Visual-Haptic Colocation in Robotic Rehabilitation Exercises Using a 2D Augmented-Reality Display

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Abstract—**Haptics-based Virtual Reality (VR) games have been found to be effective in rehabilitation from disability. Augmented Reality (AR) has gained traction in recent years in various domains including gaming, entertainment, and education. In this paper, we integrate spatial AR into robotic rehabilitation to provide colocation between visual and haptic feedback as a human user participates in a rehabilitative game. A comparison between the effectiveness of VR vs AR (i.e., non-colocation vs colocation of vision) is done. Spatial AR is the colocation of vision through the use of projection. Visual-Haptic colocation is the combination of spatial AR and haptic interaction. We also compare each visualization technique in the absence and presence of haptic feedback and cognitive loading (CL) for the human user. The system was evaluated by having 10 able-bodied participants do all 8 different conditions lasting approximately 3 minutes per condition. The results show that spatial AR (corresponding to colocation of visual frame and hand frame) leads to the best user performance when doing the task regardless of the presence or the absence of haptics. It is also observed that for users undergoing cognitive loading, the combination of spatial AR and haptics produces the best result in terms of task completion time.**

Index Terms—**Augmented Reality, Virtual Reality, Colocation, Haptic Feedback, Robotic Rehabilitation**

I. INTRODUCTION

The demand for rehabilitation services has grown significantly with the aging of population. Patients who have suffered disabling events such as stroke develop deficiencies that prevent them from making reaching motions or doing activities of daily living (ADLs) such as eating, washing, and self-care. Therefore, a number of goal-oriented tasks and point-to-point reaching exercises are provided in rehabilitation to help the patients regain motor function and consequently their independence.

While robots allow rehabilitation with minimal therapist intervention, low patient motivation is an issue. A study shows that only 31% of users maintained their weekly exercise programs [1]. Due to this, video games have become a medium for robot-assisted rehabilitation therapy. Games provide an increase in motivation by making the task less of an exercise to endure but rather a more leisurely experience [2]. This means that there is an increase in motivation in patients using these technologies.

These games typically belong in one of two categories: Virtual Reality (VR) or Augmented Reality (AR). AR, in particular, has garnered attention in the past few years alongside immersive VR with the release of the Oculus Rift [3] and Microsoft's HoloLens [4]. With regards to rehabilitation, such technologies have proved to be effective in both physical and mental therapies [5], [6].

A. Virtual Reality & Augmented Reality in Rehabilitation

Virtual Reality comes in many forms. They range from the non-immersive VR games that are displayed on a screen to immersive head-mounted displays (HMDs) such as the Oculus Rift. These games (mostly non-immersive) are now a common way to provide visual feedback about the therapy task during rehabilitation and are used by multiple rehabilitation robotics systems [7] [8].

Augmented Reality, similar to VR, has different implementations. A Video See-Through (VST) AR setup lets the patient see overlays of digital images onto the video feed [9]. An Optical See-Through (OST) setup has the digital images calibrated to match what the user directly sees through a semi-transparent mirror [10]. Finally, spatial AR or projection removes the need for the user to wear any HMDs and allows direct interaction with the projected digital image [5]. The superimposition of digital images onto the real-world geometry is the common ground between the above-noted various AR implementations, allowing the users to feel that the digitally created objects are part of the real world rather than at a separate screen or in a virtual space. Due to the direct interaction of AR, with proper calibration, colocation between the vision and the person's actions (can include haptic interaction with the digitally created object) can be achieved.

B. Haptic Feedback in Rehabilitation

Haptic feedback stimulates the user's touch senses by reflecting forces to the users hand. While commercial rehabilitation devices often do not have haptics implemented, this is a common method of improving patient experience in rehabilitation research. When combined with visual feedback, it can increase the realism of interaction and possibly the realism of rehabilitation outcomes [11]. It can also open up

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various ways of assisting the users in terms of performing the task by tuning the feedback according to difficulty of the tasks.

C. Motivation for Visual-Haptic Colocation in Rehabilitation

In this paper, visual-haptic colocation is defined as the direct mapping of vision to physical interaction (including haptic interaction) between the users hand controller and the object in the virtual scene. A majority of computer-integrated rehabilitation technologies that use robots to guide and assist users have them view computer games on a screen in order to be able to perform desired exercises. As there is a mismatch in axes of motion between the on-screen movements and the user arm's movement, the users must mentally "calibrate" themselves to map their arm movements to the coordinate frame of their avatar in the game (i.e., the users must imagine themselves positioned within the screen and move appropriately in the environment to complete the task). This causes the user to take a moment to do a mental transformation between the visual coordinate frame and their hand coordinate frame. However, the cognitive abilities of those suffering from disabilities may have also been affected negatively [12], which means they may have difficulty bridging the spatial disparity between the two coordinate frames. With a spatial AR setup, the visual and hand frames can be colocated, which could potentially lighten the mental load on the patient.

In this paper, we will be incorporating haptic feedback in an AR setting in a rehabilitation environment in order to study the effectiveness of visual-haptic colocation. We will simulate a patient with cognitive deficiency by cognitively loading healthy participants in a user study. User task performance will be compared mainly between AR and VR for the different combinations of presence or absence of haptics and CL. The effect of cognitive loading will be briefly touched upon only to confirm if it does indeed significantly affect user performance in properly simulating patients. Each AR and VR pair will be analyzed to find which one benefited the most from visual-haptic colocation. The goal will be to help therapists and physicians find more efficient methods for rehabilitation. This investigation of bridging the spatial disparity could open up new possibilities for future rehabilitation games.

The paper is organized as follows: Section II provides brief examples of work done in research literature. Section III describes the approach and game design. Section IV outlines experimental setup, challenges, experimental procedure and a discussion of the results. Finally, Section V finishes with a conclusion and future work.

II. RELATED WORK

A. Virtual Reality Rehabilitation Systems

Multiple rehabilitation tasks have been published in the literature that fall within AR and VR as categorized in the above table. VR systems often come in either non-immersive, or immersive displays. Non-immersive displays include 2D computer screens, TVs, or projection on a screen. The ReJoyce Rehabilitation Workstation is a non-immersive VR system with a multitude of interactive games to simulate a variety of ADL exercises [13]. However, it does not provide haptic feedback during the tasks, only visual and auditory. In another work, Adamovich et al. [14] presented a non-immersive haptic glove VR system to improve the hand function of post-stroke patients. Immersive VR systems typically use HMDs such as the Oculus Rift or HTC Vive. However, other systems may involve either the CAVE [15] or CAREN [16] systems that puts the user in a room with a large projected screen all around (CAVE) or in front (CAREN) of the user. In the work of Kaminer et al. [17], they used an Oculus Rift for an immersive VR pick-and-place task and used a non-haptic glove to record the hand's grabbing gesture. Likewise, Andaluz et al. [18] used the Oculus Rift and a Novint Falcon haptic device for their upper limb rehabilitation games.

TABLE I
THE TABLE CATEGORIZES THE DIFFERENT PHYSICAL REHABILITATION SYSTEMS FOUND IN LITERATURE BY THE TYPE OF VISUAL TECHNIQUE AND INCORPORATION OF HAPTICS.

Literature Comparison					
	VR		AR		
	Non-Imm	Imm	VST	OST	Spatial
No Haptic	[13]	[17]	[19], [20]	[22]	[5]
Haptic	[14]	[18]	[21]	[23]	[24], [25] ●

The black bullet represents this paper's position in the literature.

B. Augmented Reality Rehabilitation Systems

AR systems are usually displayed using either VST, OST, or projection. While often portrayed as requiring HMDs, VST and OST can also be done using a monitor screen, however it lessens the immersion. For VST setups, Burke et al. [19] used a marker-based, non-haptic setup and developed a game similar to Atari's *Breakout* and another game where the participant stacks virtual objects onto a virtual shelf. Correa et al. [20] developed GenVirtual, a musical AR game where virtual cubes light up according to a musical sequence played and the user replicates the tune by occluding, with their hand, the colored cubes in the same sequence. Vidrios-Serrano et al. [21] used an HMD and a phantom Omni haptic device to touch virtual objects in the AR environment. For OST setups, Trojan et al. [22] took an non-haptic approach in developing a mirror training rehabilitation system suitable for home use. Luo et al. [23] used an HMD and a haptic glove for their AR hand opening rehabilitation setup. The glove was used to simulate holding a real object for their grasp-and-release task. For projection setups, Hondori et al. [5] created a non-haptic tabletop system for post-stroke hand rehabilitation which incorporated different games such as reaching projected box to play sounds, holding a mug to pour virtual water, and grasping various sized circles. Finally, Khademi et al. [24] implemented a spatial AR setup and used a haptic device for monitoring the impedance of a human arm. They also did a comparison of AR vs VR for a pick-and-place task [25].

1) Projection vs. Monitor Screen: Other works such as the SITAR [26] also incorporate a tabletop workspace that uses an LCD television to visually colocate the patient's interactions with the tasks. Alongside with intelligent objects, the system can sense and provide haptic feedback. Despite having the option to choose a similar setup, we opted for a projection-based setup for a few reasons. While an LCD screen would be completely blocked off by an object above it, projection can still be seen above the placed object. There are also multiple ways to compensate for occlusion as will be discussed later. Furthermore, projection can adapt to different projection surfaces as with the case with projection mapping. This provides more potential for future studies in 3D AR viewing and dynamic interaction.

Other technologies such as the Microsoft Hololens, Oculus Rift, or HTC Vive were not considered since these devices are HMDs. For some patients, wearing an HMD may induce a sense of entrapment or anxiety from being disconnected from the real world [27]. Some works used haptic gloves for their systems. While gloves are effective in controlling finger flexion, extension and providing haptic signals around the hand, our work revolves around upper limb arm movements, therefore a haptic device or robot is more appropriate.

In our system, spatial AR, and haptics are combined in a rehabilitation task. While the work of Khademi et al. [24], [25] provide similar investigations of performance between AR and VR, our focus lies in the use of cognitive loading to simulate similar cognitive behaviours (E.g. being distracted, inability to focus on one task) found in patients with reduced mental ability due to events such as stroke. It is understandable that this simulation may not fully capture the extent of damage a patient may experience from stroke, however, our aim is to determine if visual-haptic colocation is able to alleviate the negative effects of cognitive loading which can then be applied to actual patients in future discussions. By making the task easier for the patient to accomplish, the task success rate increases, thereby engaging the patient which results in a more effective rehabilitation.

III. REHABILITATION GAME DESIGN

Our aim is to set up a robot-assisted rehabilitation environment incorporating colocation of haptics and vision that would be both engaging and intuitive to use. With a 2D spatial AR system, we create an environment to perform reaching motions in which the end-effector of the rehabilitation robot needs to be manipulated by the user to push a digitally created car around a track. In order to create spatial AR, the image of the car and the track is updated in real-time and projected on the table supporting the robot. In this way, the haptic interaction between the users arm and the robot end-effector happens in the same space where visual feedback about this interaction in the virtual environment is provided.

The goal of the game is to traverse a certain length of the track as soon as possible. The car can only be pushed from the back and cannot be moved in reverse. It is also constrained from moving sideways relative to the track. Upon collision of the end-effector with the car, force feedback is sent to the user along the contact normal. The track loops around the workspace and is composed of a Bezier spline. Every lap around the track, its curves changes slightly to keep the user stimulated and engaged. Only a limited portion – around 10% – of the track past the front of the car is seen and this is updated in real-time. The track could allow for clockwise or counterclockwise movement depending on the user's preference. The task is built in the Unity Game Engine Environment [28] and therefore uses the default Unity physics. This allows the car to have a momentum when pushed, giving the user the impression of pushing a toy car.

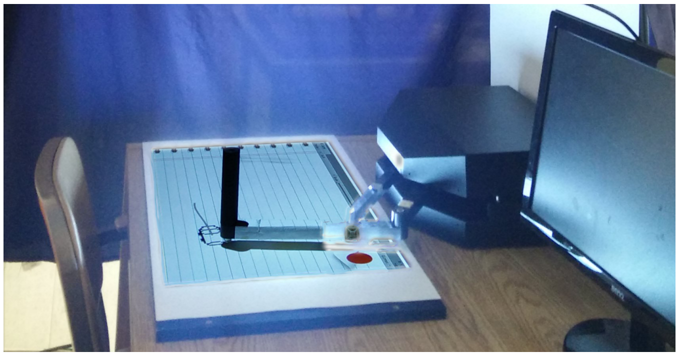

Fig. 1. Side view of the experimental setup. The projector (not seen in the image) projects the task onto the table.

A blinking red dot on the corner of the projection is used as a visual aid when cognitively loading the users. An arithmetic cognitive task is simultaneously performed with the haptic task. Commonly used in gait and postural research [29], an articulated backward counting (multiples of 3) is chosen as it has been shown to be effective in decreasing performance when combined with another task. The constant subtraction is mentally taxing in that it requires continued attention in keeping track of the counted numbers to count down properly [30]. The dot turns on and off at a frequency of 1 Hz. The user then audibly counts down (starting from a randomized number between 100 - 200) every time the red dot appears.

We provide a training period to allow the participants to familiarize themselves with manipulating the end-effector and interacting with the car. When force feedback is turned off, the task becomes easier due to the removed resistance while pushing the car. Therefore, to allow for a fair comparison between haptics and no-haptics cases while keeping the difficulty of both scenarios on the same level, we resist the robot's movement with a damping-based controller when there is no force feedback. The amount of damping force applied is the same as the force felt when pushing the car when haptics is present. Haptic feedback is provided along the contact normal by a force that increases at a rate of 1.5N/s to a maximum value of 3 N. This is done to reduce contact instability from a sudden jump in force feedback at the time of contact.

The evaluation of users performance is based on the time to traverse a fixed length of the track. For our user studies, we will be considering scenarios where force feedback, colocation of haptics and vision, and cognitive loading will be varied.

IV. EXPERIMENT

The task was tried on 10 healthy participants with age range between 23 - 31 (9 out of 10 participants were males). The participants performed the experiments with their dominant hand (all right-handed) and were all from the University of Alberta community. 6 participants had prior experience with haptic interfaces. Each participant was provided with verbal instructions and was given a maximum of 5 minutes to familiarize themselves with the task.

A. Experimental Setup & Challenges

Our setup consists of an off-the-shelf InFocus IN116A projector and a 2-DoF planar rehabilitation robot (Quanser, Inc., Markham, Ontario, Canada). The robot has a workspace of The projector is set directly above the projection space and the rehabilitation robot is positioned such that the end-effector can reach the majority of the projected area on a table. The task environment is created using the Unity Game Engine and the rehabilitation robot is controlled using MATLAB and Simulink. The experimental setup can be seen in Fig. 1.

The development of the setup involves two main challenges that needed to be mitigated.

1) Occlusion: Due to the nature of projection, occlusion can be a big issue. The user's shadow, as they move around the track, could block the user from viewing the car properly. Typically, occlusion can be handled by having a depth camera and calculating the projector and camera intrinsics to project the virtual images such that the scene looks integrated in the user's environment from their viewpoint [31]. However, for our paper, we do not intend to use the projection above the users hand as a part of the game so a depth camera is not needed. Instead, there are a few modifications added to the task to minimize the effect of occlusion. The size of the car is increased so as to make it harder to lose the car. The rehabilitation robot's arm is also wrapped in white paper for better projection results. The visible portion of the track protruding from the car also allows the user to navigate easier.

2) Calibration: The task environment comprises a circular avatar that interacts with the car in order to move it around the track. To properly implement colocation, this circle must be projected exactly on the end-effector's position as the end-effector spans the workspace. To calibrate, four points are projected in a rectangular formation to the workspace and the end-effector position is recorded for each of the projected points. The point-to-point correspondence is done with a 2D projective transformation (homography) between the robot frame (hand frame) and the virtual frame [32]. Another method considered was affine transformations. However affine transformations, a subset of projective transforms, preserve parallelism, length and angle. This would consequently amplify the errors if the end-effector placement on the projected points are inaccurate. On the other hand, projective transformations preserve only collinearity and incidence making it more general and can therefore compensate for any inaccuracies during calibration. Using the homography transformation H, each point-to-point correspondence i is mapped by the equation below:

$$\lambda p'_i = Hp_i \tag{1}$$

where λ is a scaling factor, p and p' consist of the x and y coordinates of a point in the robot frame and screen frame respectively. An expanded version is shown below:

$$\lambda \begin{bmatrix} x'_i \\ y'_i \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \tag{2}$$

When further expanded out as shown in the equations below, we can solve for x' and y' by dividing (3) and (4) by (5).

$$\lambda x' = h_{11}x + h_{12}y + h_{13} \tag{3}$$

$$\lambda y' = h_{21}x + h_{22}y + h_{23} \tag{4}$$

$$\lambda = h_{31}x + h_{32}y + h_{33} \tag{5}$$

$$x' = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \tag{6}$$

$$y' = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \tag{7}$$

We can rearrange (6) and (7) in linear terms of H

$$-h_{11}x - h_{12}y - h_{13} + h_{31}xx' + h_{32}yx' + h_{33}x' = 0 \tag{8}$$

$$-h_{21}x - h_{22}y - h_{23} + h_{31}xy' + h_{32}yy' + h_{33}y' = 0 \tag{9}$$

The above equations can then be written in matrix form:

$$\begin{bmatrix} a_x \\ a_y \end{bmatrix} H = 0 \tag{10}$$

$$a_x = \begin{bmatrix} -x & -y & -1 & 0 & 0 & 0 & xx' & yx' & x' \end{bmatrix} \tag{11}$$

$$a_y = \begin{bmatrix} 0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \end{bmatrix} \tag{12}$$

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{21} & h_{22} & h_{23} & h_{31} & h_{32} & h_{33} \end{bmatrix}^T \tag{13}$$

Since H is computed up to scale, we can impose a constraint $h_{33} = 1$. This makes the H matrix 8DOF. Each point provides 2 sets of equations, therefore a minimum of 4 points are required to get the homography transformation. Finally, we get an 8x9 matrix for A for which we use Singular Value Decomposition (SVD).

$$A = USV^T \tag{14}$$

U and V are 8x8 and 9x9 unitary matrices, respectively, and S is an 8x9 diagonal matrix whose elements are the singular values of A. The solution for H is then the last column of V, reconstructed into a 3x3 matrix. This allows the circular avatar to be aligned with the movements of the end-effector.

B. Procedure

A series of 8 different experimental conditions were presented to each participant. For each condition, the participant attempts to complete three laps around the track in the shortest time possible. The conditions defining each experimental trial involves a combination of the absence or presence of force feedback, colocation, and cognitive loading. The combinations of the task conditions are seen in Table II. The order of presenting different conditions to a participant are randomized to minimize learning.

The experiment starts with the participant sitting at arm's length from the rehabilitation robot with the projection area in between them on the table. The system is then calibrated for colocation. The participant is also given a trial run with VR and AR (without CL but with haptics) to get an initial experience of the task. The series of 8 conditions are then presented as discussed before. Condition 1 is hypothesized to be the easiest as it provides to the participant both haptics and AR but no CL. Condition 8 is predicted to be the hardest task as it removes haptics, provides only VR and imposes CL to the participant.

TABLE II

THE TABLE SHOWS THE CONDITIONS SET FOR EACH TASK. EACH SET OF CONDITIONS ARE LABELED NUMERICALLY. THESE CONDITIONS ARE PRESENTED TO THE PARTICIPANTS RANDOMLY TO REDUCE THE EFFECT OF LEARNING.

Task Performance Conditions			
		AR	VR
No CL	Haptic	1	2
	No Haptic	3	4
CL	Haptic	5	6
	No Haptic	7	8

TABLE III

TABLE OF MEAN AND STD OF THE TIME DURATION (SECONDS) RESULTS OF ALL 10 SUBJECTS FOR EACH OF THE 8 CONDITIONS.

Mean and Std in seconds of each set of conditions								
Cond. #	1	2	3	4	5	6	7	8
Mean	35.6	42.8	34.8	45.3	38.7	48.4	50.5	52.9
Std	6.0	7.3	9.0	12.6	5.0	6.2	12.8	13.7

Therefore, it is expected that the results between Conditions 1 and 8 would have the biggest gap in user performance. After the experiments are done, the participants are given a questionnaire regarding their experience. This is to provide a subjective measurement of how engaged the participants were in either AR or VR. Ethics approval was approved by the University of Alberta Research Ethics & Management Online under the study ID MS9_Pro00033955.

C. Results and Discussion

1) Duration Results: The participants were tested based on how fast they completed the trials. There is no penalty for missed counts during tasks with CL. The results are shown in Fig. 2. The mean and standard deviation of the results are reported in Table III. To find the effects of each category on user performance, a 3-way RM ANOVA is utilized using SPSS 25 [33]. The 3 main fixed effects factors, colocation, haptics, and cognitive loading each present two levels. A correction method is required due to multiple comparisons. Therefore, for our post hoc analysis, the Bonferroni correction is chosen to reduce Type I errors. The ANOVA results report a significance in colocation $F(1,9) = 8.773, p = 0.016$, marginally significant regarding haptics $F(1,9) = 4.648, p = 0.059$, and significant in cognitive loading $F(1,9) = 30.491, p = 0.000$

By conducting paired t-tests analysis with the Bonferroni correction only one notable pair is found statistically significant. In the simulated rehabilitation scenario when CL and haptics are present (Conditions 5 and 6), there is a significant difference in performance between AR and VR $(p = 0.0012)$.

Haptics play a minor part in user performance without CL. When haptics is on, the participants overshoot as they miss the car while pushing. Turning off haptics lets the participants have better control when they miss the car, resulting in less overshoot. Since there is no CL, the participants notice the overshoot quicker and can correct their mistake faster.

As expected, trials that had CL resulted in longer times overall compared to those without it. AR and haptics with CL gave the best user performance out of the other CL trials. The participants mentioned that during CL and AR, they relied on haptics to keep the end effector behind the car since they were distracted by the CL. In the same scenario but without haptics, the participants would often take a while before realizing they lost the car and therefore taking a longer time to readjust. Focusing on the results of Conditions 5 and 6, Fig.3 shows that the participants had similar counts of CL misses even though Condition 6 resulted in longer times. It can then be assumed that the CL experienced by the participants are within similar levels. This leaves colocation to be the only differing factor between the two tasks. Therefore while presence of haptics is mostly irrelevant in other scenarios, for those undergoing CL, and hence those with their mental capabilities affected by disability, visual-haptic colocation is a favourable option.

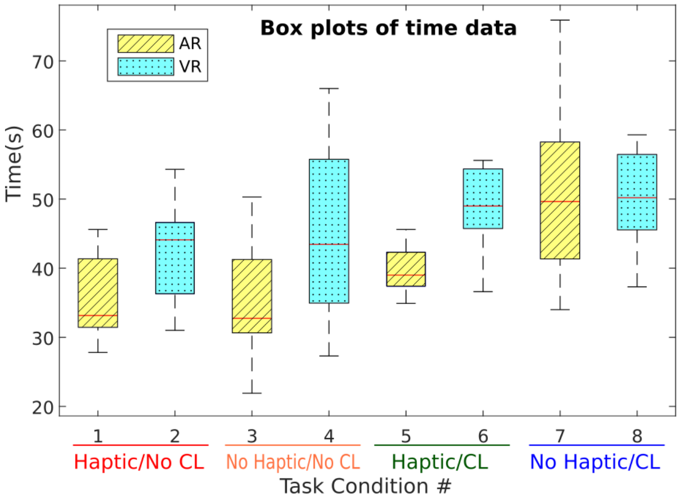

Fig. 2. Collective user performance of 10 participants on the 8 different experimental conditions. The line within the boxes represent the median time.

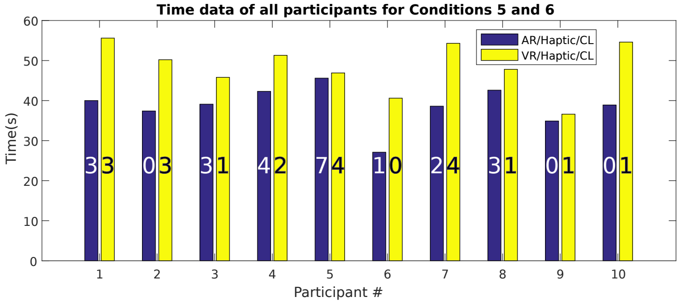

Fig. 3. Time it took for each participant to complete Conditions 5 and 6. The number within the graphs represent cognitive loading misses.

2) Spatial Results: At each time instance, the robot's end-effector should be within a certain range to ensure it is in contact with the car. This means that the distance between the car center (its axis of rotation) and the end-effector should be

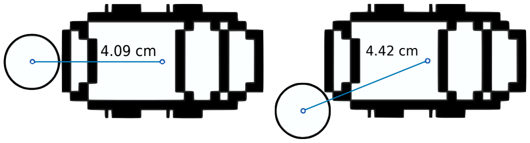

Fig. 4. Allowable distance between end-effector and center of the car.

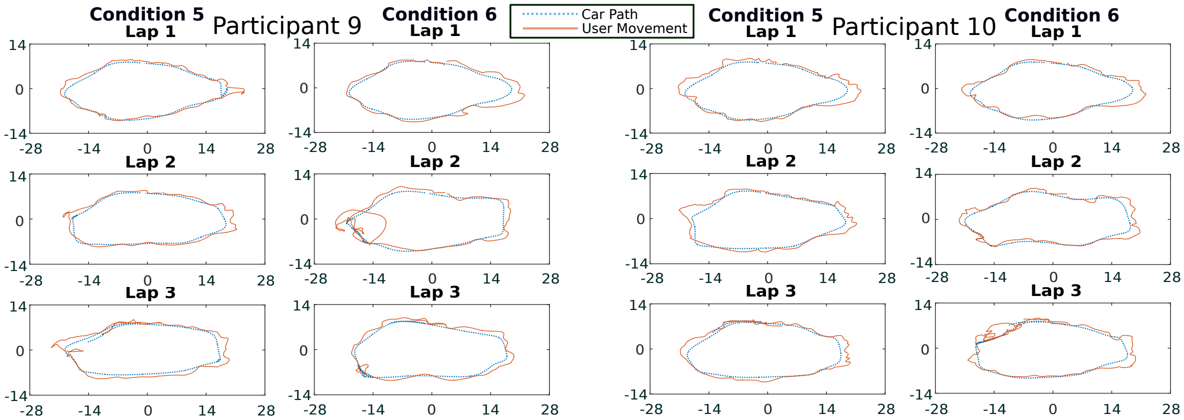

Fig. 5. Snapshot of end-effector movement of two participants for both Conditions 5 and 6. Units are in cm. Both participants moved in a counter-clockwise fashion.

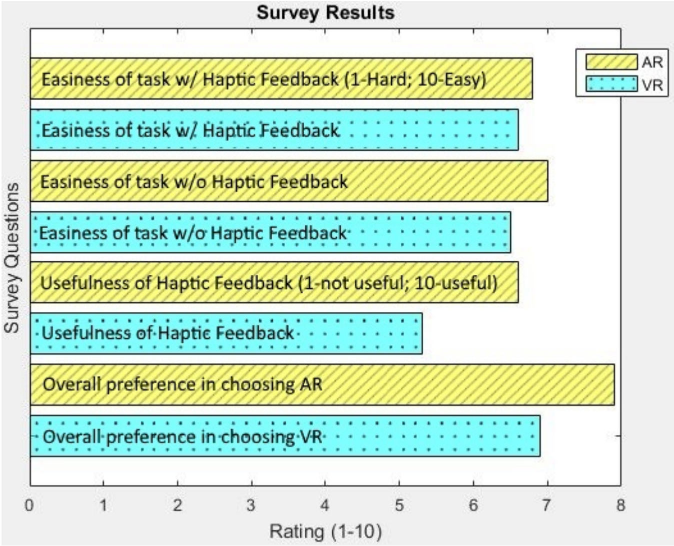

Fig. 6. Survey given to the participants after the experiments. A higher number is a better rating

between 4.09 cm and 4.42 cm as seen in Fig. 4. In Fig. 5 a sample of the car path and the user path for Conditions 5 and 6 is plotted for two participants. There is minimal direct overlap between the car path and user movement near the curved areas due to the distance as previously mentioned. This distance is taken into account for the error calculation. Taking a look at a snapshot of their performance between the two task conditions, we can observe the participants missing the car and overshooting in Condition 6 for lap 2 and lap 3 respectively. The euclidean distance between the car and end-effector is calculated at each time sample and is subtracted from or by the minimum or maximum threshold respectively, depending on if the distance is below the minimum, or above the maximum. For participant 9, the average error for Conditions 5 and 6 is 0.52 cm and 0.97 cm, respectively. For participant 10 it is 0.09 cm and 0.61 cm, respectively. These further support the results found in Fig. 2 for the increased user performance when there is visual-haptic colocation during CL.

3) Survey Results: In the survey given after the experiments the participants were asked to rate their experiences in a 1-10 scale. The type of questions asked are shown in the survey results in Fig. 6. Likely due to the overshoot found in haptics, the easiness of the task in AR and without haptic feedback is rated slightly higher. Most of the participants however, rated haptic feedback to be more useful than without. This is reflected on the time results of Fig. 2 between task Conditions 5 and 7. The survey also shows that in all cases, AR was rated higher than VR, leading to AR being the preferred technology. A 5-point Likert scale is also included regarding the participants' experience when CL is present. This is used to match the task results with the perceived difficulty of the CL tasks. Specifically, in the range {-2, -1, 0, 1, 2} the participants are asked if CL made the task much easier (-2) or much harder (2). The resulting average is 1, indicating that participants thought CL made the task somewhat harder as can be seen with the increasing trend in time duration in the Fig. 2 results.

V. CONCLUSION

We present a comparison of the effects between colocated and non-colocated visual feedback when used in a rehabilitation environment. Visual feedback comes either in the form of spatial AR for visual-haptic colocation or non-immersive VR for visual-haptic non-colocation. The two are compared by measuring the performance of 10 healthy participants in a trajectory following task. To better simulate those with cognitive deficiencies, the participants are subjected to cognitive loading while performing the task. It is observed from the results that the effect of visual-haptic colocation improves the task performance, especially for those undergoing cognitive loading. For our future work, we plan to let patients with disability use the system and we will analyze the corresponding data. Other considerations would be to include an assist-as-needed [34] functionality to help patients struggling with the task or to implement AR with a Learning from Demonstration [35], [36] framework to improve adaptability to different scenarios.

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