On Shooting Stars: Comparing CAVE and HMD Immersive Virtual Reality Exergaming for Adults with Mixed Ability

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Inactivity and a lack of engagement with exercise is a pressing health problem in the United States and beyond. Immersive Virtual Reality (iVR) is a promising medium to motivate users through engaging virtual environments. Currently, modern iVR lacks a comparative analysis between research and consumer-grade systems for exercise and health. This article examines two such iVR mediums: the Cave Automated Virtual Environment (CAVE) and the head-mounted display (HMD). Specifically, we compare the room-scale Mechdyne CAVE and HTC Vive Pro HMD with a custom in-house exercise game that was designed such that user experiences were as consistent as possible between both systems. To ensure that our findings are generalizable for users of varying abilities, we recruited 40 participants with and without cognitive disabilities with regard to the fact that iVR environments and games can differ in their cognitive challenge between users. Our results show that across all abilities, the HMD excelled in in-game performance, biofeedback response, and player engagement. We conclude with considerations in utilizing iVR systems for exergaming with users across cognitive abilities.

CCS Concepts: • **Hardware** → *Analysis and design of emerging devices and systems*; • **Human-centered computing** → **Accessibility design and evaluation methods**; **User studies**;

Additional Key Words and Phrases: Exergaming, disability, serious games, games for health, gamification, biofeedback, immersion, emotion, HTC Vive, Cave Automated Virtual Environment (CAVE), head-mounted display (HMD), immersive Virtual Reality (iVR), Project Star Catcher (PSC)

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1 INTRODUCTION

Inactivity leads to a decline of health with significant motor degradation: a loss of coordination, movement speed, gait, balance, muscle mass, and cognition [29, 45, 88]. In contrast, exercise is medicine: the medical benefits of regular physical activity prevent motor degradation, stimulate weight management, and lead to a reduction in the risk of heart disease and certain cancers [75]. Nevertheless, compliance in performing regular physical activity is avoided due to high costs, lack of accessibility, and low education [29]. Physical activities are often perceived as chores, especially by those who are not already fit, such as those with disabilities or musculoskeletal health issues. We posit that the creative use of immersive virtual environments can make physical activities be perceived as fun and enjoyable rather than chores.

Earlier generations of Virtual Reality (VR) systems have proven feasible as effective physical training platforms. For example, it was shown that the Nintendo Wii could be used for physical rehabilitation of older adults with disabilities [80], the Microsoft Kinect was shown to improve balance through exercise [57], and Oculus Rift was shown to be able to help alleviate pain during occupational therapy of pediatric burn patients [43]. However, early head-mounted display (HMD) systems had significant hardware constraints (e.g., low resolution and low refreshment rates), which lead to non-immersive experiences and motion sickness [58]. Therefore, their use as a health tool was limited. Room-sized VR systems, a more costly alternative to HMD systems, were found to be significantly more comfortable and immersive while inducing minimal motion sickness [82]. It was shown that VR systems had some track record of success in promoting exercises for users with rheumatoid arthritis [32] or children with autism spectrum disorder [28]. All of these studies point to the idea that VR holds potential both as an intervention and an assessment tool for physical exercise [94]. The power of VR systems lies in the ability of virtual environments to augment user stimuli by conveying various concepts that can be used to produce individualized exercises [94].

Modern immersive Virtual Reality (iVR) systems have gone a long way from a technical standpoint in enhancing user immersion. Such improvements include widening the field of view, increasing frame rate, leveraging low latency motion capture, and providing a more realistic surround sound experience. Mass adoption of commercial VR HMDs such as the HTC Vive, Oculus Rift, and the PlayStation Morpheus have flooded the market with a combined 200 million systems sold since 2016 [4]. The wide adoption of VR HMDs opens an opportunity to purpose them as a physical exercise platform. This leads to the question of how do we best take advantage of the advanced features that HMDs possess to motivate people from varying walks of life to do physical exercise?

1.1 iVR and Health

VR holds the unique ability to simulate complex situations that are critical to producing immersive experiences and is auspicious for improving psychologically based health applications [23]. The use of VR intervention has reported pain-relieving effects when compared to an analgesic during wound treatment [36, 42]. Additionally, VR has been shown to help with post-traumatic stree disorder [67, 85], borderline personality disorder [69], schizophrenia [86], and various phobias [23, 35, 91].

The multi-sensory, auditory, and visual feedback in a virtual environment can be crafted to persuade users further to comply with exercise protocols through increased directed stimuli [14]. Thus, VR also holds immense potential in physiological rehabilitation as a useful tool for inducing task-based physical exercises [61]. The capabilities of multi-sensory real-time feedback have shown significant outcomes in compliance to exercise protocols [14]. Numerous studies have displayed success in motor improvement from physiotherapy compared to traditional therapeutic intervention [11, 14, 50, 68, 89]. The biggest challenges of these studies were found to be technological constraints such as cost, inaccurate motion capture, non-user friendly systems, and a lack of accessibility [20, 68]. Thus, there is a need to revisit this examination of VR for health with modern iVR systems [4].

The success of iVR therapeutic intervention is often attributed to the power of immersion, or the relationship between presence and emotion in an engaging experience [67]. Subsequently, a greater immersion corresponds to a better treatment response and therefore is beneficial to improving therapy experiences through virtual environments [66]. Providing engaging stimuli through immersive systems is a crucial factor for the player's experience [2]. The emotional response generated impacts user engagement and helps motivate players to continue with the objectives of the virtual experience [12]. Thus, leveraging stimuli to try to instigate a strong emotional response as done in psychotherapy may produce better results in exercise performance. Therefore, a principal research question is this: what is the nature of the relationship between the success of VR stimuli and user emotions? Biofeedback devices may help us answer this question given that past studies have shown that biometrics can reliably record the response of users' emotional states [93].

1.2 Insights from Biofeedback

Biofeedback devices have gained increasing popularity because they use sensors to gather useful information about health states. For example, the impedance of the sweat glands, or galvanic skin response (GSR), has been correlated to physiological arousal [6, 19]. This activity can be measured through readily available commercial GSR sensors, which have been used to measure the arousal in media such as television, music, and gaming [78, 87]. Cameiro et al. [10] analyzed non-immersive VR-based physical therapy that uses biofeedback to adapt to stroke patients based on the Yerkes-Dodson law, or the optimal relationship between task-based performance and arousal [13]. By combining heart rate (HR) with GSR, the authors examined gameplay by quantitatively measuring each user to consider where that optimal performance is met. Another example can be seen with Liu et al. [59], in which the authors were able to achieve 66% average emotion classification accuracy for users watching movies with only GSR sensors. There is a definite potential in evaluating the GSR and HR of each user to determine the intensity of the stimuli between different systems of VR. However, GSR and HR are not the only biometric inputs that could be potentially leveraged into comparing immersive experiences.

Commercially available electroencephalography (EEG) sensors have shown great promise in capturing brain activity and even inferring emotional states [79]. Modern EEG sensors implemented through brain-computer interfaces (BCIs) have been successful in estimating user reaction to immersive stimuli during VR gameplay. In a review of more than 280 BCI-related articles, Al-Nafjan et al. [1] examined how EEG-based emotion detection is experiencing significant growth due to advances in wireless EEG devices. Accessible and low-cost BCIs are becoming widely available and accurate in emotion and intent recognition. These are being used for medical purposes, as well as in the non-medical domains of entertainment, education, and gaming [1]. In comparison with 12 other biofeedback experiments, studies that used EEG alone were able to reach 80% maximum emotion recognition [33]. Arguably, the most considerable challenges of BCI are costs, accuracy of sensors, data transfer errors or inconsistency, and ease of use for devices [1].

Even with these challenges, EEG has been successfully used to understand conditions like attention-deficit/hyperactivity disorder (ADHD), anxiety disorders, epilepsy, autism, and stroke [63, 64]. Brain signals that are characteristic of these conditions can be analyzed with EEG biofeedback to serve as a helpful diagnostic and training tool. For example, Lubar et al. [62] used the measurement of brainwave frequency power during game events to extract information from reactions to repeated auditory stimuli. This provided the ability to perceive significant differences between ADHD and non-ADHD groups during this study [62]. Through exploring different placements of EEG sensors along with a user's scalp and sampling multiple brainwave frequencies, different wavebands can be used to infer the emotional state and effect of audio-visual stimuli [22]. In another example, Ramirez and Vamvakousis [79] used alpha and beta bands to infer arousal and valence, which are then respectively mapped to a two-dimensional emotion estimation model. From these works, we concluded that there is the potential to analyze brainwaves during iVR stimulus to infer users' emotional responses.

1.2.1 On the Subject of Brainwaves. Hans Berger, a founding father of EEG, was one of the first to analyze the frequency bands of brain activity and correlate it to human function [37, 60]. These wavebands have been extensively researched throughout the past 80 years, and although there are mixed opinions, it is our hope to use past research to contextualize brain activity during iVR exercise. Specifically, we want to understand the change from resting state of the alpha, beta, delta, theta, and gamma brainwaves induced by the gameplay.

The *alpha band* (stress [30]) has been found to occur at frequencies between 7 and 12 Hz and is generally associated with a neural activity relating to stress and conversely relaxation. Alpha activity is reduced with open eyes, drowsiness, and sleep [30]. The *beta band* (focus [3, 81]) occurs at frequencies between 12 and 30 Hz and is generally associated with focus, as well as active cognition such as arousal, anxiety, excitement, and concentration [81]. Increases in beta waves have been correlated to active, busy, or anxious thinking and concentration [3]. The *delta band* (awareness [9, 41, 47, 98]) occurs at frequencies between 0.5 and 4 Hz and is suggested to relate to awareness and sleep [98]. Delta waves have been found to have the highest activity during deep sleep, where the deeper the sleep, the higher the activity [47]. Researchers have also reported that this frequency band relates to memory interaction [41], such as flashbacks and dreaming [9]. The *theta band* (sensorimotor processing [34, 38, 72, 99]) occurs at frequencies between 4 and 7 Hz and is associated with sensorimotor processing [34]. This includes spikes in theta activity for planning motor behavior [99], path spatialization [72], memory, and learning [38]. The *gamma band* (cognition [46, 73, 92, 97, 100, 101]) occurs at frequencies between 30 and 100 Hz and has been correlated to thought, consciousness, and meditation [46]. Research has theorized that gamma activity is relational to conscious perception [92]. Through studying proponents of meditation and mindfulness training, gamma activity appeared elevated when a "conscious experience" would occur, such as shifting mental states in meditation [73]. There are mixed opinions on whether gamma bands are reliable due to biological artifacts such as eye movement and jaw clenches [97, 100, 101]. However, many researchers argue that gamma bands show evidence of correlating perception with careful signal processing [73]. Through combining active EEG sensing with VR gameplay, it may be plausible that the success of the VR stimuli in the virtual experience could be quantitatively measured.

1.3 Related Work

Previously, VR HMDs had significant hardware limitations that often caused adverse effects such as motion sickness and eye strain [17]. Thus, many immersive media researchers opted to explore alternative VR systems such as room-scale projector-based immersive experiences, which is exemplified in our study by the Cave Automated Virtual Environment (CAVE) [18, 32]. Although CAVEs and other room-scale systems have shown great promise, they are an expensive solution—usually in the order of 20 to 100 times more costly than modern iVR HMD [4, 32]. Hatada et al. [39] suggested that the wider field of view of CAVE lends to a more immersive experience, with even increased angles as small as 20 degrees vertically and 30 degrees horizontally compared to iVR HMDs inducing a "sensation of reality." For example, a study exploring acrophobia compared CAVEs to HMDs in 2001 and found that CAVEs created a higher sense of presence and elicited more anxiety [53].

Some past studies have also compared egocentric HMD-style devices to CAVE-like systems. Bowman et al. [7] did not find significant differences concerning player performance and immersion between HMDs or CAVEs. Philpot et al. [76] compared user experience for panoramic video with CAVE and HMDs using interview and survey analysis. The authors found that user responses to thematic relations such as engagement, embodiment, and preference were very similar between the systems as well. Meyerbröker et al. [65] used Virtual Reality Exposure Treatment to compare the effectiveness of CAVE and HMD. Similarly to Philpot et al. [76] and Bowman et al. [7], the authors reported no significant differences in effectiveness between the two iVR systems. In a differing example, a comparative study by Kim et al. [54] of desktop, CAVE, and HMD systems found CAVE to be the best performing against HMD-style systems. However, this performance was examined with older HMDs that used a 40-degree field of view [54].

To summarize our literature search, the majority of these past studies either did not find any significance between CAVE and HMD or found that CAVE excelled. More recent works suggest a possible shift in this trend, such as the comparison between Oculus Rift DKII and CAVE2 [15] for collaborative data analysis. Cordeil et al.

[15] determined that user analysis between the systems did not hold significant differences, yet the HMD-based system was suggested to enable faster analysis [15]. The past 3 years leading up to 2020 have seen a considerable improvement in HMD technology and consumer adoption, much faster than CAVE's technology. Pixel density is increasing exponentially in modern devices, increasing more than 30% since 2016 [21]. Given that the issue of affordability can affect public adoption of the iVR system, our study aims to answer the question of whether modern VR HMDs have finally surpassed room-scale VR systems such as CAVE in the context of physical exercise. We aim to answer this unexplored question by examining game behavior, biometric activity, and survey questionnaires.

1.4 Study Goals and Impact

This article reports on a comparative study between the Mechdyne Flex CAVE and the HTC Vive Pro 2018 HMD. We utilize an in-house customizable iVR exercise game that rewards users with and without a disability to overcome difficulties in exercising the weaker side of their upper body. From gameplay, we record each user's game behavior, physical movement, biosignals, and subjective response of gameplay and system use. Through the differences in immersive experience between these two mediums, we aim to understand the effects of room-scale versus HMD-based physical exercise.

Specifically, the goals of this study are as follows:

(1) To compare gameplay effects of the immersive exercise experience between the room-scale and HMD iVR mediums with natural arm movements.
(2) To identify insights in system usability for users with varying cognitive abilities.
(3) To examine the feasibility of the two iVR systems for exercise and healthcare.

This article is among one of the first studies to compare the game behavior, motor movement, and physiological activity of iVR exergaming between room-scale and HMD systems. We examine these systems with users who have a wide range of cognitive abilities to make sure that our results generalize across a wider range of the population.

2 SYSTEM AND EXPERIMENTAL DESIGN

This study uses Project Star Catcher (PSC) [25, 27] an iVR experience designed to encourage upper extremity physical exercises through motivating users to catch shooting stars in a cosmic virtual environment with their weaker arm. PSC uses a customizable mix of auditory, visual, and haptic stimuli as score incentives to motivate users to exercise. The game requires users to follow different arm positions and vary the range of motion to succeed in a star catch. Users receive three times as many points when using their weaker, weight constrained, non-dominant arm but may also use their strong arm for fewer points. To perform well in the game, the user must use a large amount of full-body movement, including side stepping and reaching in many directions, and should comply with weak arm usage. Adults with developmental disabilities (DD) previously tested PSC. Our prior study showed that these users were able to understand and achieve the objectives of the game [27]. To ensure that the participants were challenged and understood the rule of the games, a weighted arm strap was utilized to examine weak arm compliance with the protocol from our previous exploration of PSC [27].

In this study, users were recorded playing PSC with both systems: EEG, GSR, and HR were collected at runtime, as well as post gameplay surveys, as seen in Figure 1. The order of which system was played was counterbalanced (some users were tasked to the HMD first, and some to CAVE first) to prevent bias. We carefully designed the experiment so that users were exposed to a similar level of difficulty in both systems and similar features (e.g., soundtrack and screen brightness). In CAVE, four walls are used to project multiple views at 90-degree offsets, whereas the HTC Vive implemented the native SteamVR camera allowing for a 360-degree view. From the viewpoint of user behaviors, HMDs and CAVE have many similarities; however, they are quite different in

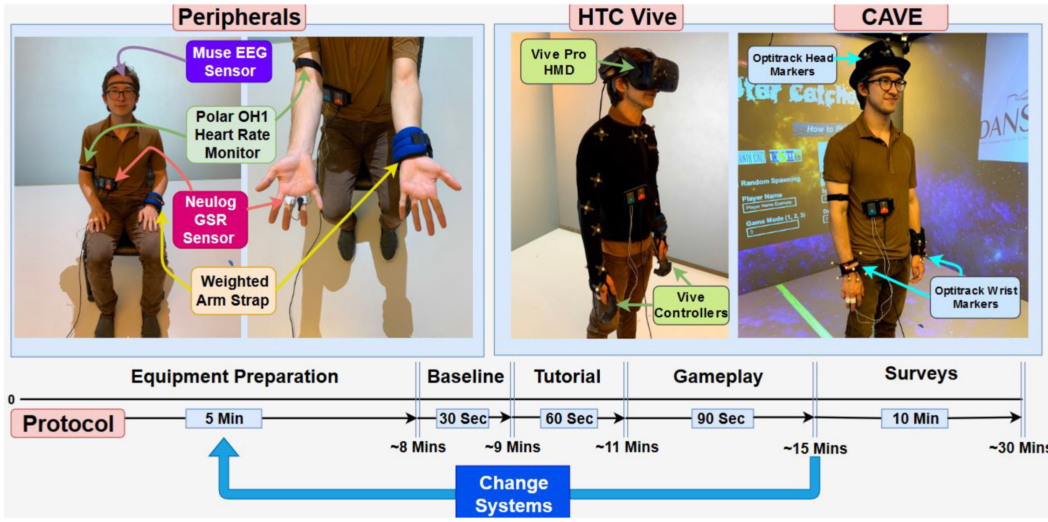

Fig. 1. System diagram and experimental protocol: sensor placement (top left), systems (top right), and experimental protocol (bottom).

the level of immersion (i.e., users can still notice the outside world with CAVE, whereas with HMDs, they are completely isolated from the external visual stimuli). Additionally, the Vive HMD has more weight compared to CAVE's motion capture markers.

2.1 Participants

Our participant cohort includes a mix of adults with DD and college students. This study was approved by the Institutional Review Board of the University of California Santa Cruz (UCSC) Office of Compliance and Research Administration. For our volunteers with DD, 3 female and 10 male users (ages ranged from 20 to 30 years) were recruited from the Santa Cruz Hope Services Day Center and provided consent that had been vetted by their medical caregiver as understandable. Hope Services is Silicon Valley's leading provider of services to people with DD, such as intellectual disabilities, cerebral palsy, epilepsy, autism, and Down syndrome [90]. Although they vary in their medical diagnosis, they all have a minimum cognitive ability specified by Hope Services' medical professional as likely to be able to comprehend the experimental protocol. Due to HIPAA regulation, we were not provided information on their diagnoses and the severity of their conditions. However, this information was available to our Hope Services collaborators during recruitment and formed the basis of their selection as volunteers. We shared our initial experimental protocol and questionnaires with Hope Services. We adapted our study protocol to ensure that these users could accurately reflect their feedback and participate in gameplay between CAVE and the HTC Vive. Additionally, a caregiver was present during all trials to help explain the study, the game, and survey questions, and to monitor safety and comfort, and provide further feedback about the participants. These 13 users were selected by Hope Services medical professionals to ensure that they can articulate opinions about system preference and gameplay experience.

We also recruited 27 college students without any visible disabilities (12 male and 15 female with ages ranging from 19 to 28 years), who also provided written consent to participate. These students were recruited by flyers, word of mouth, and emails sent to the student body at UCSC. Through this diverse group of study participants, we were able to gather a mixed set of data between the CAVE and HTC Vive systems for the same iVR exercise game.

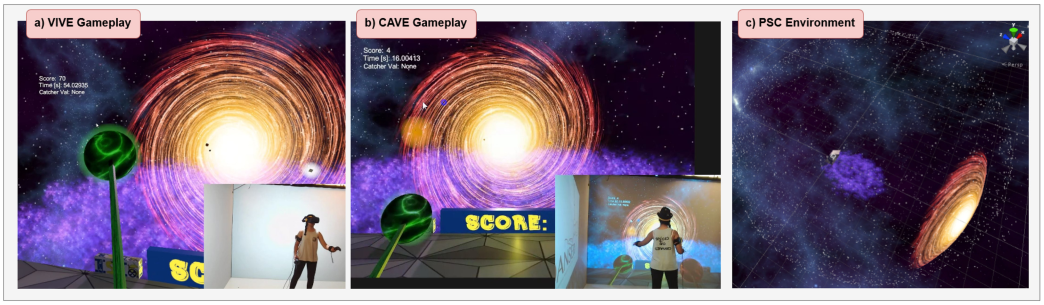

Fig. 2. System gameplay. (a) A user catches a shooting star with the HTC Vive. (b) A user prepares to catch a shooting star with CAVE. (c) The PSC virtual environment.

2.2 Data Collection

The following data was collected during the study:

(i) *HR—Polar OH1 Sensor* [77]: An armband with an embedded optical sensor was utilized to wirelessly collect beats per minute by sampling HR activity at 1 Hz.

(ii) *GSR—Neulog GSR sensor NUL-217* [71]: A USB-200 logger sensor module was used to measure GSR at a 5-Hz sampling rate in micro-Siemens by attaching Velcro strap electrode points to the skin between the index and ring finger.

(iii) *EEG—InteraXon Muse 2—Brain Sensing Headband* [49]: Collects filtered brainwave data of the prefrontal cortex. The application that communicates with the device uses Cooley-Tukey FFT to extract waveband power from brain activity [83]. Although this headset is relatively low resolution compared to other clinical-grade EEG systems, researchers have used Muse in understanding mindfulness [5], mental states [55], and event potentials [56].

(iv) *iVR—The CAVE (Mechdyne Flex 1) and HTC Vive Pro 2018 systems*: The room-scale CAVE system and HMD HTC Vive Pro implemented the Unity Game Engine to run the same iVR experience through PSC. PSC collected player data at 90 Hz of motion capture pose and game behavioral events such as star catches [27]. Motion tracking was achieved with CAVE through the Natural Point Optitrack Motion Capture System [70], whereas the HTC Vive utilized its native lighthouse localization system for outside-in tracking [16].

(v) *Questionnaires—modified survey by Jennett et al.* [51]: Users completed the survey about user experience twice, once for each system. The users also completed a third survey that compared their preference of the two systems.

HR, GSR, and EEG measurements were chosen to give further insight into users' physiological responses to the gaming environment and provide quantifiable data beyond the game performance. The sampling frequency between all of the sensors was not equivalent. As a result, data were exported to comma-separated values (CSV) files post hoc and synchronized for each baseline and gameplay using Python scripts. A custom MATLAB script was implemented to collect all sensor data in a single nested struct for comparison while also running raw sensor data through a smooth data moving window filter. Statistical significance between systems was determined in MATLAB through the Wilcoxon signed-rank test, which is a non-parametric statistical method to compare two related groups by mean rank difference [31, 44].

2.3 Experiment Design

Our experimental protocol consisted of four stages that were completed one time on each system, followed by a final set of surveys. This order can be seen in Figure 1 and is described in detail as follows:

(i) *Equipment preparation*: The HR monitor was placed on the dominant arm, and two GSR electrodes were positioned on the middle two fingers for the participant's dominant hand. The EEG sensors were set on the forehead located on the AF1, AF7, TP9, and TP10 prefrontal cortex positions. A weighted arm strap (selected to be approximately 3% of the participant's body mass) was fixed to the participant's non-dominant wrist to challenge and remind the user to catch stars with the non-dominant arm. Finally, either the HTC Vive controllers or Optitrack markers for CAVE were given to the user depending on the counterbalanced system starting order.

(ii) *Baseline*: Before any gameplay, the participant was asked to stand still with arms at the side and eyes closed for 15 seconds, followed by 15 seconds with the eyes open. We recorded sensor data during this step to determine changes from resting state to gameplay.

(iii) *Tutorial*: The evaluator then started the tutorial game, began to give scripted verbal instructions on how to play, and answered any participant questions. The evaluator administered the tutorial for approximately 60 seconds to ensure the user had grasped the concepts of the game.

(iv) *Gameplay*: After the tutorial, the evaluator set up the game, let the participant know he or she had 90 seconds to play the game, would no longer receive feedback or verbal instructions, gave a count down, and began the game. After the 90 seconds of gameplay, the evaluator gave a verbal countdown to warn the participant the test was ending.

(v) *Change systems and repeat (i) through (iv)*: Next, the participant was outfitted with the other game system. There was another baseline measurement, tutorial stage, and gameplay identical to the previous ones.

(vi) *Surveys*: The evaluator then removed the game system and provided a chair for the user to sit while filling out the surveys.

Between each stage was a transition period of about 1 to 3 minutes of rest time. A table comparing baseline biometric state indicated that this rest period was adequate with no significant differences of biometric measurements between recordings, as shown in Table 1.

3 RESULTS

Session data was post-processed using the MathWorks MATLAB 2018b Statistics and Machine Learning Toolbox [40]. We examined each of the user's recorded metrics between systems and groups for box-plot distribution, significance, and similar metrics. Significance was determined through a Wilcoxon signed-rank test, a confidence statistic used to compare non-parametric data such as the samples obtained in our study [84]. The intent of this data collection was to determine the physical and biometric performance between each system and user group in the context of feasibility, immersion, and potential for iVR exercise experiences. These results indicate that both systems are useful in obtaining high levels of compliance with game goals during physical exercise. We define compliance as the rate of catches with the weighted non-dominant arm over the total amount of catches. From these metrics, the HTC Vive was found to be significantly more effective than CAVE in inducing more significant movement of the non-dominant limb, a greater resting state change in biometric response, a more significant emotional response, and an increased immersion. These findings are particularly exciting because prior studies that have explored CAVE and HMDs have not found significance in their task-based comparisons [7, 15, 54, 65, 76]. We discuss these findings in the following sections.

3.1 Physical Movement and Gameplay

Recording runtime motion capture and behavioral game datum served to help understand the physical performance of the users across different cognitive abilities between the two iVR systems. As we are interested in how the users with and without cognitive impairments differ in their gameplay behaviors, we separated the users into two groups. Physical displacement of each user's non-dominant arm, dominant arm, and head positions are shown in Figure 3. For both user groups, the HTC Vive induced significantly more gameplay movement of all

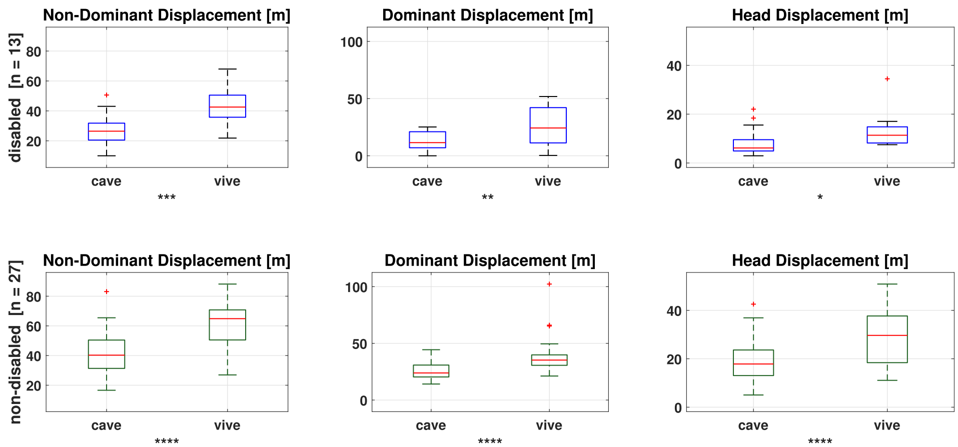

Fig. 3. Player movement of users with disabilities (row one) and without disabilities (row two). The Wilcoxon significance level between CAVE and VIVE is indicated in asterisk notation, and "ns" indicates not significant (highlighted in red). Note that "Non-Dominant Displacement" indicates the total movement of the weighted arm during PSC gameplay between systems.

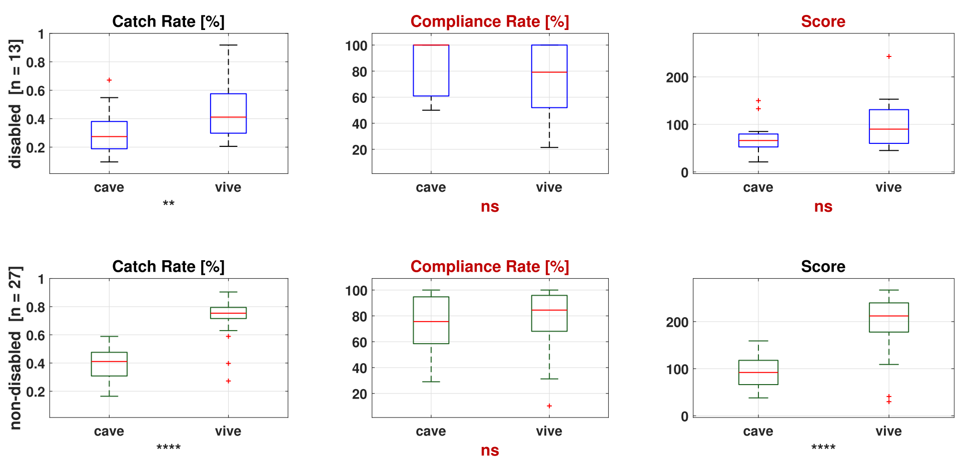

Fig. 4. Gameplay score and success rates of users with disabilities (row one) and without disabilities (row two). The Wilcoxon significance level between CAVE and VIVE is indicated in asterisk notation, and "ns" indicates not significant (highlighted in red).

tracked limbs when compared to CAVE. The user group with disabilities also had more movements when using the HTC Vive than the cohort without disabilities.

To examine compliance, we set the game mechanics so that users achieve higher scores when performing successful catches with the non-dominant arm than when using the dominant arm. We define compliance as the total catches with the non-dominant weight-constrained arm over total star catches. This can be seen in Figure 4 along with a successful star catch rate and game score. Both user groups had a significantly higher catch rate (successful movement completion) on the HTC Vive yet did not hold significant differences in compliance between the two systems. The groups differed in game scores, where users without disabilities had a significantly

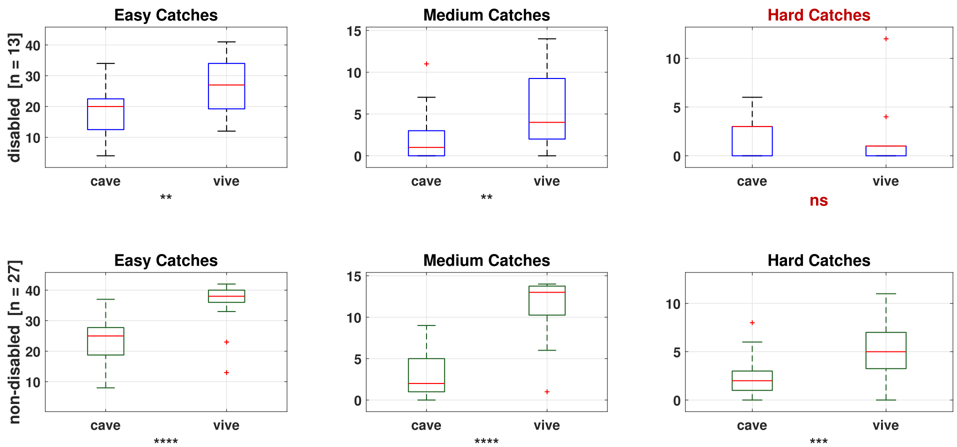

Fig. 5. Successful star catches with difficulty of users with disabilities (row one) and without disabilities (row two). The Wilcoxon significance level between CAVE and VIVE is indicated in asterisk notation, and "ns" indicates not significant (highlighted in red).

higher score with the HTC Vive than with CAVE, but users with disabilities did not have significant differences in scores between the two systems.

PSC varies the difficulty of star catches by movement speed through spawning bronze, silver, and gold stars as slow, medium, and fast, respectively. For example, bronze stars are the easiest to catch because they move three times slower than gold, but the reward is also three times less in score. Figure 5 highlights successful star catches in terms of difficulty. As expected, both groups completed significantly more easy and medium catches with the HTC Vive. However, users with disabilities did not have a significant difference in hard gold catches between systems. The group without disabilities caught more stars than users with disabilities across all difficulties, which was expected.

To summarize, both groups performed significantly better on the HTC Vive in terms of physical movements and successful star catches, yet groups differed in strategies where the users with disabilities did not significantly overcome challenges associated with hard catches between the two systems.

3.2 Biofeedback Responses

Three sets of biofeedback data were collected during and before gameplay to infer physiological activity: HR as a measurement of physical intensity, GSR as a marker of arousal, and brainwave activity (EEG) as inferences for stress (alpha power), focus (beta power), awareness (delta power), motor activity (theta power), and cognitive state (gamma power). For the context of this article, these physiological effects from biometric activity are used to contextualize resting state change induced from gameplay between the two systems. A pre-gameplay baseline was recorded before every user trial to determine and normalize possible abnormalities produced from daily living. For example, if a user were overstimulated by an intense conversation before testing, this stimulation would be offset by examining the difference in the gameplay and baseline states. We were careful to not unnecessarily converse with users during the study to avoid individual differences due to protocol deviation. The results showed that the HTC Vive produced considerably more biometric changes compared to CAVE, with noticeable differences between the two user groups. The Wilcoxon significant levels between pre-gameplay states of both user groups are shown in Table 1 and indicate no significant difference between pre-gameplay states between systems, with the exception of the gamma band for the group without disabilities.

Table 1. Biometric Baselines Taken at the Resting State Between Two User Groups for Both Systems

	With Disabilities			Without Disabilities		
Data Type	CAVE Mean (std)	VIVE Mean (std)	sig	CAVE Mean (std)	VIVE Mean (std)	sig
HR [bpm]	104.9 (38.97)	116.6 (29.74)	ns	94.5 (24.53)	91.1 (21.11)	ns
GSR [uS]	2.49 (1.330)	2.54 (1.195)	ns	3.18 (2.322)	3.14 (2.123)	ns
Alpha [bels]	0.70 (0.396)	0.60 (0.253)	ns	0.66 (0.139)	0.63 (0.143)	ns
Beta [bels]	0.52 (0.361)	0.44 (0.331)	ns	0.50 (0.221)	0.39 (0.201)	ns
Delta [bels]	0.98 (0.503)	0.95 (0.403)	ns	0.75 (0.325)	0.75 (0.278)	ns
Theta [bels]	0.54 (0.418)	0.43 (0.283)	ns	0.41 (0.195)	0.40 (0.180)	ns
Gamma [bels]	0.34 (0.367)	0.17 (0.394)	ns	0.30 (0.323)	0.10 (0.279)	***

Note: "sig" indicates Wilcoxon significance level in asterisk significance notation, and "ns" indicates no significance. No significant difference was found between pre-gameplay states for all groups with the exception of the gamma band for the non-disabled group.

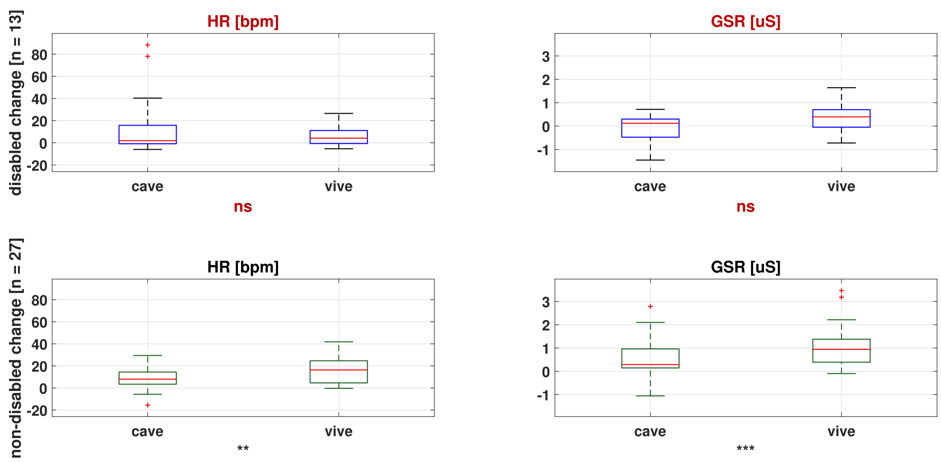

Fig. 6. HR (in beats per minute) and GSR (in micro-Siemens) resting state change from gameplay of users with disabilities (row one) and without disabilities (row two). The Wilcoxon significance level between CAVE and VIVE is indicated in asterisk notation, and "ns" indicates not significant (highlighted in red).

Figure 6 shows the resting state change of HR and GSR induced by gameplay with PSC. Users without disabilities had significantly higher HR and GSR when using the HTC Vive, which may indicate higher intensity in physical activity and arousal. However, users with disabilities had no significant differences between the two systems, yet HR tended to remain at a definite increase from the resting state baseline, and much of the GSR distribution for CAVE indicated a decrease of arousal from the resting state. This may indicate that users with disabilities were either overstimulated before playing PSC with CAVE or that CAVE was ineffective in stimulating arousal for these users. Table 1 suggests similar pre-gameplay states, so it was more likely that CAVE itself induced this negative change in arousal. For the cohort without disabilities, both systems produced an increase in all biometric recordings from resting state, and the HTC Vive had a significantly higher increase of intensity and arousal than CAVE from the HR and GSR readings. Interestingly, brainwave activity represented an inverse outcome between the two user groups.

The resting state change of the different EEG brainwave bands induced by gameplay with PSC is displayed in Figure 7. Both user groups had significantly higher beta and gamma power when using the HTC Vive against CAVE, which may indicate an elevated level of focus and cognitive processing. The groups differed where the cohort with disabilities had significantly higher alpha, delta, and theta (stress, awareness, and motor processing)

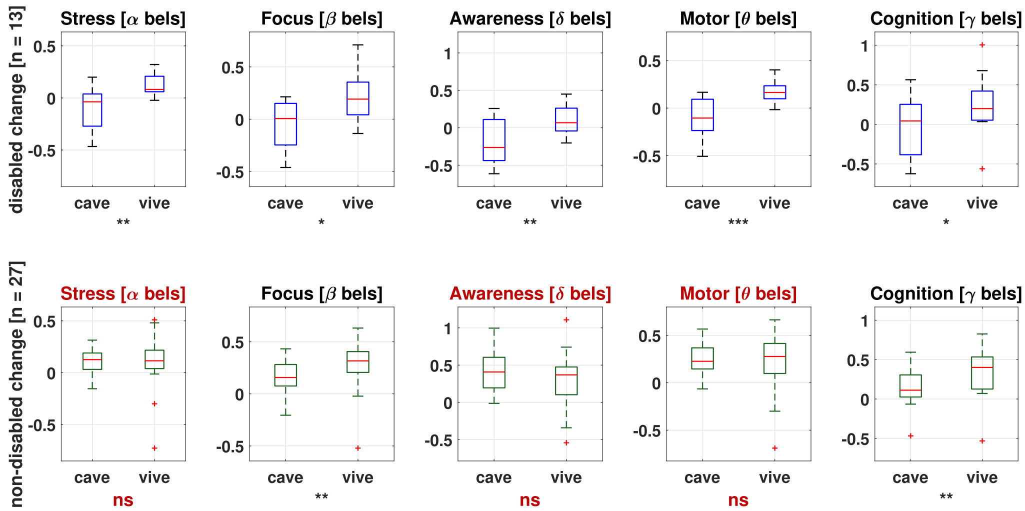

Fig. 7. EEG brainwave power in bels from resting state change induced during gameplay for users with disabilities (row one) and without disabilities (row two). Note that stress, focus, awareness, motor, and cognition are represented by the alpha (α), beta (β), delta (δ), theta (θ), and gamma (γ) band powers. The Wilcoxon significance level between CAVE and VIVE is indicated in asterisk notation, and "ns" indicates not significant (highlighted in red).

power. Furthermore, the group with disabilities generally experienced negative resting state change on CAVE for alpha, beta, delta, and theta bands, which may imply that the users did not remain focused and lost awareness, as well as motor activity, when compared to the resting state. This negative resting state change is consistent with the change seen with CAVE for HR and GSR; however, all brainwave bands were significantly higher on the HTC Vive inversely to the relationship seen between the two groups in Figure 6.

In general, these biometric recordings suggest that the HTC Vive induced higher focus and cognitive processing than CAVE for both groups. Unlike the group without disabilities, users with disabilities had significant increases in all bands of brain activity. Conversely, CAVE induced a lower power from resting state change for the beta, delta, theta, and gamma bands, unlike the HTC Vive, which resulted in all significantly higher powers than the resting state. This differs from the group without disabilities, where all brain activity remained at a positive change regardless of the iVR system medium. This outcome is especially interesting because it may indicate that iVR system mediums have a more considerable effect on the mental state for adults with cognitive impairment. To further understand these results, each user was queried for subjective response in our immersion and system preference questionnaires—it is through this medium that we hope to reinforce and better understand the physical and biometric performance of our users.

3.3 Response for Immersion, Emotion, and System Preferences

In this study, we used two surveys to collect subjective responses between the HTC Vive and CAVE from our two user groups. The immersion questionnaire was adapted from an extensively explored survey by Jennett et al. [51], which measures immersion and presence in games. For the group with cognitive disabilities, pre-experimental trials were run to understand the feasibility of the original immersion survey and help us modify the survey. These trials were useful, as they provided us with some insights. Generally, users would lose interest in the high number of questions in the original survey. Additionally, the phrasing of most of the original questions was often too complicated for users to comprehend fully and required the Hope Services caretakers to intervene and give further explanations and provide examples. Last, many of the users were not always able to communicate

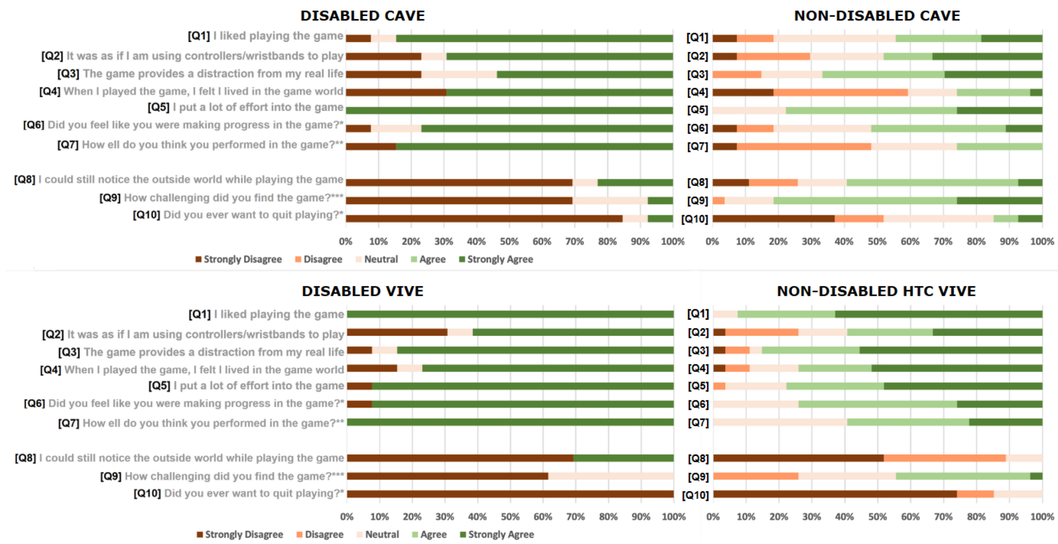

Fig. 8. Subjective rating questionnaire responses for the between user groups and systems. For Q1–7, strongly agree is the desired outcome. For Q8–10, strongly disagree is the desired outcome. Disabled user responses were modified to a 3-point scale as recommended by healthcare professionals from Hope Services California to increase accuracy. (*, “not at all” to “ a lot”; **, “very poor” to “v ery well”; ***, not at all” to “very challenging.”)

their responses verbally—usually giving a thumbs up, down, or sideways. With this trail testing in mind, we condensed the Jennet et al. survey to 10 simplified questions in collaboration with healthcare professionals. Furthermore, a checkbox emotion question and system preference survey were created to enable more significant user input from the group with disabilities. Our final version of the questionnaires consisted of one survey with 10 immersion questions on a subjective scale, one question on intense emotions felt, and a second survey with 3 questions on system preference and a section for additional comments. Through this process, we were able to gather more significant input from both user groups for comparison with the biometric and game datum collected.

The immersion survey results, as seen in Figure 8, indicate responses on statements querying presence (Q3–4 and Q8), engagement (Q1–2 and Q9–10), and effort (Q5–7) concerning gameplay between the two systems and groups. Questions Q8–10 have reversed scales to ensure respondents read the survey carefully. A majority of users from both groups indicated that presence, engagement, and effort was higher on the HTC Vive than CAVE. The groups differed in agreement, where higher percentages of users with disabilities felt they “lived in the game world,” were distracted “from my real life,” and “put a lot of effort into the game.” Interestingly, the majority of the disabled cohort found the game to be not challenging (Q9), unlike the non-disabled cohort, even though their physical performance was on average less than the non-disabled group (as seen in Figures 3 and 4). The disabled group responses to immersion questionnaires were nearly identical between all users regardless of system, which may indicate a lack of comprehension of the survey questions regardless of our modifications or that users generally responded positively to all survey questions. There are slight differences in the distribution, which may indicate that the HTC Vive was received better in comparison to CAVE (Q1, Q7, and Q10). This was not the case for the non-disabled cohort, where users had significantly higher agreement rates with the HTC Vive than CAVE. These immersions were most likely influenced by the emotional response felt during gameplay.

Self-reported emotions felt during gameplay can be seen in Figure 9. At the end of each session, users were tasked with checking off any intense emotions they believed to have felt during the 3 minutes of playtime between the systems. The emotions cover a wide range of feelings from “Happy/Joyful” to “Neutral (no emotion)”

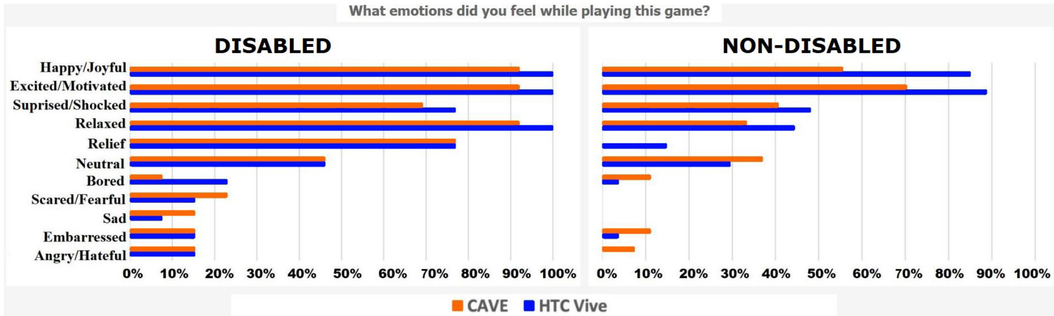

Fig. 9. Self-reported emotions strongly felt between the two different systems and user groups.

to "Angry/Hateful/Disgust." For the purposes of visualization, such emotions are organized subjectively from top-down positive to negative in Figure 9. All users from each group reported feeling at least one intense emotion from gameplay between each system. The non-disabled group generally reported more feelings of positive emotion with the HTC Vive, and CAVE was shown to receive higher responses for negative emotions such as anger and embarrassment. Conversely, minimal difference between the two systems on self-reported emotion was found for the disabled group, where CAVE had a slightly higher emotion response rate than the HTC Vive by one or two users. The ratio of intense feelings for users with disabilities was also significantly higher than their non-disabled cohorts, which may be in line with the increased disabled group brainwave activity, as seen in Figure 7. These near-identical distributions in emotions felt between the systems may indicate that the majority of users with disabilities may just be answering these surveys identically. This behavior, however, was not seen in the preference survey between systems for the group with disabilities.

At the end of the experiment and after the two immersion/emotion surveys, a preference survey was given to each user asking which system was preferred and why. Users were also given the option to fill out checkboxes on indications such as comfort, ease of use, and engagement, as well as an input field for additional comments. Figure 10 showcases these final preference results. The majority of both groups preferred the HTC Vive over CAVE; however, 100% of users without disabilities preferred the HTC Vive, unlike the 62% of the cohort with disabilities. These groups appeared to generally differ in system preference by emotion and comfort with CAVE when compared to ease of use and immersion with the HTC Vive. For the group with disabilities, the users who chose CAVE indicated that the most active reasoning was "it made me feel relief," " it was easier to use," and "it was more comfortable," whereas the users with disabilities who chose the HTC Vive indicated top reasoning to be "it was funner to use," along with a near-identical indication of greater comfort, ease of use, immersion, and relief. The users without disabilities' top reasonings for unanimously choosing the HTC Vive over CAVE was "it was easier to use," "it felt more immersive," and "it was funner to use."

Additionally, about 50% of participants wrote in or verbally addressed additional comments about system preference. A word cloud of these comments can be seen in Figure 10, where the largest words indicate the most recurring topics of discussion. Only four of the users with disabilities who preferred CAVE left additional comments and indicated that they enjoyed wearing the motion capture hat, unlike the HTC Vive HMD. For other users, comments were left about navigation, perception, latency, and freedom of movement appearing best on the HTC Vive against CAVE. Participants felt that PSC was more stimulating on the HTC Vive than CAVE, as the colors were crisper, the depth perception felt more viable, and the controls were more natural, according to them. One user even indicated the preference of blocking reality out with the HTC Vive, unlike CAVE, as they felt that the HTC Vive was "more immersive [because] my virtual self was already in there [the game]."

To conclude, the HTC Vive is the preferred system between both user groups. The HMD-based system was perceived to have a higher sense of immersion, ease of use, and enjoyment of gameplay than the room-scale

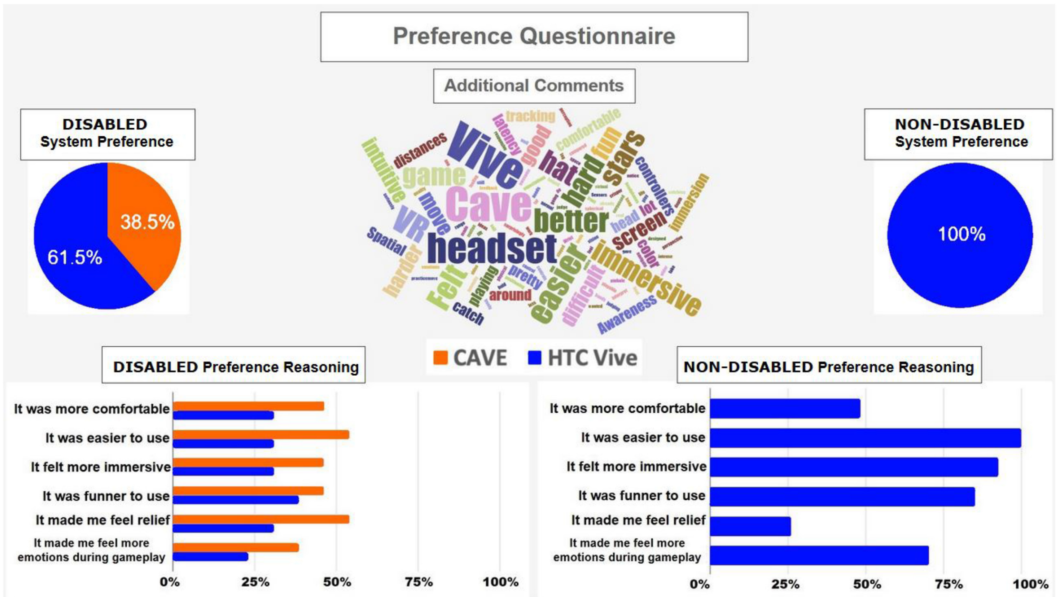

Fig. 10. System preference between the two user groups with reasoning for preference.

alternative. These responses are in line with both the physical performance of each user group and the biometric response. The significantly higher brainwave activity among users without disabilities on the HTC Vive is in line with the self-reported levels of immersion, where they saw significant increases in arousal and physical activity and subsequently unanimously preferred the HTC Vive. The responses of users without disabilities tended to be emotionally based, with a significantly higher distribution of these users' self-reported intense emotions felt. Last, users generally scored higher, moved more, and caught more stars on the HTC Vive against CAVE—this can be explained by users feeling that the HTC Vive was "more fun."

4 DISCUSSION

This study explored the experience of adults with varying cognitive abilities when using room-scale and HMD-based iVR systems for gamified physical exercise. A mixture of motion capture, game behavior, and biofeedback, along with questionnaire data, was collected. The HTC Vive, a widely adopted commercial iVR HMD system, showed significant benefits of use when compared to CAVE during physical exercise with the game we built. This section highlights our findings.

4.1 Key Findings Between the Two User Groups

We explored two user groups in this study—adults with cognitive disabilities and college students—in an attempt to make sure that our results and the design implications for our findings can be generalized across cognitive abilities. Through our testing of these systems, the data we collected helped us address our study goals to formulate the following interpretations.

4.1.1 Users with Cognitive Disability Were More Emotionally Receptive to iVR Exercise. All bands of brainwaves were seen to be significantly different between the systems, which may have influenced the noticeably higher self-reported emotions by the group with disabilities. From the immersion survey, we saw a similar response for virtual presence, engagement, and effort given during gameplay. This may indicate that our game was a successful experience in inducing immersion regardless of the system. Furthermore, the preference survey indicated that it was, by a majority, guided by emotion. For the users who chose CAVE over the HTC Vive, the top reason was due to feelings of relief. Additional comments indicated that users enjoyed the way the motion capture hat felt and looked in comparison to the HTC Vive HMD. These users chose CAVE even though they often overcame greater difficulty, caught more stars, and had higher movement with the HTC Vive. From an engagement and immersion perspective, designing future experiences for adults with cognitive disabilities may be improved by expanding on this emotive perspective. PSC uses score and sensory feedback as a motivator to keep the user engaged over their exercise sessions [27]. Another one of our previous studies has explored iVR games to strictly follow exercises by protecting a "cute" virtual butterfly in "Project Butterfly" (PBF) [26]. With therapeutic goals in mind, designing iVR experiences like PSC and PBF where the user is in complete control of the environment and is guided by emotive-based incentives can be an excellent approach for iVR physical exercise experiences. The physical tasks require only user movements, and the objectives of the game are simple enough to start and interact with the environment without reading an instructional guide on controls or game objectives. As a result, emotive task-based iVR experiences for exergaming will most likely increase the adherence, engagement, and success of an exercise protocol.

4.1.2 Users Without Disabilities Were More Physiologically Receptive with iVR Exercise. These users physically performed in all areas of gameplay with more significant movements, successful catches, difficulty overcome, and higher game scores. Arousal and physical intensity were seen to be significantly higher on the HMD when compared to the room-scale medium, unlike the user cohort with disabilities. Resting state change of brain activity was insignificant on three out of the five wavebands, where only beta and gamma were found to have a significant change with the HTC Vive. Subsequently, all 27 of these participants unanimously preferred the HTC Vive. Unlike the cohort with disabilities, whose preference was primarily driven by elements such as the feeling of the motion capture hat and other emotive reasoning, the group without disabilities valued the HMD's ease of use, control, and increased immersion for completion of exercise tasks. For these users, the higher physical performance with the HTC Vive impacted immersion, emotion, and system preference, as shown by the apparent significant differences for HMD questionnaire responses. The HTC Vive is the clear winner here when compared to CAVE.

4.1.3 Both Cohorts Performed Better with HMD-Based iVR Exercise. Our user groups shared many similarities. The HMD system induced more significant physical movements, difficulty overcome, brainwave activity of the beta (focus-related), and gamma (cognitive processing–related) bands, and they both subjectively reported higher levels of immersion, engagement, and effort during gamified exercise with the HTC Vive. The majority of both groups preferred the HTC Vive over CAVE, even though CAVE provided an untethered physical medium for experiencing the virtual world. HMDs enable a full virtual immersion where users preferred this medium because the experience felt "more immersive [because] my virtual self was already in there [the game]." This detachment from reality proved to result in higher engagement, which may have attributed to a better physical and biometric performative response. Based on our results, we can conclude that for future experiences employing gamification for task-based exercise goals, HMD-based systems of iVR (which are significantly less expensive and more portable than the room-sized versions) are the apparent decision to maximize performance and engagement.

4.2 Has Modern Commercial HMD-Based iVR Surpassed the Research Grade Room-Scale Medium in the Healthcare Context?

This study has shown that HMD-based VR is a better medium compared to the room-sized version for maximizing physical performance, immersion, engagement, and effort of task-based exercises. Research has shown that the full exclusion of the real world provided by the HMD enables higher immersion, which is a powerful tool to distract users from pain and discomfort [36, 42]. Applying these immersive effects to overcoming adversity and difficulty in exercise is useful. In a past study with stroke survivors, PSC has shown that the gamification with iVR of physical therapy can increase compliance by nearly 40% compared to traditional therapies with the HTC Vive [27]. Subsequently, from the perspective of accessibility, accuracy, and affordability of exercise-based healthcare, HMD-based commercial iVR systems may have finally surpassed the alternative and more costly room-scale mediums.

CAVE does not exclude reality from the virtual world, as the user's physical body itself becomes a part of the visual iVR experience. Researchers have argued that this nature of CAVE—to be able to include multiple people in a space with their physical presence—can be advantageous for collaborative task-based needs [15]. However, we argue that modern commercial HMD-based systems have fully surpassed the advantages that CAVE used to hold with multi-user applications. For a fraction of the price, multiple HTC Vive–like HMD systems can be purchased and may enable multi-user interaction via virtual avatars from any location through the internet. The cost of an installation of a CAVE and its lack of mobility makes CAVE less flexible compared to the HTC Vive. New inverse kinematic techniques are being developed and shared across the research community, with integration for off-the-shelf systems like the HTC Vive to show full-body motion capture approximation and ease of implementation [52]. Furthermore, there is a vested interest in producing full-body motion capture by industry competitors for the future of iVR interaction with HMDs [48, 74]. In summary, iVR HMDs are gaining popularity: the cost of headsets are decreasing, systems are becoming ever more mobile and untethered through new inside-out sensor fusion tracking techniques, and new input mediums such as hand tracking, eye tracking, voice control, and even more, are being integrated [4]. We should also note that the integration of these features into a volumetric space like CAVE would cause a significant increase in cost compared to the HMD medium.

4.3 Considerations and Limitations

This study was one of the first to compare room-scale and HMD-based iVR through game performance, biofeedback, and questionnaires for exergaming with adults of different cognitive abilities. However, some limitations need to be considered.

Past studies with the PSC iVR framework have shown great potential to increase compliance for adults with physical disabilities [26, 27]. Nevertheless, these users have not been explored with CAVE in this study due to resource constraints. Future studies should explore a higher number of users of varying physical and cognitive ability to dive deeper into these immersive effects between the iVR mediums. Additionally, more systems should be explored beyond the Mechdyne CAVE Flex and the HTC Vive Pro 2018, especially with the deluge of mixed reality devices hitting the market such as Magic Leap, Microsoft Hololens, and more. Although these are costly devices at the current moment, a similar trend with iVR technology may occur in the near future.

Furthermore, this study was not conducted in a clinical setting and did not utilize clinical-grade biometric sensors. Due to the physical constraints of CAVE, users were tested on-site at UCSC with only caretakers present, although healthcare professionals were involved either through remote meetings, check-ins, or email correspondence rather than on-site at a therapy clinic. For our vision of the future, it is our hope to integrate these immersive experiences in each user's household, which will require this detachment from the clinical setting. With cost and user experience in mind, we chose to work with commercially available biometric sensors to collect biofeedback. This resulted in a lack of resolution from the biometric collection, where brainwave sampling was limited to the prefrontal cortex as opposed to clinical full head caps. In addition, HR was only collected through a single-site optical sensor as opposed to clinical multi-site sticktrode locations. Although these devices did not have the best resolution or sampling sites, the alternative would have been introducing higher setup times and discomfort for our users through costly sticktrodes, electrogels, and other materials required by these clinical-grade biometric sensors. It should be noted that other researchers are reporting success in using these commercially available sensors by implementing computational and sensor fusion techniques for better analysis [5, 24, 55, 56].

With these limitations in mind, we are preparing future experiments to address these challenges with various local healthcare organizations in Santa Cruz, California. The framework shown in this article for analyzing game performance, biometric response, and survey collection will be utilized in these upcoming studies to personalize and adapt the healthcare experience for users of varying abilities.

5 CONCLUSION

Modern iVR systems are becoming ever more prevalent in the consumer marketplace, and thus it is critical to compare room-scale and HMD-based iVR mediums. To the best of our knowledge, this study is one of the first to compare these iVR systems in the context of physical exercise. Our findings suggest that HMDs have finally caught up to and may have even surpassed CAVEs with our exercise game for adults with and without disabilities. We also highlight a pipeline for multi-modal exercise analysis from game behavior, physical movement, and biometric response. These insights may be useful to future developers and engineers from a system design, user experience, and data analytics perspective.

With a high number of VR systems commercially available and emergent immersive accessories being created, there are numerous platform options for experimentation by healthcare researchers. In the future, it is our hope to refine comparison measurements between iVR systems and address different populations of all abilities in iVR health applications. More studies must be conducted in comparing these systems, especially with the goal of addressing a greater variety of healthcare issues. One possible future application for healthcare is where users connect virtually with therapists for evaluation, perform gamified task-based objectives to meet exercise goals, and use analytics to adjust the difficulty and speed of prescribed exercises.

More than 50 years ago, Ivan Sutherland demonstrated the first iVR HMD to the world [96]. For Sutherland, his vision of the future of iVR was one of an ultimate display: "[T]he ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming, such a display could literally be the Wonderland into which Alice walked" [95]. Modern iVR systems are enabling deeper and more rich experiences of presence into the virtual world [4]. These elements of the ultimate display that influenced modern iVR as we know it appears to be near at hand [8]. Given this progress of immersive mediums into the virtual world, we ask: what would the ultimate iVR system be for exergaming and health?

This work supports that a modern HMD such as the HTC Vive is more engaging and produces better physical exercise performance than the more expensive room-scale CAVE medium. Through PSC and its framework, we have explored the effects of the virtual world for individuals with and without disabilities [27]. Through our comparative study, we have seen that modern HMDs have a vast potential for physical exercise games for users of mixed abilities. In addition, through integrating biofeedback and motion capture analytics, iVR healthcare experiences can be personalized to match the needs and motivations of the user. With growing advances in artificial intelligence and machine learning, perhaps future iVR exergames can learn from both the users and therapists to best prescribe and augment VR stimuli for exercise. We envision this medium to be one that adapts the virtual world to the runtime emotional and physical state of each user to create a profound and maximally engaging experience. Subsequently, there are far more stars to catch and biofeedback to record as we collectively build our vision of the ultimate immersive display for healthcare and exergaming.

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