Improving User Performance in Haptics-Based Rehabilitation Exercises by Colocation of User's Visual and Motor Axes via a 3D Augmented-Reality Display

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***Abstract*—Serious games are recently becoming a common sight in rehabilitation settings to provide motivation for patients undergoing therapy to regain upper limb function after disability. These are often presented using a 2D monitor to the patient who uses a robotic device (haptic user interface) as the game controller. In this paper, we develop a 3D spatial Augmented Reality (AR) display to colocate visual and haptic feedback to the user in three rehabilitative games. The same games are also displayed in a 2D non-immersive Virtual Reality (VR) and are compared against their AR counterpart in terms of user task performance to evaluate the benefit of the 3D AR system. To simulate a rehabilitation scenario, able-bodied participants are put under cognitive load (CL) for simulating disability-induced cognitive deficiencies when performing the tasks. A within-subjects analysis of 10 participants was carried out for the rehabilitative games. The results show that AR leads to the best user performance with or without cognitive loading. This result is most evident in dynamic exercises where the participants are required to have quick reaction times and fast movement. Furthermore, even while AR had a significant difference over VR, one of the tasks showed that performance in AR between non-CL and CL cases were similar, thereby showing how AR can alleviate the negative effects of CL.**

***Index Terms*—Virtual Reality and Interfaces, Haptics and Haptic Interfaces, Rehabilitation Robotics**

I. Introduction

In recent years, rehabilitation has incorporated serious games using non-immersive virtual reality to motivate patients during therapy. Serious games are defined as video games designed for a purpose other than pure entertainment. Traditional rehabilitation training may involve training with real-world objects to do activities of daily living (ADLs) in order to help regain motor function. However, the repetitive nature of these exercises can make therapy a tedious process for the patients. Motivation is a key factor in predicting the success rate of rehabilitation [1] [2]. In a study that involved post-stroke patients, only 31% of the patients maintained their weekly exercise programs [3]. For rehabilitation therapy involving serious games, it has been shown that there is an increase in motivation, providing patients with a more leisurely experience as they go through their therapy [4].

Manuscript received: September 10, 2018; Revised November 22, 2018; Accepted December 26, 2018.

This paper was recommended for publication by Editor A. M. Okamura upon evaluation of the Associate Editor and Reviewers' comments. This work was supported by the Canada Foundation for Innovation (CFI) under grant LOF 28241; the Alberta Innovation and Advanced Education Ministry under Small Equipment Grant RCP-12-021; the Natural Sciences and Engineering Research Council (NSERC) of Canada under the Collaborative Health Research Projects (CHRP) Grant #316170; and the Quanser, Inc.

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Digital Object Identifier (DOI): see top of this page.

A. Virtual Reality & Augmented Reality Game Displays

The games are typically presented to the user in one of two forms: Virtual Reality (VR) or Augmented Reality (AR). Virtual Reality consists of a fabricated environment where the user controls an avatar or cursor to interact with the virtual world. This is often done through non-immersive VR that is typically displayed on a flat 2D screen. However, technologies like the Oculus Rift and HTC Vive have boosted the popularity of immersive VR as a medium for serious games [5].

Augmented Reality is about the superimposition of digitally fabricated objects onto the real world environment. Applications for this can range from providing information to allowing interaction with the digital objects as if they existed alongside real world objects. AR consists of three main categories: Video See-Through (VST), Optical See-Through (OST), and Spatial AR (projection) [6]. VST utilizes a video feed where digital objects are overlaid onto the screen to interact with the real world objects [7]. OST overlays the digital images on a semi-transparent screen which allows the user to directly see the real world unlike VST [8]. Finally, Spatial AR projects the digital images directly onto the physical environment [9].

B. Visual and Motor Axes Colocation

While serious games are advantageous in enticing the patients to stick with their therapy program, they lack realism. The games need an interface which allows it to be controlled, such as a joystick or a haptic user interface. However, while using these interfaces, the game is typically displayed on a screen at a distance in front of the patient. However, in real-world tasks (e.g. peg-in-the-hole insertion), the patients directly interact with objects, feeling and seeing them at the same location. In the games used for rehabilitation, however, there is a disconnect between the visual space and the movement space of the patient's arm. The mismatch between the axes of motion between on-screen movements and the patient arm movement require the patients to mentally "calibrate" themselves to map their arm movements to the coordinate frame of their avatar in the game. The scaling of movements between the virtual and real workspaces may also have to be accounted for. For those affected by events such as stroke that could have affected their cognitive processes negatively [10], doing a mental transformation between the visual and hand coordinate frame could be a difficult task. The principal idea of this paper is that to lighten the mental load on the patient and improve task success rates, the spatial disparity between the coordinate frames can be bridged using AR.

Two hypotheses are investigated:

1. *Regardless of the presence or absence of cognitive loading, AR improves user performance over VR.*

2. *The results of AR during cognitive loading is not significantly different from AR without cognitive loading.*

The focus of this paper is only to show that AR can make it easier for the patient to perform the task, thereby increasing the likelihood of success in performing that task. Actual motor scores comparing improvements of AR against VR will not be shown. That would require a longitudinal study on a treatment group and a control group of patients who would come into the clinic for at least 3 months every week, 3 times a week. In such a study, treatment group would be receiving AR, while the control group receives AR. Standardized assessments such as Fugl-Meyer would be used to compare the scores. This will not be included in this paper but is instead future work.

C. Related Works

Most rehabilitation literature that incorporate serious games involve 2D non-immersive VR implementation, or AR in 2D or 3D but without colocation of visual and motor axes. Devices such as the ReJoyce Rehabilitation Workstation have multiple interactive 2D games to motivate patients and improve upper limb function after stroke [11]. Correa et al. [12] created a musical AR game called GenVirtual which is a spatial 2D AR game where the user replicates the tune produced by virtual cubes that light up in a sequence by touching the cubes in the same order. Gama et al. [13] developed MirrARbilitation, a VST 2D non-colocated AR system to encourage and guide users in a shoulder abduction therapy exercise.

For the case of 3D, Vidrios-Serrano et al. [14] used a VST 3D non-colocated AR system integrated with a phantom Omni device to interact with the virtual environment in a rehabilitation exercise. Broeren et al. [15] and Murphy et al. [16] used a haptic immersive workbench to test both able-bodied and stroke-impaired persons for rehabilitation and assessment with their OST 3D colocated AR system. Swapp et al. [17] studied the effectiveness of a 3D stereoscopic display AR system for colocated haptic feedback. Swapp examined if there is a benefit in having Visual-Haptic colocation as opposed to not having it. However, the study did not look at its effects in rehabilitation exercises and did not adjust the display as the user moved his/her head. Unlike Swapp's work, we hope to show that by using a 3D AR system, even users who are unable to perform with their full mental capacity are able to show improvement over the 2D system.

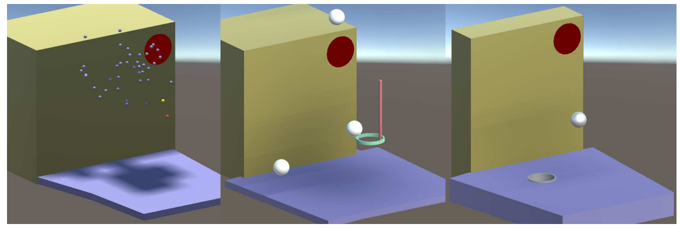

Fig. 1: The three tasks, *Snapping* (left), *Catching* (centre), *Ball Dropping* (right).

This paper investigates, using a 3D Spatial AR setup, the effectiveness of 3D AR Visual and Motor Axes Colocation compared to 2D non-immersive VR in a rehabilitation context. User task performance is compared between AR and VR cases. A patient with cognitive deficiency will be simulated by cognitively loading able-bodied participants. We expect that if AR is able to make differences in performance for able-bodied participants who are distracted by cognitive loading, then it is possible to see such differences in actual cognitively-challenged patients as well. The paper is organized as follows: Section II describes the tasks for the proposed system and the experimental setup. Section III explains how the experiments are carried out and provides a discussion of the results. Section IV concludes the paper by summarizing the work and findings.

II. Proposed 3D Spatial AR System

A 3D AR rehabilitation environment should have the same elements of a traditional rehabilitation environment but with the flexibility and creativity that a virtual environment can bring. The proposed system involves visual and motor axes colocation and depth perception to immerse the user in the task. Three tasks are created to test the user performance between 3D AR Visual-Motor Colocation and 2D non-immersive, non-colocated VR: *Snapping, Catching, and Ball Dropping*. The tasks can be seen in Fig. 1.

A. Representative Tasks

The *Snapping* task requires spatial awareness and accuracy. The user controls a small ball and manipulates it around 40 other small spheres. At any given moment, only one of the spheres will be highlighted to indicate the target position for the ball. The user has to move the ball to the location of the highlighted sphere. When the ball and the target sphere overlap, the end-effector holding the ball will snap onto the sphere letting the user know via haptics that they succeeded. This prompts a new sphere to be highlighted, which the user has to get to next. Each highlighted sphere that is reached scores a point. Collision with the unhighlighted spheres must be avoided since it will reduce the score by one for each point hit. Overshooting a highlighted sphere that was just hit (thus becoming unhighlighted) and coming back to also subtracts one score. This encourages the users to maintain a balance between speed and accuracy throughout the 60s the task is run. If the user is able reach all 40 spheres, the first sphere becomes highlighted again and the exercise continues.

The *Catching* task tests the user's performance with manipulating the end-effector in a fast-paced scenario. The task is to catch balls that fall from a ledge using a hoop attached to a stick which is controlled by the end-effector. This requires the user to reach around the workspace, have good reaction time, and have spatial positioning accuracy to catch the balls. The balls spawn above the ledge at random locations every 2 seconds and come towards the user at different speeds; therefore, they fall to different areas of the workspace depending on their speed. Each time a ball enters the hoop successfully, the user scores a point. The task runs for 60s and 30 balls in total are spawned. Whenever the balls hit the edge of the hoop, the user feels confirmatory haptic feedback on the end-effector.

The *Ball Dropping* task requires precision and accuracy. A hole is spawned at a random position on the desk surface. The user controls a ball that is positioned approximately shoulder height of the person and aims it above the hole. The ball is released by pressing the spacebar on the keyboard. The location of the hole changes as soon as the ball goes through the hole and the ball returns to the user. Otherwise, the user will have to try dropping the ball into the same hole until it successfully goes in. The task runs for 60s, giving the user a point for every time the ball falls through the target hole.

For each of the tasks, a red dot blinking at 1 Hz is placed on a virtual wall across from the user. This is the visual aid that is used to keep the users in tempo during cognitive loading. To simulate cognitive deficiency in able-bodied participants, an arithmetic operation is done by the participants alongside each of the three previously mentioned tasks. Counting backwards in multiples of 3 has been shown to be effective in decreasing user performance during dual task performance [18] [19]. A random number between 100 - 200 is given to the participants before the start of each task. Every instance the red dot appears, the participant is to audibly count down, constantly subtracting by 3 each time.

B. Experimental Setup

The system uses a High Definition Haptic Device (HD^2) from Quanser, Inc., Markham, Ontario, Canada. The HD^2 device is used as the interface to interact with the digital objects. An off-the-shelf InFocus IN116A projector is mounted above on the wall behind the user. It projects the task on the curved screen similar to [20] that is $65cm$ tall, $85cm$ deep, $56cm$ wide. Similar to the work of Swapp et al. [17], a television or monitor could have been chosen as the display medium. However, a projector was chosen due to its versatility. A projection setup will be able to keep our options open for future work for larger scale exercises that may involve walking, or even users moving around in a wheelchair. With the depth information provided by the Kinect, a model of the scene can be constructed and projected on to such that from the user's viewpoint, the virtual object is displayed properly. This is achieved using the RoomAliveToolkit [21]. The use of two perpendicular surfaces as the display allows for more creative tasks and better immersion for the user. The curved screen is for a seamless projection surface since having no corners or creases improves the user experience [20] [22].

A Kinect V2 sensor is located above the screen facing the user for head tracking purposes. Head tracking is crucial to the

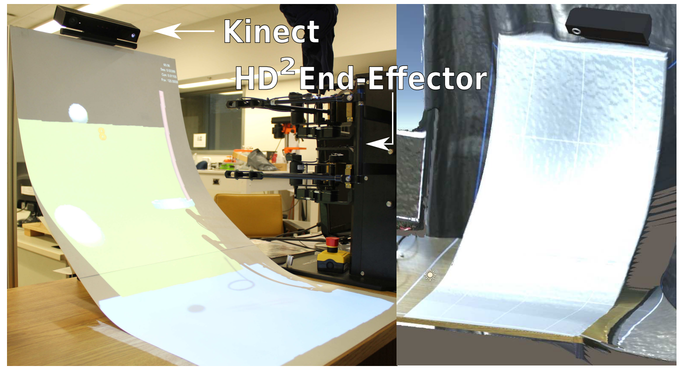

Fig. 2: Left: Actual setup. Task is projected onto the screen (projector is not in view). Right: Model of the setup created in Unity.

setup of the system to allow patients to have the freedom of movement while still having proper perspective on the virtual environment. Otherwise, they would need to keep their head positioned on the same spot during the entire exercise in order to keep the correct perspective. The HD^2 is located on the right side of the screen such that the end-effector can be moved around the centroid of the curved screen. The HD^2 was used to interact with the virtual environment rather than utilizing the Kinect depth sensor to interact using freehand motions. Freehand lacked the haptic functionality that robotic devices have. The haptics add another layer of feedback with the virtual environment, increasing immersion.

The task workspace where interaction with digital objects occur is in the space between the screen and the user. The task is created using the Unity Game Engine [23] and utilizes the open-sourced RoomAliveToolkit [21] to handle the kinect-projector calibration. The HD^2 is controlled using MATLAB and Simulink. The experimental setup can be seen in Fig 2. The virtual camera within Unity, which provides the view of the virtual environment, is positioned such that the virtual environment is integrated in the real environment when seen from the user's viewpoint. This camera acts as the user's eyes and is displaced left and right at 60Hz to enable stereo-viewing for 3D depth perception. The user then wears active DLP-link 3D shutter glasses to properly see the environment in 3D.

1) Calibration: To match the HD^2's end-effector movement with the virtual environment, the position of the HD^2 only needed to be aligned to match the position of the user-controlled virtual object. The HD^2 encoders provide accurate readings for the end-effector and Microsoft's RoomAlive-Toolkit scaled the Unity environment to match the real-world. Head-tracking with the Kinect is also aligned such that both virtual and real world environments are matched in scale to ensure that regardless of the position and angle it is viewed from, the virtual world would seem part of the real world.

2) Occlusion: As with any projection systems, occlusion is an issue when objects create a shadow that blocks the projection onto the screen and instead the images gets projected on the object (e.g. on a user's hand). Likewise, improper rendering of the virtual objects when the projection surface changes reduces the immersion of the user with the virtual environment. Positioning the virtual objects that the user controls directly onto the user's hand breaks this immersion.

Task Performance Conditions		
	VR	AR
No Cognitive Loading	1	2
Cognitive Loading	3	4

TABLE I: Each task is split into 4 conditions. Each condition is presented twice to the participant to increase the validity of the results. There are 3 tasks, 4 conditions/task, 2 trials/condition to give a total of 24 trials. The numbering on the table is only for reference for the other figures in this paper and does not reflect the order the conditions are presented to the participants.

In light of this, the virtual objects are positioned at a small offset (1 cm) to the left and back of the end-effector to prevent improper rendering and shadow occlusion. This is also done to prevent the end-effector of the HD^2 from occluding the controlled object. The virtual environment is also displayed such that the majority of the workspace the user interacts with is projected on the upper area of the screen to reduce shadow occlusions. The head tracking carried out by the kinect also helps the user look around objects in the case occlusion occurs.

III. Experiment

A total of 10 able-bodied participants (ages 22-32) from the University of Alberta community took part in the experiments. All participants were right-handed and had prior experience with haptic devices. 5 out of 10 had experience with using shutter glasses or VR headsets. Verbal instructions were provided alongside a trial run for each task for familiarization.

A. Procedure

Each participant is presented with three tasks: *Snapping, Catching, and Ball Dropping*. The order of presentation is randomized to prevent any bias in learning effects happening between tasks. Each task is done in either 3D AR or 2D non-immersive VR. The presence of cognitive loading is also switched on or off. Haptic feedback is turned on for all trials. Thus, there are 4 conditions to be tried for each task. Each condition is presented twice to the user and is given in random order. Since the random generation of locations for each task may bias the results (e.g., the balls in the catching task might spawn in similar locations/speed for one participant, but far apart for another), two sets of spawn points are generated for each task. Therefore, each participant attempts each of the three tasks 8 times, giving a total of 24 trials per participant.

Each participant is seated at arms length from the projector screen with the HD^2 to their right side, giving the end-effector access to the area between the projector and the participant. While they are wearing the shutter glasses, the eye separation is then measured by having the participant compare a virtual end-effector with the HD^2's end-effector. The separation is adjusted until the virtual end-effector is parallel to the HD^2's. Then in random order, the sets of tasks are presented, each with 8 trials that are also randomized. A trial run for each task is given in 3D AR for the participants to get a feel of the 3D environment and the tasks. Overall, the experiment lasted for approximately an hour and fifteen minutes per participant, including the resting time between each task. This study was done with approval from the University of Alberta Research Ethics & Management Online, ID MS9_Pro00033955.

Mean and Standard Deviation of Outcome Measures of Each Task				
Cond. #	**1**	**2**	**3**	**4**
Snapping Task				
Total Score	23.0 ± 7.7	27.0 ± 10.6	17.9 ± 5.3	23.2 ± 9.0
Wrong Hits	6.5 ± 4.3	5.3 ± 4.5	3.8 ± 2.3	2.5 ± 1.7
Net Score	16.6 ± 4.9	21.7 ± 10.7	14.1 ± 3.8	20.7 ± 8.2
Time/point	1.8 ± 1.2	1.5 ± 1.2	2.2 ± 1.5	1.7 ± 1.4
Catching Task				
Score	6.9 ± 2.1	14.2 ± 2.9	3.7 ± 1.6	9.5 ± 3.4
Ball Dropping Task				
Score	7.9 ± 2.2	11.0 ± 3.6	4.9 ± 2.3	8.9 ± 2.9
Tries/Hole	3.2 ± 1.0	2.2 ± 0.7	6.0 ± 3.7	2.5 ± 0.9
Time/Hole	8.5 ± 1.9	5.7 ± 1.6	16.3 ± 11.2	6.6 ± 2.7

TABLE II: Table of mean and standard deviations for the outcome measures for the three tasks. Results show the average per person.

RMANOVA Results			
Task	**Measure**	**VR vs. AR**	**No CL vs. CL**
Snapping	Total Score	**F= 6.4, p= .0321**	***F= 22.0, p= .0011***
	Wrong Hits	$F = 3.4, p = .1004$	**F= 8.3, p= .0179**
	Net Score	**F= 6.7, p= .0291**	$F = 3.0, p = .1178$
Catching	Score	***F= 46.7, p= .0000***	***F= 103.3, p= .0000***
Ball Dropping	Score	***F= 38.3, p= .0002***	***F= 14.1, p= .0045***
	Tries/Hole	***F= 12.1, p= .0069***	**F= 8.1, p= .0194**
	Time/Hole	***F= 10.9, p= .0093***	**F= 8.0, p= .0196**

TABLE III: The RMANOVA results of each task category for each main fixed effects (VR vs. AR and No CL vs. CL). The F-ratio and p-values are reported. **Bolded** values represent $p < 0.05$ significance. ***Bolded italicized*** values represent $p < 0.01$ significance.

B. Results and Discussion

No penalty is applied to cognitive loading miscounts. Since each of the 4 conditions are presented to each participant twice, the results present the average of the two trials. A Kolmogorov-Smirnov test with Lilliefors modification [24] for normality was done for the net score of the snapping task, and both score results of the catching and ball dropping task. All three passed the normality test ($p < 0.05$). A 2-way Repeated Measures Analysis of Variance (RMANOVA) [25] is applied to the results to determine if there is a significant difference between the results for the different conditions. The main fixed effects are the visual techniques used (AR or VR) and cognitive loading (on or off). The False Discovery Rate (FDR) correction is chosen to reduce Type I errors for our post-hoc analysis [26]. A Type I error is also known as a "false positive" result, which is the rejection of a true null hypothesis. In the box plots in Fig. 3, the significance is represented by the stars (*) on the horizontal line above two sets of conditions; One star (*) represents a significance value of $p < 0.05$ and two stars (**) represent a significance value of $p < 0.01$. If there is no horizontal line above two the results for conditions, there is no statistical significance between them.

1) Score Results: The mean and standard deviation (std) results of each task and its conditions are shown in Table II. For the Snapping task, four areas of scoring were collected: Total Score - the number of highlighted points reached, Wrong Hits - the number of unhighlighted points hit, Net Score - the final result after subtracting wrong hits from the total score, and Time/point - the amount of time it took to travel between points. The Catching task only includes the amount of times a ball successfully caught in the hoop, denoted as the score. The

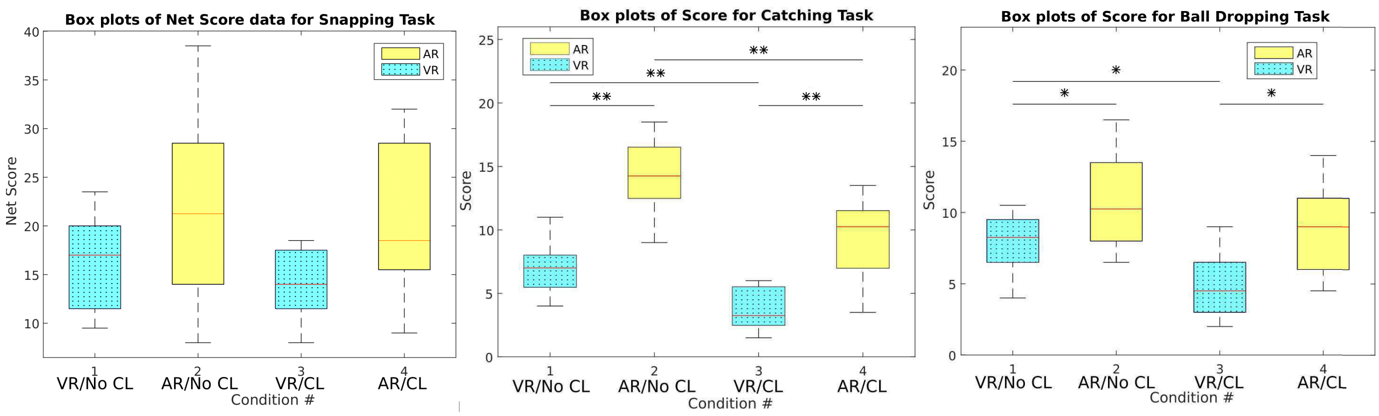

Fig. 3: Box plot results for Snapping (left), Catching (centre), and Ball Dropping (right). The line within the boxes represent the median score. The horizontal line above the conditions show the statistical significance of the two conditions. One star (*): $p < 0.05$. Two stars (**): $p < 0.01$. No horizontal line represents no statistical significance.

Ball Dropping task has three outcome measures: Score - the number of balls successfully dropped into the hole, Tries/Hole - the number of attempts the participants had to try before successfully getting the ball in, Time/Hole - the time it took, in seconds, before the ball went in.

2) Statistical Significance between Conditions: As seen in the box plots, the scores for AR are generally higher than VR for all tasks and all cognitive loading conditions. RMANOVA results in Table III show significance in all measures for both fixed effects except for two from the Snapping task.

A paired t-test with the FDR correction, as seen in Table IV, is utilized to closely inspect if there are significant differences between the conditions. While the RMANOVA results for the three measures in the Snapping task showed significance in some of the main fixed effects, t-test results show a lack of significant difference between the condition pairs. From observation in both the data in Table II and during experiments, participants moved between points faster when there was no cognitive loading. Consequently, the gross number of points reached (total score) was much higher than their CL counterpart. However, this also caused a larger amount of unhighlighted points hit. With CL, the participants took longer and acted more carefully, therefore colliding less. This provided an unintended result with cognitive loading that does not reflect what is perceived to be a patient with cognitive deficiency and therefore no conclusions can be made with the analysis for this task.

For the Catching task, RMANOVA shows a statistically significant difference between the presence and absence of both visual-haptic axes colocation and cognitive loading. Paired t-tests show that our first hypothesis is met; AR resulted in better success scores compared to VR regardless of the presence or absence of CL. However, the second hypothesis is not met. For this task, visual-motor colocation via AR enhanced user performance over VR, however it did not greatly improve it such that the CL case would produce similar results with the non-CL case.

For the Ball Dropping task, there is statistical significance between the average scores, average tries per hole and the average time the participants took per hole as seen in the RMANOVA results. This suggests that for AR, participants spend less time and are more confident in how they position the end-effector. Mostly seen in the VR case, the participants also utilized the ball's shadow to gain depth information. According to RMANOVA, cognitive loading produced a significant effect in decreasing user performance. However, paired T-tests show that this significance is more prominent between VR results. Therefore, both hypothesis 1 and 2 have been met. AR in both non-CL and CL case had significant improvements over VR, but under AR, there was no significant difference between CL cases. This shows that AR was able to alleviate the negative effects of CL.

Paired T-test p-value results between Conditions				
Condition Pairs	**1 vs 2**	**3 vs 4**	**1 vs 3**	**2 vs 4**
Snapping Task				
Score	0.3929	0.2531	0.2531	0.3929
Wrong Hits	0.5644	0.2236	0.2047	0.2047
Net Score	0.2913	0.1325	0.2913	0.8081
Catching Task				
Score	***0.0000***	***0.0003***	***0.0016***	***0.0041***
Ball Dropping Task				
Score	**0.0425**	**0.0129**	**0.0168**	0.1808
Tries/Hole	**0.0415**	**0.0415**	**0.0481**	0.3779
Time/Hole	***0.0072***	**0.0321**	0.0600	0.3513

TABLE IV: Table of Paired T-test results between two conditions using the False Discovery Rate correction. **Bolded** values represent $p < 0.05$ significance. ***Bolded italicized*** values represent $p < 0.01$ significance.

3) Observations: The three tasks tested spatial manipulation, accuracy, and awareness. Each task also differed in regards to how dynamic the participants had to be with their movements, speed, and reaction time.

The Catching task, for instance, consistently required fast movements to catch the balls while the Ball Dropping task allowed the participants to take their time in determining the positioning required to successfully drop the ball in the hole. Effects of cognitive loading also varied between the three tasks. CL had the biggest influence in decreasing user performance in the Catching task. This is mostly due to requiring fast movements and reaction time while simultaneously undergoing CL. Participants would often slow down their movements while thinking of the next number.

In the Ball Dropping task, participants counted down in sync with the moment they press the spacebar to drop the ball while expecting the ball to fall in. When it does not go in, they press the spacebar again to retrieve the ball as quickly as possible, causing a break in concentration during CL and thus slowing them down. Its effect in VR compared to AR is much greater due to the lack of depth perception, requiring more attempts.

For the Snapping task, while the paired t-test fell short of providing a significant difference, the box plots portray hints of improvement in the AR cases. Due to the task not requiring quick reaction times like in the Catching task, nor anticipation of success as seen in the Ball Dropping task, participants in the Snapping task moved more carefully and steadily when CL was applied. They also moved in sync with their counting, snapping onto the target points during each countdown. These factors have contributed to our varied score results.

Feedback from the participants came in the form of verbal comments and certain habits noticed while the tasks were being done. All the participants made use of the head tracking to view the environment from different angles for better depth information. This was more evident in the snapping task which needed spatial awareness of the surroundings to avoid the unhighlighted points. Halfway the 24-trial point of the experiments, a few of the participants became accustomed to the backwards counting. Two of them suggested different ways of providing cognitive loading such that it is variable, making it harder to get used to. While the learning is evident in prolonged trials, the randomization of the trials aided in reducing its effect. Participants with experience in either immersive VR or AR technologies adapted faster to the tasks. Those without experience often needed more time, in the earlier trials, to adjust their eyes to the AR environment.

IV. Conclusion

Comparisons are performed in user task performance between 2D non-immersive VR and 3D spatial colocated AR. We showed that by bridging the gap between visual coordinate frame and hand coordinate frame, able-bodied participants with a simulated cognitive deficiency will experience improved success rates in the rehabilitation exercises. Since disabling events such as stroke affects the central nervous system and therefore possibly causing cognitive disability, we simulate this cognitive disability through cognitive loading in the form of an arithmetic operation. Three tasks were presented to the participants: Snapping, Catching, and Ball Dropping. In terms of superiority of performance in AR over VR, the main hypothesis of the paper was not met in the Snapping task. The Catching task met the requirements of the main hypothesis; AR proved to significantly enhance user performance in both non-CL and CL cases. The Ball Dropping task also confirmed the first hypothesis, but further improved the success rate of AR during CL, therefore meeting the requirements of the second hypothesis in which the negative effects of CL are alleviated to allow the user performance of AR during CL to not be significantly different from the non-CL AR case. Future work include testing the system on actual patients as part of a longitudinal study. Incorporating the system with assistive functionality to further improve success rate is also considered. By introducing the benefits of visual-motor colocation in a 3D augmented reality rehabilitation system, we hope to inspire new possibilities of rehabilitation games that are not bound by the limits of 2D monitors.

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