< 2m; within arm's length), the action space (2-30m; where someone can reliably and accurately interact

with other entities) and the distant/vista space (>30m; everything beyond the action space) [11]. Typically, people underestimate objects in the action and distant spaces but overestimate objects in the personal space [12]. In my VR game, I am focusing on depth perception within the personal space, where the user will have the virtual content within their arm distance. The distant space has a mountain range projected with the appropriate shadowing and depth modelled, while the action space can be judged with the "platform" that the user is on and that the tasks are contained in.

People combine different cues when perceiving an object's depth; a four-stage integration process of the different depth cues was defined as Perception/Adjustment, Comparison, Judgement, and Description [40,55]. A person's perception of a visual scene depends on an intersection between their knowledge of the environment and their movements. More specifically, the process of estimating distance involves judging the distance between them and the object and actively moving to the object [1]. Each of the different cues give the person a different estimation of distance. The distance estimations are compared and receive a coefficient/degree based on how reliable each of the cues are, external factors, and the influence of each cue. The estimations are then integrated into a single estimation to determine the actual judged distance of the object that the person can describe. What was found is that if the visual cues are consistent/coherent, they lead to an improvement of depth perception. However, if they are conflicting, they lead to a deterioration of depth perception where the estimation is inaccurate and the visual cues not being reliable enough to influence their perception [1].

Depth Perception in a Virtual Environment

After researching both depth perception and VR, I want to explore their intersection. Implications of this intersection are important both for virtual vision therapy applications and for high stakes applications that use VR and rely on accurate depth perception. Information on the estimation of distance, depth, and shape is crucial to support diagnosis and therapy decisions. Perceptual issues with the visualization in VR can influence this process and may lead to false conclusions [23].

Limitations of Depth Perception in Virtual Environments

One of the most used techniques in VR to improve depth perception is stereoscopy, a technique to reproduce certain binocular vision cues. However, just using this technique is not sufficient because it does not accurately reproduce all the visual cues and leads to discomfort for users [3,38]. Discomfort and motion sickness are a serious limitation of VR therapy; if there are too many discrepancies between the visual system and vestibular system, users experience dizziness, especially when doing exercises like jumping. A way to mitigate this and improve user experience and depth perception in VR, specifically with a HMD, is to give users more control over the virtual scene [14]. I hope to mitigate this in my immersive virtual environment by allowing the user to move the model to wherever they are most comfortable before beginning the task and will measure subjective comfort and motion sickness.

There are also limitations of a completely virtual environment compared to an AR environment; depth is underestimated when completely immersed in a virtual

background in VR [46]. Jones et al. [31] found less depth underestimation in AR using motion parallax and a blind walking protocol. However, this finding that AR is better with depth perception than VR is contradictory.

A popular application of AR/VR is in the medical field; with this technology, surgeons can visualize anatomical structures of organs beneath the surface, can increase the field of view during laparoscopic surgeries, can plan an operation before performing it, can assess vascular structures in tumor surgery, etc. [4,9,23]. Depth perception is a major issue in AR-based surgical navigation. This is important because a patient's life is at the hands of a surgeon's accuracy using this computer assistance. Heinrich et al. [24] found that perceptual issues with AR visualizations affect the estimation of distances and depth, which therefore can lead to critically wrong assumptions by users. They call for future work to investigate the effects of visualization concepts on depth perception, particularly for dense scenes with less inter-object distances and more complex object shapes.

In another work, Heinrich et al. [23] also investigated how an immersive VR setup with an HMD compared to a traditional desktop setup. They found that depth judgments are less error-prone and more certain in VR than in desktop environments. Most consumers report a richer experience from VR than desktop applications which is causing an increase of applications being converted to VR [27].

Therefore, a proposed solution to AR's limitations is to integrate VR into the applications. Researchers developed a new method that can seamlessly switch from AR to VR by manipulating the virtual camera parameters. The results of their

experiments confirmed that the proposed technique can improve depth perception in surgery by adding VR aspects into AR devices because VR is more effective for accessing a 3D point than pure AR [9]. However, in minimally invasive surgery, the use of technologies such as 3D HMDs has shown several problems with depth perception: lack of binocular disparity, small field of view, limited range of laparoscope motion, restricted location of port insertion, shadowless operation field, and image resolution [4]. The Human-Computer Interaction (HCI) field has conflicting views on whether VR is better than AR for depth perception. I will explore how to improve depth perception in a completely immersive VR environment and offer insight on where it falls short.

How to Accurately Measure Depth Perception in Virtual Environments

To learn how the limitations of depth perception in VEs can be improved, I must first understand how it can be measured and analyzed. In perception experiments, depth perception and the estimated distance of objects are determined through various complex measurement protocols. Experimenters have asked subjects to estimate distance by verballing using an internal scale [22], by estimating a relative measure between the two objects [13], and by using directed action [36]. In perceptual matching protocols, the user has a target object and can adjust a different object to match the position/distance. The user must use their own judgement on whether the object they are manipulating is farther/closer to the target and then act accordingly.

Advantages of perceptual matching protocols include that they only rely on visual perception, and that they are related to many useful VE applications [65]. However, a limitation of perceptual matching is that it does not give an absolute measurement of perceived distance; it is all relative [36]. My study design is modelled towards perceptual matching and directed action over other protocols such as verbal estimation, visually guided actions, and visually imagined actions for a distance perception measurement. With a connect the dots game, each dot is a target location that the user must adjust the paintbrush to hit and has a direction to draw in.

The measures to assess the capacity of a VE to make the most of the human visual system include its horizontal and vertical field of vision, the presence of a stereoscopic rendering (3D), visual content, and the stability of the visual environment [17]. One of the advantages of using an HMD is that the optical system provides the largest possible field of vision horizontally and vertically, which is one of the most difficult constraints to achieve. Another advantage is that it can detect movements like rotations and translations of the head much faster than other devices. I must assess the accuracy of the horizontal and vertical points of view relative to the user's tasks in the VE, as well as varying the 2D and 3D content.

In an exergame to pop distant balloons, measures were taken with VIVE trackers for controller coordinates relative to the HMD. Data was collected for joint angles positions, joint reaction forces, and torque, and was analyzed using inverse kinematics to model the kinematic arm [54]. The goal was to determine an exergame

player's 3D spatial range of motion and areas of comfort by analyzing their physiological performance and movements. Joint (shoulder, elbow, wrist) and muscular efforts were crucial in their studies.

How to Effectively Improve Depth Perception in Virtual Environments

When developers transfer applications from desktop to VR, suitable/precise visualizations need to be prioritized due to the difference in spatial and temporal performance in a VE. A misinterpretation of shape or distance in a medical VR simulation can affect a chosen treatment and directly impact the outcome. In Hombeck et al.'s [27] study on the performative differences between different visualizations for 3D surfaces, they found that performance varies depending on the task, system, and surface type. However, they saw improved performance results with VR compared to desktop applications. Therefore, applications will continue to be integrated into VEs but visualizations, especially for 3D surfaces, must be precise.

When creating VR applications, developers must consider the autonomy of the virtual world, the interaction between the user and the virtual world, and the immersion of the user in the virtual world. Immersion is important because users must feel present in the virtual environment with modalities such as vision, audition, and touch [14]. My VR therapy game sits at the intersection of these important cues where the user has the task object at a distance and must move the paint brush to each red dot in the model. My application allows the user autonomy over the virtual task by

moving it to an optimal visual level and gives the user auditory and visual feedback when dots are correctly hit based on their movements.

Looking at kinematic variables like wrist velocity has provided researchers with a way to study movement. Given simple conditions, movement profiles in a VE were found to resemble movements in the real world. However, in more complex conditions like blind reaching (no target in sight), the user made a lot of corrective movements based on the availability of haptic and visual feedback. It is important to look at these kinematic variables and movement profiles when designing VEs because human movement can be better modeled and predicted and therefore better / more accurate graphics can be generated. In a VE, visual information about the moving limb and haptic feedback about the object have critical effects on human performance [47].

Depth perception can be improved using practiced exercises in a VR world. In a study by Sik-Lányi et al. [59], children were tasked with first solving traditional orthoptic tests (visual acuity, ophthalmic investigations, space- and depth-vision tests) on paper. They were then instructed to complete a computer task of cutting rotated/transformed 3D cubes and matching it with a 2D perception. They would then redo the paper tests to see if there was improvement after the VR exercise. The investigators found through this experiment measuring before/after test scores that the VR programs helped children gain better space perception, and further recommend such programs in the education of 12–15-year-old children to improve space-vision.

Reaching Tasks in Virtual Environments

Mason et al. [47] explore the intersection between reaching tasks, VR/AR, and depth analysis. Their study looks at reaching for both physical and virtual targets with AR. They measured TCT and wrist movements to determine how haptic and visual feedback affects reaching movements. They also studied depth analysis for reaching kinematics and found that participants took more time decelerating towards smaller targets with haptic feedback provided. However, when haptic feedback was absent, deceleration time was constant. Also, without the feedback, Fitts's law to predict human movement does not always hold. These findings suggest that virtual visual feedback for the moving limb and haptic feedback about contacting objects are important for performance in a VE. They also support that reaching tasks can be used for depth analysis in a VR/AR environment.

In another study [20], participants had to reach real world objects, but were given different visual depth cues and only some used an HMD. Interestingly, participants using an HMD performed better and visual depth cues only had a minor impact on reaching performance. This shows how an immersive VR environment can be best for reaching and depth perception. It also indicates that no one visual depth cue weighs more than others and a combination of many depth cues do not necessarily correlate to accuracy.

Gagnon et al. [18] aimed to assess whether feedback from reaching improves depth judgement and if recalibration changes due to feedback across reaching

behaviors. They tested judgments of action capabilities within a VE for two different reaching behaviors, reaching out and reaching up. Only some participants received feedback on whether they reached the target dot. The investigators found that reach was initially overestimated, but with feedback, perceptual estimates decreased and became more accurate. They also found that targets just beyond reach were more difficult to judge. In a different study about depth perception in an immersive VE, 3D objects and closer objects were found to provide better accuracies of depth estimation than 2D objects significantly and far away objects [53]. When looking at hitting a distant target in a VE, participants had to use greater upper limb motor functions like muscular effort and torque of the shoulder to hit more distant objects [54]. Feedback on reaching activities on objects placed far away in an immersive VE is important for improving depth perception. VEs can be used to assess estimates of action capabilities and improve those estimates through visual-motor feedback. Reaching tasks, especially for distant and 2D objects in a VE, require more upper limb effort and are harder to judge distance / depth.

When someone overextends their elbows, rigid joints, etc., their different formations and movements can affect depth cues and impressions. The precision of depth and directional judgement is affected by the pendular (contracting and relaxing muscles) motion of the limb segments. Kioumourtzoglou et al. [35] studied how extending your forearm with the elbow at 80 degrees can be used to measure a sense of kinesthesis and how we perceive our body's movement. Palaniappan et al. [54] used inverse kinematics to analyze joint angle positions, joint reaction forces, and joint

torque to show how VR therapy is more effective than conventional therapy for rehabilitation. I will explore how extending and contracting the elbow relates to how well a user judges depth and performs in an immersive VR reaching task. Users are also given feedback when they correctly hit a dot in the task.

ENJOYABLE PHYSICAL THERAPY EXPERIENCE WITH INTERACTIVE DRAWING GAMES IN IMMERSIVE VIRTUAL REALITY

In this chapter, I review my SUI paper that proposes my VR creative drawing game as an effective therapy tool for upper extremity rehabilitation.

Problem Statement

I introduced an interactive drawing game, in which the users can complete different shapes of line art drawings using hand-held controllers, as a PT exercise—for upper extremity rehabilitation (see Figure 1). The game encourages broad arm motions while still being entertaining as the user strives to connect the dots of the drawing. The user can perform the drawing game with a different level of the user's bodily involvement e.g., while standing and seated, to investigate the effects of the body position on their drawing and therapy experience. Overall, I aimed to investigate how effective the VR therapy interventions with different drawing contents are in terms of the user's perception of difficulty and enjoyment, and how the perceptions can be related to each other, establishing the research questions below:

- RQ1: Do simple, yet objective adjustments of VR contents, such as the length or shape of line art drawing, influence the subjective perception of difficulty (or intensity) in the VR drawing therapy system?

- RQ2: How does the user's position influence the VR drawing therapy experience?
- RQ3: How is the perceived enjoyment of the drawing game associated with the perceived difficulty of the therapy?

Methods

In this section, I describe my first preliminary experiment that was conducted to investigate the influence of different VR drawing settings and user positions for the PT experience.

Participants

For the experiment, a priori power analysis was conducted to determine my sample size for interaction effects for ANOVA (repeated measures, within-between interaction) F tests. We used G*Power for a large effect size (η^2_p: 0.14) which gave the effect size f = 0.403 [15]. With a power of 0.80, two groups, and two measurements, the result was a total sample size of 16. I recruited a participant pool of 16 non-clinical volunteers enrolled in University of Delaware's undergraduate program (8 male and 8 females; age ranged from 18 to 20, M=19.06, SD=0.56). There was no monetary compensation for the participants.

All the participants were asked about their demographics, prior VR and video game experience, and experience of upper body injuries. Ten of participants (62.5%) have Caucasian or White ethnicity, five (31.25%) came from an Asian or Pacific Islander background, and one (6.25%) was Hispanic or Latino. Most participants

lacked prior VR/video game experience; 11 (68.75%) have never used VR headsets before and only five (31.25%) reported playing videogames weekly. Three participants (18.75%) have previously experienced a severe upper body injury, either due to sports or other incidents, and one (6.25%) needed to participate in rehabilitation sessions to recover from an upper body injury.

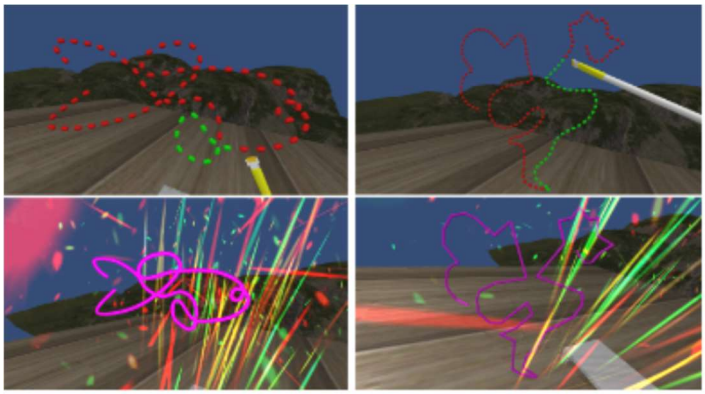
Apparatus

For my study, I developed an interactive VR drawing game using Unity game engine (version 2019.1.0f2). The game was compatible with several VR HMDs, but I chose the HP Windows Mixed Reality Headset Developer Edition for my study.

In the drawing game, participants were presented with a warm, welcoming home page, in which they could choose one of the drawing contents, either a fish or a chicken (see Figure 2). I developed these drawing contents using Autodesk Maya and Blender. The goal of this game was to connect the dots of an outline drawing of the content using a virtual paint brush. The virtual representations of the hand controllers were the only objects in the user's personal space (a cube for the non-dominant hand that controls the model's position/rotation and the paintbrush for the user's dominant hand to perform the task). The background was a simple, serene mountain scape in the distant/vista space, with a blue sky and wood floor to identify the action space. The minimalistic subspaces in the VE allowed users to focus on the task at hand in a relaxing, distraction-free environment.

The goal of this game was to connect the dots of a traceable outline of the drawing content using the paint brush. When each dot was hit, it turned from red to green, and a positive and pleasant audio feedback sound was played to the user. When all the dots were green, the user successfully connected all the dots of the drawing, they were celebrated by visual firework animations with sound effects (Figure 2). This positive visual feedback can offer a more enjoyable therapeutic experience to users, especially with the positive audio feedback with each successful dot hit.

The way to perform the game was flexible; participants could switch a controller to draw with either their left or right hand, though for the study I asked for them to choose their dominant hand. The other controller that was not drawing could be used to adjust the dot model to the height or position the user felt most comfortable with, which allowed this game to be played in both Seated and Standing settings. No matter where they adjusted the drawing content to be, they were still reaching and moving their body to complete their drawing. I wanted to compare the range users could reach and the accuracy of their movements were while seated or standing.



(a) Easy (Fish) (b) Hard (Chicken)

Figure 2 Virtual contents used for the drawing game: (a) Easy and (b) Hard contents. The images on the top show the contents in the middle of drawing exercise with a virtual brush, and the celebration effects after the task completion (bottom images)– this positive visual feedback can offer more enjoyable therapeutic experience to users

Study Design

To address my research questions, I used a 2×2 mixed design with the following between-subjects and within-subjects factors. The four study conditions following the mixed design were Seated Easy, Seated Hard, Standing Easy, and Standing Hard. The conditions were assigned to the participants in a counter-balanced order.

As a between-subjects factor, I prepared two virtual drawing contents, in which I objectively adjusted the content difficulty with different numbers of drawing dots. The difficulty levels of these virtual contents were empirically tested while preparing the experiment. I chose to use a between-subject design for the drawing contents because it could reduce confounding variables due to the exposure of multiple treatments in the drawing exercise.

- **Easy (2D Fish):** the drawing content was a shape of abstract outline fish image with 69 drawing dots, which could be easier to draw.
- **Hard (2D Chicken):** the content was a shape of abstract outline chicken image with 150 drawing dots, which could be harder to draw.

As a within-subjects factor, I had two drawing positions for the participants. I chose a within-subject design for the drawing positions because it could allow us to see how differently the same person could feel about the VR drawing therapy with respect to their position.

- **Seated**: Participants performed the drawing activity while they were seated on a chair.
- **Standing**: Participants performed the drawing activity while standing.

The following hypotheses were established with respect to these two factors:

- **H1**: Participants' objective drawing performance and subjective perception of the therapy experience will be influenced by the virtual content.
    - **H1-1:** Participants' drawing performance will be reduced with the Hard Chicken content (more drawing dots), compared to the Easy Fish content.
    - **H1-2:** Participants' perception of easiness and comfort will be improved with the Easy Fish content (fewer drawing dots), compared to the Hard Chicken content.

- **H2**: Participants' therapy experience will be influenced by their position during the drawing exercise.
    - **H2-1**: Participants will perceive that their body is more stretched in the Standing position, compared to the Seated position.
    - **H2-2:** Participants will enjoy the exercise more in the Standing position, compared to the Seated position.

Measures

For my study, I utilized both objective and subjective measures to assess the perceived difficulty of the drawing activity and other perception related to the VR therapy experience. I prepared the following two objective measures, the task completion time and normalized number of mistakes, to objectively evaluate the drawing performance in the drawing activity.

- **Task Completion Time (TCT):** The completion time of the drawing task was calculated based on the starting time when the participants pressed the controller button and the ending time when they released the controller button. The unit is in seconds.
- **Normalized Number of Mistakes:** The number of mistakes, e.g., when the participants missed any drawing dots while performing the exercise, was counted during the study sessions. The number of mistakes was normalized over the task completion time for the fair comparison among the participants; thus, the unit for this measure is the number of mistakes per second.

I also collected some perception measures through subjective questionnaires, using Qualtrics survey platform. Most of the measures were in five-point Likert scale (1: strongly disagree, 5: strongly agree), except for the "Willingness to Recommend," which was collected separately in a semantic differential scale (1–10). Here I describe the detailed question for each of the measures.

- **Easiness**: "It was easy to complete the virtual drawing task."
- **Comfort**: "I felt comfortable while completing the task."
- **Body Stretch**: "Using the VR drawing activity, I did stretch my body more than I normally do."
- **Enjoyment**: "I enjoyed playing the creative drawing game."
- **Willingness to Recommend:** "I would recommend this creative therapy game to friends or family members as a therapeutic exercise."

In the end, I also collected the participants' general feedback through text entries, asking for thoughts on how to improve this activity for future use and their preferences for the study conditions.

Procedure

The experiment was approved by the Institutional Review Board (Protocol #:1658782-1) and was conducted following the University of Delaware COVID-19 safety guidelines. Each participant was required to wear a mask for the entire duration of the study, and only one participant was allowed to be in the room at a time. All equipment was also wiped down with a disinfectant wipe and air-dried for 30 minutes

before the new participant was available. Once participants arrived, I received verbal consent after describing the purpose of my study and their rights and responsibility. After consent, the participants were randomly assigned to one of the four study conditions based on the 2×2 study design. They then filled out a pre-questionnaire about their demographics, experience with VR/video games, and experience with physical therapy/exercise. After getting explanation of study directions, participants were guided to a chair or the middle of the room to stand depending on their study conditions. I then gave them the headset to put on, and their hand controllers so that they draw with their dominant hand for the drawing activity. The session was with either the Easy or Hard level content (Figure 2)—each participant experienced only one content as a between-factor. The content was adjusted to a comfortable height and distance away from the user, depending on their assigned position, e.g., seated or standing, and the user's approval.

I recorded how many times they made a mistake in their continuous drawing stroke, e.g., when a dot does not turn green because they missed it, and their TCT. They were then asked to complete the post-questionnaire for the drawing therapy session they just experienced. The task was repeated in the other position configuration, either the Seated or Standing setting, which they did not experience in the previous session. After the second session with a different position setting, participants filled out the post-questionnaire again for the new position configuration. A unique ID was generated by each participant and was repeatedly used incompletion

of the questionnaires to assist us keep track of their data while preserving their anonymity. The entire experimental session for each participant took 10–15 minutes.

Results

I present the results of my objective measures, which are related to the user's performance in the VR drawing exercise. I used a two-way mixed ANOVA for the analysis of the results with statistical significance (α=0.05). The descriptive objective results are shown in Figure 3.

- **Task Completion Time**: I did not find any significant effects in the TCT for the Content factor (F (1, 14) = 4.245, p=0.058). However, the mean of TCT for the Hard Chicken content (M=36.10, SD=5.66) was larger than the Easy Fish content (M=29.67, SD=6.74). There was no main effect for the Position factor or the interaction effect.
- **Normalized Number of Mistakes**: I found a main effect of the Content factor for the normalized number of mistakes (F (1, 14) = 9.047, **p=0.009**, η^2_p=0.393; large effect). This indicates that participants made more mistakes with the Hard Chicken content (M=0.24, SD=0.09) than the Easy Fish content (M=0.13, SD=0.06)—the raw numbers of mistakes before normalization: Hard Chicken (M=8.38, SD=2.22) and Easy Fish (M=3.81, SD=1.38). I did not observe a main effect of the Position factor and the interaction between the factors with statistical significance.

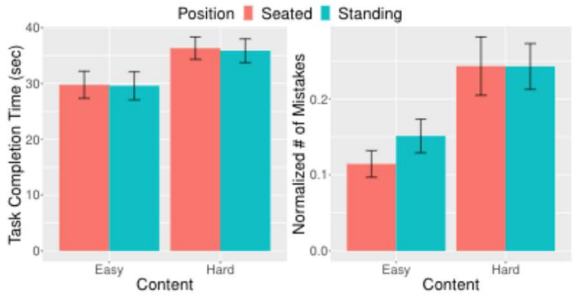


Figure 3 Results of objective measures. Standard error of the mean (SEM) was used for the error bar with the mean. There was a main effect of Content (Easy vs Hard) for the normalized number of mistakes.

I present the results of participants' subjective measures of their perception of the drawing exercise. The descriptive results are shown in Figure 4.

- **Easiness**: I did not find any main effects and interaction among the study conditions regarding the perceived easiness. Seated position (M=4.88, SD=0.34) and standing (M=4.75, SD=0.45).
- **Comfort**: There was no main effect of the Position factor (F (1,14) = 3.611, p=0.078); however, the mean score of the comfort measure for the Seated position (M=4.81, SD=0.40) was higher than the Standing position (M=4.38, SD=0.72). I did not find a main effect of the Content factor or an interaction effect.
- **Body Stretch**: I found a main effect of the Position factor (F (1,14) = 9.800, **p=0.007,** η^2_p=0.412; large effect). This means that participants thought they stretched their body more in the Seated position (M=3.31, SD=1.14), compared to the Standing position (M=2.44, SD=0.81). There was no main effect of the Content factor or an interaction effect.

- **Enjoyment**: I found a main effect of the Content factor (F (1,14) = 8.000, **p=0.013,** η^2_p =0.364; large effect). This indicates that participants enjoyed the VR drawing exercise with the Hard Chicken content (M=4.88, SD=0.34), compared to with the Easy Fish content (M=4.38, SD=0.50). There was no main effect of the Position factor or an interaction effect.
- **Willingness to Recommend:** I did not find any significant effects in this measure, but the mean score for the Seated position (M=8.44, SD=1.46) was higher than the Standing position (M=8.25, SD=1.57), with respect to the Position factor (F (1,14) = 4.200, p=0.060).

There was no main effect of the Content factor or an interaction effect. There were no interaction effects with statistical significance reported; thus, we did not go further for post-hoc tests.

Besides, a correlation analysis was conducted using the Pearson's correlation coefficient. The objective raw number of mistakes was correlated with the subjective enjoyment with statistical significance (r (30) = 0.471, **p=0.007**). So, we conducted a linear regression (Equation 1) to predict enjoyment based on *raw* number of mistakes (F (1,30) = 8.532, **p<0.001**, R^2=0.221). The enjoyment score is relatively high even there is no mistake.

$$enjoyment = 0.079 \times number\ of\ mistakes + 4.146 \quad (1)$$

In addition, there was a statistically significant correlation between the *raw* number of mistakes and the willingness to recommend measures (r (30) = 0.447, **p=0.010**). The

linear regression to predict recommendation based on *raw* number of mistakes (F (1,30) = 7.493, **p<0.01,** R^2=0.200) results in Equation 2.

$$\textit{willingness to recommend} = 0.227 \times \textit{number of mistakes} + 6.961 \quad (2)$$

These results indicate that participants who drew the hard chicken model tend to enjoy the VR drawing exercise more and be willing to recommend it to their friends and family.

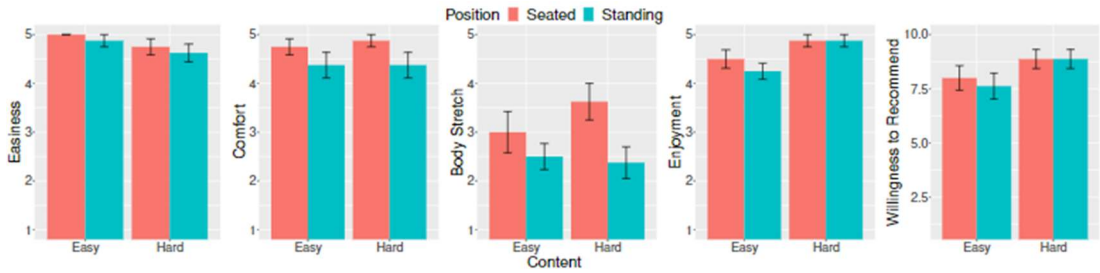


Figure 4 Results of subjective measures. Standard error of the mean (SEM) was used for the error bar with the mean. There was a main effect of Position (Seated vs. Standing) for the perception of body stretch, and a main effect of Content (Easy vs. Hard) for the enjoyment

Discussion

Here, I summarize my main findings with respect to my established hypotheses, based on the results reported in the previous section. I discuss implications behind the findings considering the therapeutic context.

Effects of Drawing Content

My results from objective measures support **H1-1**, showing that the participants made more mistakes when they drew the Hard content than the Easy

content. In contrast, the results of the subjective measures related to the perceived easiness and comfort did not show any differences among the study conditions, resulting in no evidence for the **H1-2**. These contrary observations about objective and subjective measures are particularly interesting in an aspect that one may eventually moderate the duration and intensity of a therapy session objectively through the simple adjustment of the virtual drawing content. More work needs to be done to explore the most challenging level of the game without compromising patients' sense of comfort during the game.

My findings are further interesting when it comes to the participants' enjoyment during the drawing exercise. I initially set a hypothesis expecting a higher level of enjoyment for the Standing setting compared to the Seated setting, with respect to the Position factor **(H2-2)**, considering the higher level of bodily involvement in the Standing setting. However, what I found was a main effect of the Content factor instead. I observed that the slight change of content to the chicken model (the Hard content) could increase the enjoyment score. It is noteworthy that this effect was found when each participants experienced only one of the virtual contents, either the Easy or the Hard content, as a between-subjects factor even without comparing the contents directly through the repeated measures. Knowing that there is low adherence to therapeutic exercise in typical PT settings, this observation can be useful to design more engaging and enjoyable therapy interventions. Many of participants' feedback after the experiment also supported the validness of the interactive VR drawing game for the enjoyable PT exercise, including the comment

from Participant #13: *"When I broke my arm from hockey and got my cast off, I had to do several exercises like bending/straightening my arms, rotating my wrists, and other things to regain my strength. I could see how this game could be helpful and fun at the same time."*

Effects of Drawing Position

I had established a hypothesis that participants would feel they stretched their body more in the Standing setting than the Seated setting (**H2-1**), due to the potential increase of movement in the Standing setting. On the contrary, however, they thought they stretched more in the Seated setting. The reason could be because the restriction of movement on the chair encouraged the body stretch, which is also reported by several participants. For example, Participant #4 said *"When I was sitting, I had to reach more and wanted to lift myself off the chair a bit to get to the highest parts of the chicken. But since I couldn't I had to really stretch my arm and controller out to hit the dots."*

This finding has implications for PT exercises for patients who have severe restrictions of lower-body movement, such as rehabilitation for post-stroke patients in seated settings. The Seated setting could also strengthen the compatibility/accessibility of my therapy game for a limited space, e.g., for remote at-home therapy interventions. Although I need a further investigation to examine the participants' bodily movement objectively, this benefit of the seated setting for the sense (or intent) of body stretch is promising for effective VR-based PT interventions, especially considering the simplicity of the proposed line art drawing game together.

Correlations

The correlation analysis revealed that there are positive correlations between the number of mistakes, and the enjoyment and the willingness to recommend measures. More investigations will certainly be required to make more personalized therapy experience possible with appropriate difficulty levels in the virtual contents for individual PT patients. However, considering mental frustrations of patients during the PT exercises [57], my findings are interesting and important. Ideally, PT patients could enjoy more and be satisfied with the VR therapy experience when they make more mistakes, based on the results from the healthy participants in the correlation and regression analysis. Further research with a more representative group of PT patients will be conducted also to validate this.

The main findings of my results with respect to my hypotheses are centered around evaluating my VR Therapy game in terms of user performance, user perception of depth, and user ease and comfortability. The findings are important to the HCI, physical therapy, and depth perception fields and offer insight on what could be improved for future similar exergames.

Study Limitations

As with most studies, the design of the current study is subject to limitations. My research motivation was drawn from post-stroke rehabilitation, but the conducted study was based on a convenience sampling, which involved young, healthy students

selected from the university community. The study sample was also relatively small (n=16) which may influence the generalizability of the results.

Broader Implications and Future Work

I presented a simple, creative, and portable VR drawing game as an effective tool for PT, which can be useful for at-home, remote therapy interventions. My proposed VR drawing game can allow patients to perform their therapy sessions at the comfort of their homes, helping both physical and emotional health of the individuals. The scope of the VR drawing game is currently focused to the upper extremities; but the implications of the work can be extended to different disciplines in PT interventions, e.g., for lower-body or any different body parts rehabilitation. Beyond PT, VR experience has been implemented for enhancement of cognitive skills [8,30], and is considered as an effective tool for the prevention and treatment of stress-related psychopathological symptoms and PTSD, with therapeutic benefits [6,10]. While the importance of mental health is growing and emphasized during/after the COVID-19 pandemic and for shelter at home, I consider how my therapy game can be received as a remote therapy tool, like "The Secret Garden" by Imperatori et al. [29]—a 10-minute self-help VR protocol made to reduce the burden of the coronavirus.

While the drawing experience that the participants had was short and happened only a couple of times per participant, my study was conducted with non-clinical participants as convenience sampling, which was in part due to restrictions from the COVID-19 pandemic for conducting more structured studies. I plan to extend my

work with a larger sample for repeating measures and representative participant pools, with upper extremity injuries, or post-stroke patients to further validate my findings.

From a technical point of view, it would be beneficial for patients to receive real-time or after-action feedback on their performance to check their rehabilitation progress. While the current system can provide various positive feedback in various stages of the game to user during or after completion of the drawing, a variety of interactive VR interventions and a dashboard to summarize user's progress in various levels of the game would be desired. Research on the effects of iVR interventions comparing with augmented/mixed reality (AR/MR) interventions could be interesting in terms of the patient's distraction from the therapy by real-world occurrences.

Conclusion

I present a creative VR therapy game using line drawing activities and investigated how the drawing content and the user's position could influence the user's performance and perception in the drawing exercise. The results showed that the proposed VR drawing game is an effective tool for enjoyable physical therapy, which has much potential for customized therapy experience. While considering the broader use cases of this interactive VR drawing intervention for several types of PT exercise, we will extend our study and further investigate the effectiveness of VR therapy.

VIRTUAL THERAPY EXERGAME FOR UPPER EXTREMITY REHABILITATION USING SMART WEARABLE SENSORS

In this chapter, I discuss my CHASE paper that focuses on multi-modal data collection for upper extremity therapy with more customizations that relate to how dimensions and depth may affect the user's therapeutic experience.

Problem Statement

I previously introduced an interactive drawing game, in which the users can complete different shapes of line art drawings using hand-held controllers, as a PT exercise for upper extremity rehabilitation. To address the need for tracking throughout the limb, I will introduce a non-invasive fabric sensor that is sewn on an elbow sleeve. I also vary the virtual content in orientation and dimensions to offer different customizations and a way to investigate how different drawing contents and modalities for data collection affect the difficulty and user enjoyment, which is important because inaccurate depth perception is a limitation of many VR applications. I establish the following research questions:

- RQ4: How does the objective multi-dimensional adjustment of the virtual content influence the therapeutic experience in the VR drawing exergame?

- RQ5: How is the participants' drawing performance influenced by the orientation of the virtual content?
- RQ6: How is the subjective perception of the VR drawing exergame, such as easiness, comfort, and enjoyment associated with different conditions of the virtual content?

Methods

In this section I will describe my second preliminary experiment keeping in mind my goal to investigate the influence of different VR drawing configurations for depth perception and upper extremity rehabilitation while also adding an elbow sensor as another modality to collect data from the upper extremities.

Participants

For the experiment, a priori power analysis was conducted to determine my sample size for interaction effects for ANOVA (repeated measures, within factors) F tests. We used G*Power for a large effect size (η^2_p: 0.14) which gave the effect size f = 0.403 [15]. With a power of 0.80, one group, and four measurements, the result was a total sample size of 10. To keep a balanced design of three participants for each of the four measurements while still being greater than n=10, I recruited a participant pool of 12 non-clinical volunteers enrolled at the University of Delaware (5 male and 7 females; age ranged from 20 to 29, M=22.67, SD=2.78). There was no monetary compensation for participation.

All the participants were asked about their demographics, video game and VR experience, prior upper body injuries, and visual impairments. Eight of participants (66.66%) have Asian or Pacific Islander ethnicity and four (33.33%) are from a Caucasian or White ethnicity. Most participants had prior VR but lacked prior video game experience; ten (83.33%) have used VR headsets before but only three (25%) reported playing video games daily or weekly. Two participants (16.67%) have previously experienced a severe upper body injury, either due to sports or other incidents, and needed to participate in rehabilitation sessions to recover. Only one participant (8.33%) was visually impaired beyond their glasses/contacts. However, when asked how strongly they agreed to having difficulty judging how far objects are in the distance, four participants (33.33%) somewhat agreed. For having a challenging time focusing both eyes on one object, one participant (8.33%) strongly agreed, and two participants (16.67%) somewhat agreed.

Apparatus

For this second study, I expanded on the apparatus from my first study in Chapter 3. In the drawing game, participants could now choose one of four drawing contents ranging in difficulty; in this study, participants will only use the 2D and 3D fish drawing contents (Figure 5). The drawing contents were developed using Autodesk Maya and Blender with the help of Brian Cohn, Matthew Dwyer, Aishwarya Chandrasekaran, and Yufan Wang. No modifications were made to the simple background/subspaces in the VE to allow users to focus on the task at hand in a

relaxing, distraction-free environment without any other cues that could throw off the depth perception.

I collaborated with engineers for a data collection sleeve [49] that provided an elbow stretch factor (the resistance of the fabric-based sensor that is sewed into the sleeve). This sleeve was worn on the user's dominant arm to collect how much that joint extended/relaxed throughout the reaching drawing task. On the nondominant hand's controller was a button that I wrote code to flip the virtual content to be vertical or horizontal when pressed. My goal was to compare how accurate participants' movements were while viewing the virtual content horizontally vs. vertically, and in 2 dimensions vs. 3 dimensions.

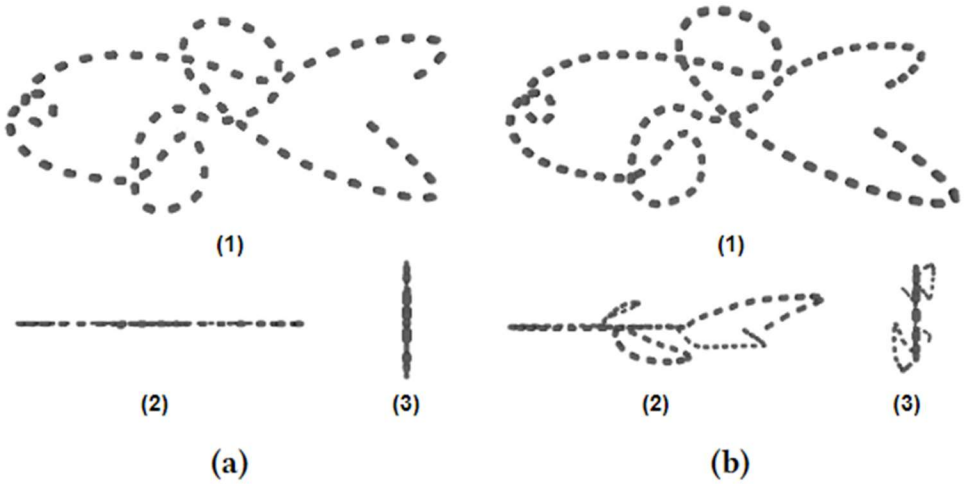


Figure 5 (a) 2D Fish and (b) 3D Fish drawing content in the following rotations: (1) side view (2) top-down view (3) front view

Study Design

To address my research questions, I used a 2×2 within-subjects study with a balanced design with the following factors: (1) level orientation: Horizontal vs. Vertical, and then (2) configuration: 2D vs. 3D. There is no trial in the studies since no identical conditions are expected to be performed twice by the subject. But since I have within-subjects design, this means participants will take part in four study conditions: 2D Fish Vertical, 2D Fish Horizontal, 3D Fish Vertical, 3D Fish Horizontal. I avoided the phrase "repetition" as its definition can vary from one discipline to another. The order to complete the four study conditions was based on a balanced Latin Square (4x4) [26], see Table 1.

A	B	C	D
B	A	D	C
C	D	B	A
D	C	A	B

A: 2DV B: 2DH C:3DV D:3DH

Table 1 4x4 Latin Square to randomly assign an order of the study conditions to participants

For the content of the study conditions, I prepared the virtual drawing content in two different dimensions, in which the 2D fish model was objectively adjusted with

more drawing dots for the addition of dimensions/depth. The difficulty levels of these virtual contents were empirically tested while preparing the experiment.

- **2D Fish:** the drawing content was a shape of abstract outline fish image with 69 drawing dots, which could be easier to draw because they are all on the same z-plane.
- **3D Fish:** the drawing content was a shape of abstract outline fish image with 91 drawing dots, which could be harder to draw because some dots are closer/farther than others in respect to the z-axis and more dots were required to add this dimension while keeping the same shape.

For the orientation, the two virtual drawing contents were rotated around the x-axis for a vertical view of the model and a horizonal view of the model, see Figure 6. The difficulty levels of these orientations were empirically tested while preparing the experiment.

- **Vertical:** Participants performed the drawing activity while looking at the model head-on/straight up, with their reaching motions moving primarily up and down.
- **Horizontal:** Participants performed the drawing activity while looking at the model lying flat down, with their reaching motions moving primarily out and in.

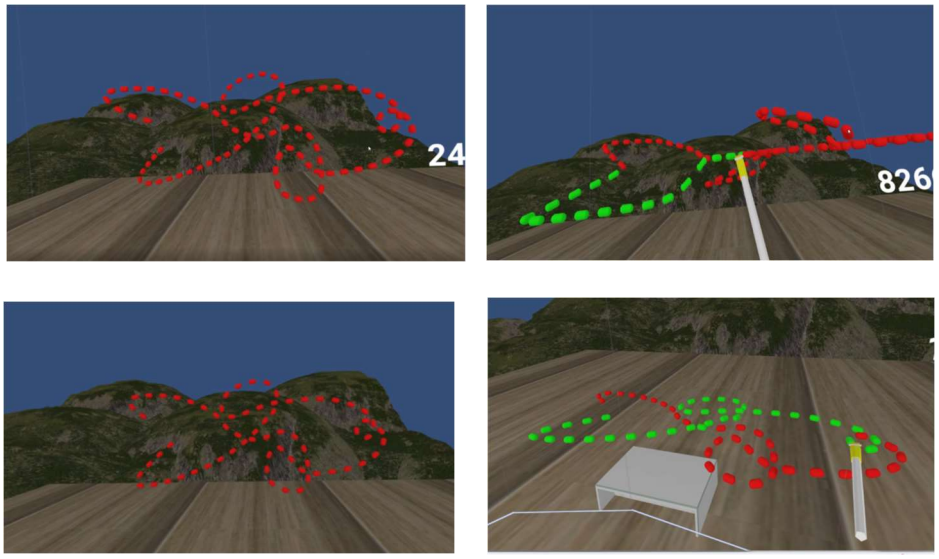


Figure 6 Virtual contents used for the drawing game: (top) 3D Fish and (bottom) 2D Fish. The left images show the contents at the start of the drawing exercise in the vertical orientation. The images on the right show the contents in the middle of the drawing exercise with a virtual brush in the horizontal orientation

The following hypotheses were established with respect to the content and orientation factors:

- **H3**: Participants' objective drawing performance and subjective perception of the therapy experience will be influenced by the virtual content.
    - **H3-1:** Participants' drawing performance will be reduced with the 3D Fish content (more drawing dots and dimensions), compared to the 2D Fish content.
    - **H3-2:** Participants' perception of depth will be improved with the 2D Fish content (the distance from the user to the dots are the same for each dot), compared to the 3D Fish content.

- **H4**: Participants' therapy experience will be influenced by the orientation of the virtual content because it offers different viewpoints and reaching advantages of the dots.
    - **H4-1:** Participants' drawing performance will be reduced with the horizontal orientation compared to the vertical orientation because their perception of depth will be reduced with reaching out than reaching up.
    - **H4-2:** Participants' ease and comfortability will improve with the vertical orientation compared to the horizontal orientation because they can better see the content's full shape.

Measures

I utilized both objective and subjective measures to assess the perceived difficulty of the drawing activity and other perceptions related to the VR therapy experience through quantitative data collection and usability post-questionnaires.

For the objective measures, I prepared three measurements to objectively evaluate the user's drawing performance and reaching/joint movements during the exercise.

- **Task Completion Time (TCT):** The completion time of the drawing task was calculated based on the starting time when the participant hits the first dot and the ending time when the final dot is hit, collected by a script. The unit is in seconds.
- **Number of Mistakes**: The number of mistakes, e.g., when the participants missed any drawing dots while performing the exercise, was counted during the study

sessions; a different data collection script also tells me the order in which they hit the dots, so an error is indicated when the dot numbers are not sequential.

- **Elbow Stretch:** The sleeve over the elbow detects when the elbow extends and contracts, quantifying it over the period from when I start a data streamer script (when I tell the user to begin drawing) to when I end the script (when I see they hit their last dot). The unit is the resistance factor provided by the sleeve.

For the subjective measures, I collected data on usability and perception based on subjective questionnaires, using Qualtrics survey platform. Most of the measures were in five-point Likert scale (1: strongly disagree, 5: strongly agree), except for the "Willingness to Recommend," which was collected separately in a semantic differential scale (0: Not at all likely, 10: Extremely likely). At the end, I also collected the participants' general feedback through text entries, asking for thoughts on how to improve this activity for future use and their preferences for the study conditions. Below is the detailed question for each of the subjective measures:

- **Easiness**: "It was easy to complete the virtual drawing task."
- **Comfort**: "I felt comfortable while completing the task."
- **Enjoyment**: "I enjoyed playing the creative drawing game."
- **Body Stretch:** "Using the VR drawing activity, I stretched my arm out more than I normally do."
- **Depth Perception:** "I could easily reach the objects and judge the distance from the objects in the creative drawing game."

- **Visual Cues:** "The virtual drawing model was realistic" and "I could easily see things and objects in the creative drawing game."
- **Willingness to Recommend:** "I would recommend this creative therapy game to friends or family members as a vision therapeutic exercise" and "I would recommend this creative therapy game to friends or family members as an upper-limb therapeutic exercise"

Procedure

This experiment was approved by the Institutional Review Board (Protocol #:1658782-1). I received participants' verbal consent after explaining the study and their rights, then randomly assigned them to an order to conduct the 4 study conditions. They then filled out the pre-questionnaire about their demographics, experience with VR/video games, experience with physical therapy/exercise, and experience with visual impairments. After getting explanation of study directions, participants were guided to the middle of the room to stand in a cleared area. I then adjusted the data collection sleeve to be right on top of their dominant hand's elbow, gave them the headset to put on, and placed their hand controllers so that they draw with their dominant hand (Figure 1). They were guided on how to start the assigned content in the VE: 2D Fish Vertical, 2D Fish Horizontal, 3D Fish Vertical, 3D Fish Horizontal. The model was adjusted to a comfortable height and distance away from the user with their approval.

When starting the task, I triggered the data collection scripts to record the objective measures. When the task was completed and the victory animation was finished playing, I collected the HMD and hand controllers and asked them to complete the post-questionnaire for the drawing therapy session that they just experienced. The user was then asked to put on the VR devices again and do their next task in a new configuration/orientation. Once again, participants fill out the post-questionnaire for each of the new configuration/orientations. A unique ID was generated by each participant and was repeatedly used in completion of the questionnaires and saving of the data files to keep track of their data while preserving their anonymity. The entire experimental session for each participant took 20-30 minutes.

Results

For the objective measures of my second preliminary study, I found the following effects of the VR drawing game on user performance. I used ANOVA for examining the main and interaction effects. Here, I report the results mainly focusing on the findings with statistical significance ($\alpha=0.05$).

- **Normalized Task Completion Time:** When looking at the average TCT in seconds for each of the virtual contents, there was no statistical difference ($p=0.1005$; non-significant) from an overall F test. However, when I compare each version to another individually, there is statistical significance between just 2DV and 3DV (**$p=0.0164$**; $p<0.05$). To account for the fact that there is a difference in

number of dots for 2D vs 3D, I normalized TCT by dividing the TCT by number of dots, making the unit seconds per dot. The results from normalized TCT were like average TCT results; there was a statistically significant difference on the interaction effect between the orientation and configuration **($p<0.03$),** see Table 2. Even though there was no significance on the main effect of the conditions, with a pairwise t test there was a difference in 2DH vs 2HV (**$p< 0.03$**). The results (Figure 7) show that vertical model performance was faster than horizontal model performance for 2D configurations.

- **Normalized Number of Mistakes:** For average number of mistakes for each of the virtual contents, the overall F test indicate that there is a statistically significant difference (**$p=0.016$**; $p<0.05$). Knowing that at least one version is statistically different from the other versions and there is a relationship between the virtual content and average number of mistakes, a pairwise t test compared individual versions. 2DV had significance against 3DH (**$p=0.0057$**; $p<0.05$) and against 3DV (**$p=0.0069$**; $p<0.05$). The rest of the virtual content versions did not have statistical significance. This measure shows insight on user accuracy when completing the tasks.

When I normalized the number of mistakes by dividing the raw number of mistakes by the TCT, I measured the number of mistakes per second. This helped explore if there would be significance when accounting for the fact that more dots could mean more time taken and more mistakes objectively, not just because it is

3D instead of 2D. The results showed no significance after normalization, see Table 2. Only when we observe the means of the normalized results subjectively, it shows that the number of mistakes of 2D configurations are averagely lower than 3D configurations, with vertical being relatively lower than the horizontal orientation in 2D (Figure 7).

- **Normalized Elbow Stretch**: The compression sleeve to measure elbow stretch provides a resistance measurement for the duration of the collection [27]. At first, when looking at the average resistance factor from the sleeve, no data was significant. Because each individual participant had a different base value for the sleeve when resting their arm (sleeve stretches more for bigger arms than smaller when not extended), I then looked at resistance changed. This was done by taking the average of the resistance change for each participant to see how the range of elbow stretch compares across versions. Resistance is indicated by how much the elbow sleeve stretches. For resistance change, outliers were removed outliers and the percentage changed was calculated with

$$((Resistance - Min\_Resistance) * 100) \ / \ Min\_Resistance$$

There was significance ($p=0.032$, $p<0.05$) between 2DH ($M=20.6$) and 3DH ($M=17.9$). This means that a participant's % change of elbow stretch was higher during a 2D horizontal fish version than a 3D horizontal fish version.

When I normalized the resistance change by dividing it by TCT, the unit was resistance change per second. Normalization showed a different significance than average resistance changed. There were significant differences on orientation (**p<0.04**), configuration (**p<0.03**), and the interaction between orientation and configuration (**p<0.01**), see Table 2. The results of pairwise t test show a significant difference between 3D vs. 2D (**p<0.002**), particularly when looking at 3DV vs. 2DV (**p<0.004**). For orientation, there was a difference between 2DV vs. 2DH (**p<0.01**). The results indicate that the 2D model induced more elbow stretches than the 3D model in the vertical orientation, see Figure 7. Furthermore, the vertical orientation induced more stretches compared to the horizontal orientation during the drawing performance of virtual content.

Variable	df	F	p	Sig	η^2
Task Completion Time					
Orientation	1	1.292	0.27		0.015
Configuration	1	0.001	0.96		0.00003
Orientation * Configuration	1	5.872	<0.03	*	0.082
Mistakes					
Orientation	1	1.681	0.22		0.016
Configuration	1	2.068	0.17		0.023
Orientation * Configuration	1	0.479	0.50		0.013
Resistance Change					
Orientation	1	4.990	<0.04	*	0.054
Configuration	1	11.823	<0.005	*	0.168
Orientation * Configuration	1	8.528	<0.01	*	0.076

Table 2 Summary of statistical results for normalized objective measures (p<0.05). There was significance in the interaction effect between orientation and configuration for TCT. There was also significance in orientation, configuration, and their interaction for resistance change

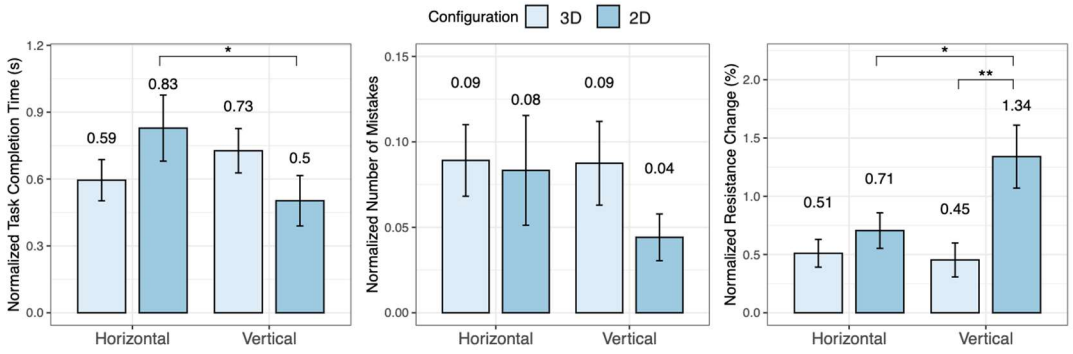


Figure 7 Results of normalized objective measures: (left) task completion time, (middle) number of mistakes, and (right) resistance change

For the subjective measures of my study, I discovered the following results from the participants' subjective perception of the creative exergame.

- **Easiness, Comfort, and Enjoyment:** There was no main effect of the perceived easiness ($p=0.1165$, $p>0.05$) using the F-test in One-Way ANOVA on the mean score, see Figure 8. The comfortability measure when compared to content version ($p=0.6975$, $p>0.05$) and enjoyment measure compared to version ($p=0.7531$, $p>0.05$) also did not produce significant results. I also did individual comparisons between version pairs and none of those tests produced main effects either. The perceived easiness of the content for 2D versions was averagely higher than the 3D versions.

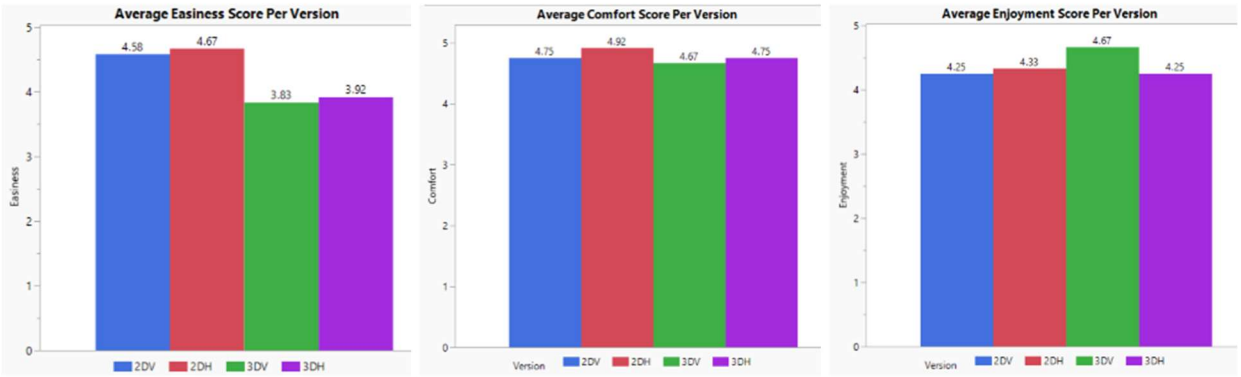


Figure 8 Results of the average perceived easiness, comfort, and enjoyment scores with no main effect of content version (2DV, 2DH, 3DV, 3DH)

- **Body Stretch:** The perceived stretch of the participants' arm was not significant per version (p=0.3384, p>0.05). There was also no significance when compared in pairs rather than across all 4 versions. When looking at the averages, 3D versions were higher than 2D versions and the horizontal models were higher than their respective vertical models (Figure 9).
- **Depth Perception**: The perceived easiness to reach objects and judge the distance from objects for participants was significant between versions (**p=0.0428**; p<0.05). When looking at how the versions compared in pairs for the depth perception scores, there was significance between 2DV and 3DH (**p=0.0189**, p<0.05). There was also significance between 2DV and 3DV (**p=0.0295**, p<0.05). When looking at the averages, 3D versions were lower than 2D versions and the horizontal models were lower to their respective

vertical models; this is the inverse of the perceived body stretch observations (Figure 9).

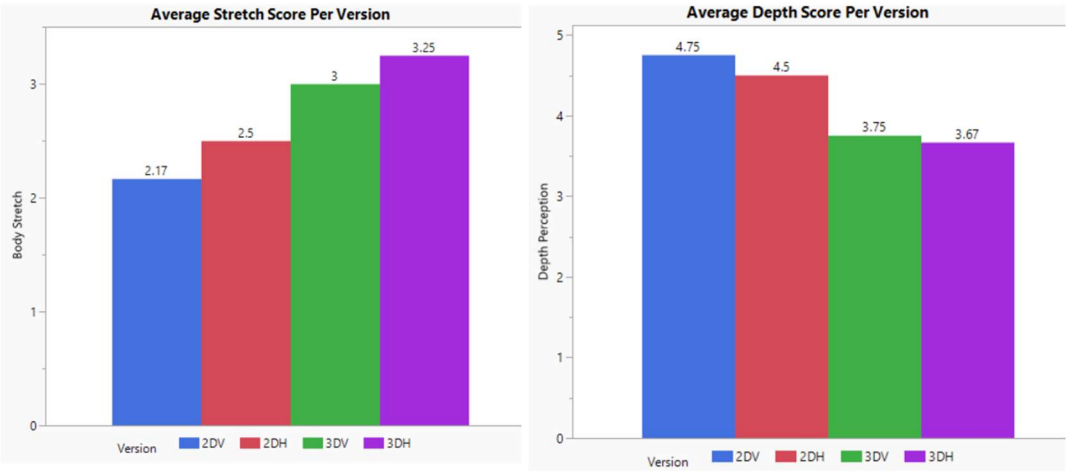


Figure 9 Results of the perceived body stretch and subjective depth perception. There was no main effect of content version for body stretch, but there was a main effect of overall depth perception scores and specifically between 2DV vs. 3DH, and 2DV vs. 3DV

- **Visual Cues**: To get an insight into how accurate the visual cues were for the virtual contents; I measured the perceived easiness to see the objects in the VE. There was no significance for the perceived easiness between versions ($p=0.7196$, $p>0.05$). I also looked at the perceived realism of the virtual drawing models, which was also not statistically significant overall ($p=0.1187$, $p>0.05$). However, when individually comparing the realism scores, there was a main effect of 2DH vs. 3DH (**$p=0.0379$**, $p<0.05$). 2DV and 2DH had the same mean, so there was also a main effect when comparing 2DV vs. 3DH (**$p=0.0379$,** $p<0.05$). It is also interesting that for both easiness and realism, the

averages decreased for 3D compared to 2D (Figure 10). This follows the same observation from the depth perception measures.

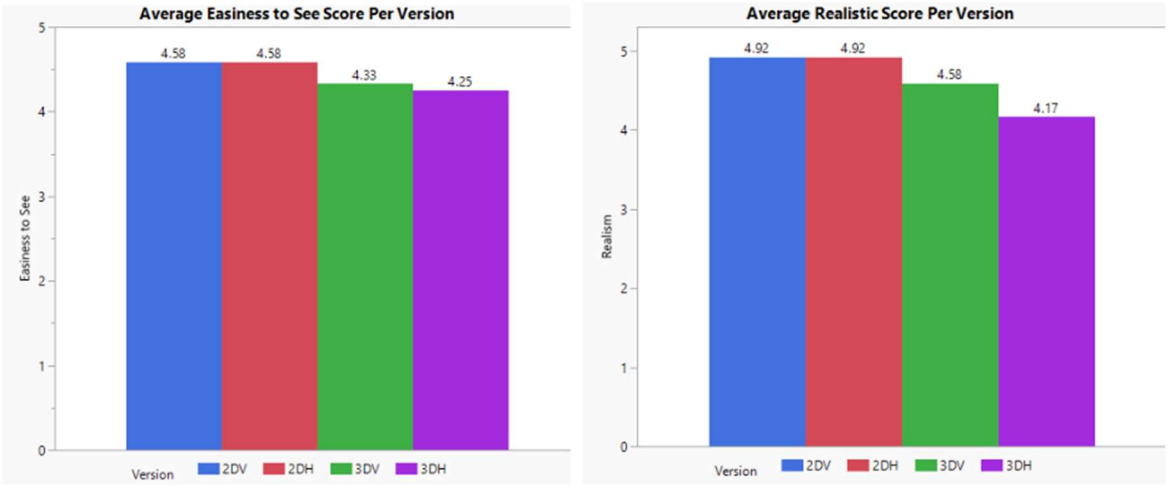


Figure 10 Results of the average visual cues scores with no main effect per version for both the easiness to see and the realism of objects measures. There was a main effect of realism of 2DH vs. 3DH, and 2DV vs. 3DH

- **Willingness to Recommend:** There was no main effect for the willingness to recommend the creative drawing game as an upper extremity therapy per version ($p=0.2834$, $p>0.05$) nor as a vision therapy per version ($p=0.222$, $p>0.05$). However, it is interesting that both 3D versions' means were higher (promoters) than the 2D versions' means (passives), see Figure 11.

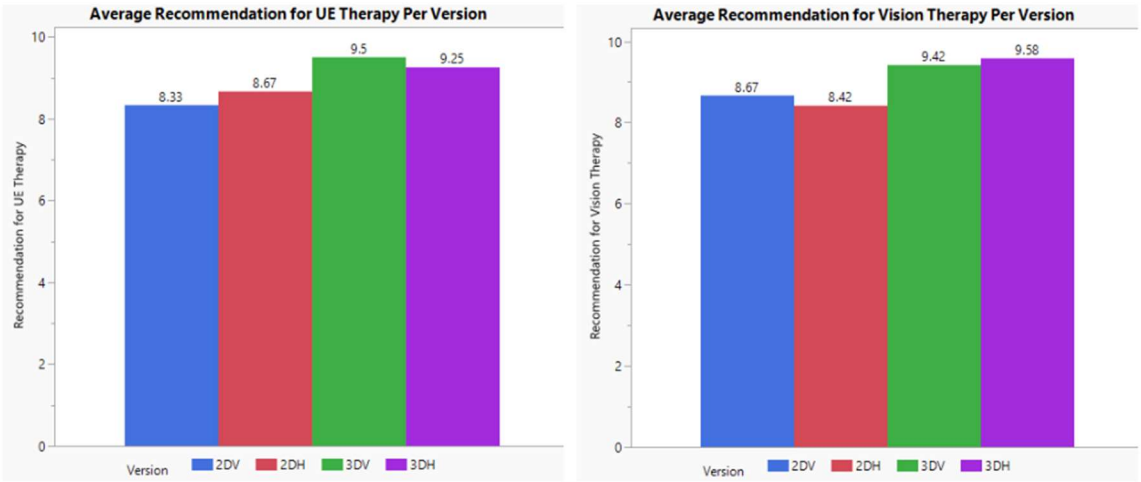


Figure 11 Results for the willingness to recommend was not significant between versions for neither an upper extremity therapy nor a vision therapy

Discussion

Here, I summarize my main findings with respect to my established hypotheses H3-H4, based on the above results. I discuss implications behind the findings considering the visual and upper extremity therapeutic context. I discuss the significance and limitations of adding another modality to collect data from the dominant hand performing the exercise.

Effects of Depth

To understand the depth perception scores and significance, I looked at visual cues. Visual cues measures only offered statistical significance for the perceived realism of 2DH vs. 3DH and 2DV vs. 3DH. However, the means for the perception of visual cues were observed to be lower for 3D versions than the 2D versions. A similar

observation can be made for subjective depth perception scores. The means for 3D versions were lower than 2D versions; unlike the visual cues means, the depth perception means were observably lower for horizontal versions than vertical versions. This has the potential to support the correlation between accurate visual cues and accurate depth perception with further work.

This also provides insight into **H3-2** that participants' depth perception is greater in 2D content than the 3D content. There was significance between 2DV vs. 3DV, where the mean of 3D perceived depth is reduced compared to the mean of 2D. Though there was no significance between 2DH vs. 3DH, the 3DH mean was still smaller in comparison to 2DH. Because of the subjective measure that users found it easier to judge the distance from the objects and easier to reach them with 2D content than 3D content, I speculate that the reason their perception of depth was improved with 2D is because the distance from the user to the dots was uniform across all dots.

In contrast, the participants' subjective perception of body stretch had higher means for 3D versions than 2D versions, perhaps because 3D models are a combination of reaching out/in and reaching up/down. However, when looking objectively at body stretch with the normalized resistance change of the elbow sleeve, there was significance that reaching in 2D models encouraged more stretching than the 3D models. This is interesting because perceived body stretch and elbow stretch were contradictory, and though 2D models indicated improved objective body stretch they also indicated reduced subjective depth perception.

H3-1 that performance would be reduced with 3D content compared to 2D content was not supported. Because normalized TCT and normalized number of mistakes did not differ across configurations, it can imply that there was no change in difficulty with a change in multi-dimensional content. This can lead to the customization of therapy with multiple levels that share the same intensity and have the same subjective easiness, enjoyment, and comfort.

When looking at willingness to recommend, there was no statistical difference of willingness to recommend for an upper extremity therapy vs. a vision therapy. However, participants were more likely to be promoters for the exergame for the 3D models. Easiness, comfortability, and enjoyment do not improve nor worsen with the change in configuration or orientation. Participants are more appreciative of the game as a UE and vision therapy exercise for the multi-dimensional levels despite there being no change in difficulty, easiness, comfort, or enjoyment. This encourages researchers to look at how more dimensions and the combination of reaching up/down/up/in can be used in future studies for enjoyable telerehabilitation.

Effects of Orientation

For **H4-1** that participants will have worse depth perception in horizontal models than vertical models, there was no significance with the results from visual cues measures. However, there was significance for depth perception overall and specifically with 2DV vs. 3DH. In general, the horizontal means were averagely lower than the respective vertical means. This could be because reaching out/in for

horizontal model is harder than reaching up/down for vertical models. In terms of the reaching aspect of **H4-1**, what was interesting is that the subjective body stretch measure showed the opposite effects of the subjective depth perception measure. Though there was no statistical significance, reaching out/in movements (horizontal versions) showed a higher mean of perceived body stretch than the reaching up/down movements (vertical versions). More work needs to be done to explore if an inverse correlation between perceived body stretching and perceived depth exists.

None of my objective measures offered any significance for user performance / accuracy for horizontal version versus vertical. This could mean that there is no increase/decrease in difficulty based on orientation. Therefore, the exergame can be played in either the vertical/horizontal mode and will not affect a patient's therapy performance. This is important to study because the horizontal model can be better suited for seated positions than standing for those therapy patients with limited lower limb mobility. Because participants were standing and reported better depth perception with vertical models, it is possible that the horizontal model could be better suited for a seated position. The creative exergame's usability for vision and upper limb therapy will not be compromised if played in this more accessible position. Such interchangeability of orientation leads to the customization of therapy for each user.

I also did not find support for **H4-2** that easiness and comfortability would improve for vertical versions than horizontal versions. Perhaps this implies that all levels provide adequate enjoyment, easiness, and comfort for a satisfactory virtual

therapy environment. No matter the configuration or orientation, the users will still be engaged in their therapy treatments and think of it as a safe space.

When asked on their thoughts on how to improve the VR drawing activity for future use, participants responded with feedback on the difficulty, easiness to see, and the stretch required to reach the tasks. Participant #6 reported that for the 3D configuration, in horizontal orientation, it was *"hard to reach the furthest part of the fish from standing in one spot"* and in vertical orientation, it was *"hard to tell what dots were farther away/closer to me."* This shows how orientation affects how much a user perceives body stretch while reaching and estimates distance from an object in a VE. When drawing the 2D fish in a vertical orientation, they expressed that *"this level was too easy".* Similarly, Participant #11 expressed that the flat model drawn vertically *"felt like I finished this model really fast so [it] wouldn't be that practical for a game."* Such suggestions offer insight on how my task can be used as short repeatable exercises for patients that are not too strenuous in each iteration.

Participant #12 said that they liked the 2D model more in horizontal orientation than vertical orientation because they could *"look down on it as I draw"* and the horizontal task was *"realistic, easy, enjoyable"*. However, Participant #9 expressed that with 2D model with horizontal orientation, *"it was a little challenging to see the order of the dots in this setting, and I think I traced some of the dots out of order because of this."* The significance that there is no statistical difference in user accuracy/performance depending on orientation is that the participant can pick whatever orientation they prefer for their therapy without compromising its integrity.

Study Limitations

The data collection sleeve developed by M. Doshi et al. [49] was one size fit all, however on some participants it was too loose so needed to be secured with rubber bands. After data collection was already completed, I realized that in the middle of a couple trials, the sleeve would lose connection with the data streamer for some frames, which needed to be omitted from the data analysis. In future studies, I will omit participants data that had significant loss of sleeve data and will work with the creators to resolve the issue. Also, though the creative drawing model was meant to be drawn in one continuous arm stroke, participants had a difficult time following my intended path, which led to inconsistencies on what order they hit the dots. Again, our sample size was relatively small (n=12) which may influence the power in rejecting / supporting the hypotheses with the results.

Broader Implications and Future Work

To improve my creative drawing exergame, future work should add a feature that would help with uniformity of the therapy is to make sure the one-stroke path to draw the model is well defined, perhaps by changing dots to triangles that indicate a direction to draw in. I also have a 2D Chicken and 2D Square model that can be converted into 3D in the future to add more variety to the difficulty and intensity of the therapy. I have written data collection scripts to store the dominant hand controller's coordinates and coordinates of the model, which can be graphed (Figure 12). This is important because in the future, I can look at distance misestimation for

depth in terms of overestimations (controller goes past the dots) or underestimations (controller did not reach the dot). This will give me an idea on where depth perception falls short in my immersive virtual game.

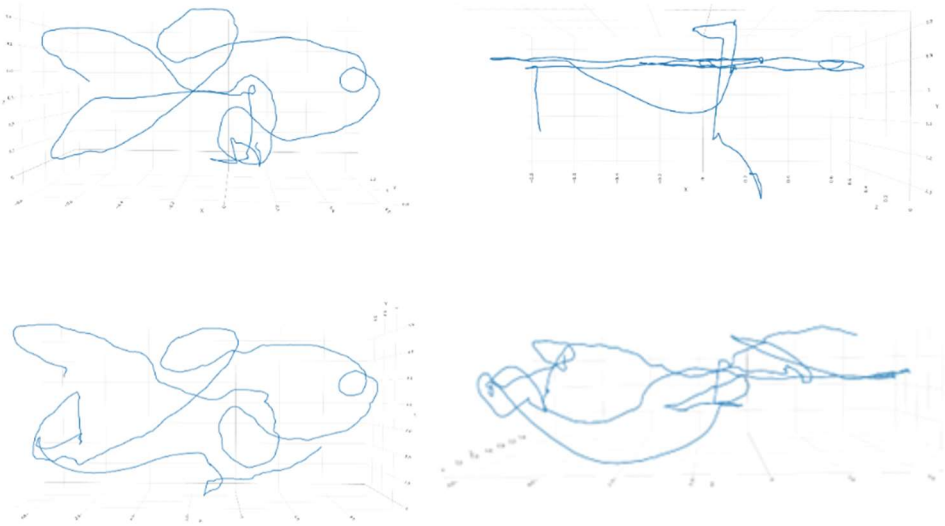


Figure 12 VR hand controller data collection for a (top) 2D Fish and (bottom) 3D Fish that can model the user's path during the task

Conclusion

I have presented modifications to my VR therapy exergame for upper extremity rehabilitation with multi-dimensional reaching tasks while capturing the movement of the rest of the limb using the smart wearable sensor. The results provide insights that the orientation and configuration of virtual content can be used for therapeutic applications without a decrease in patient accuracy or depth perception and will increase body stretching; this is positive for exercises that prefer a seated position of the user and want to focus on upper extremity mobility exclusively. Further

research is required to study how to improve visual cues, depth perception, and reaching capabilities for 3D objects in virtual environments, especially for VR therapy where accuracy is important for a patient's healthcare. Furthermore, investigating with collaborative VR and using multi-model sensing data for further analysis and prediction could be interesting as well.

CLOSING REMARKS

In my research, I presented a creative VR therapy game using line drawing activities and investigated how the drawing content and the user's position could influence the user's performance and perception in the drawing exercise. The results of my first preliminary study showed that the proposed VR drawing game is an effective tool for enjoyable physical therapy, which has much potential for customized therapy experiences. The results of my second preliminary study showed that user accuracy is not affected by the version of virtual content they are asked to draw despite differences in body stretch and depth perception, which can also contribute to the customization of therapy. More work needs to be done to study how to improve visual cues, depth perception, and reaching capabilities for 3D objects in virtual environments, especially for VR therapy, where accuracy is important for a patient's healthcare. A non-invasive sleeve can be integrated into the fabric to better track the entire limb, and not just the hands, during reaching tasks in a virtual environment. While considering the broader use cases of this interactive VR drawing intervention for various types of PT exercise, I will extend my studies and further investigate the effectiveness of VR therapy in the future. Future studies should be conducted on a larger sample and, later a participant pool of those with upper extremity injuries to further validate my findings and generalizations of my results.

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