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Understanding Human-Robot Interaction in Virtual Reality

Oliver Liu, Daniel Rakita, Bilge Mutlu, and Michael Gleicher

***Abstract*— Interactions with simulated robots are typically presented on screens. Virtual reality (VR) offers an attractive alternative as it provides visual cues that are more similar to the real world. In this paper, we explore how virtual reality mediates human-robot interactions through two user studies. The first study shows that in situations where perception of the robot is challenging, a VR display provides significantly improved performance on a collaborative task. The second study shows that this improved performance is primarily due to stereo cues. Together, the findings of these studies suggest that VR displays can offer users unique perceptual benefits in simulated robotics applications.**

I. Introduction

Many applications involve users interacting with simulated robots. For example, robotic-surgery training, remote manipulation interfaces, manufacturing training exercises, and human-robot interaction studies are often run on screen in a simulated environment to afford a safe and low-cost human-robot interaction experience. Virtual reality (VR) is an attractive alternative for interacting with simulated robots because it affords a more immersive experience by better creating visual cues of real environments. However, how virtual reality compares to an on-screen interface for robotics tasks and whether or not there is a difference between the two viewing modalities under certain conditions are still unknown.

In this work, we compare virtual reality and on-screen viewing to assess how VR affects simulated human-robot interactions. Specifically, we aim to understand if VR makes a difference in simulation and, if so, which aspects of VR contribute to this difference. Through two user studies, outlined in Section IV and Section V, we show that virtual reality does improve performance over on-screen under certain task conditions, and we show which VR features influence those differences. Our studies use a simulated collaborative task from prior work [1] that affords an objective task metric, allowing us to compare the perceptual outcomes of VR and on-screen viewing. Prior work using this task replicated results obtained from in-person studies with a physical robot in on-screen studies with a simulated robot. However, these results were obtained in a situation where the viewing task did not involve perceptual challenges and thus did not benefit from the improved depth cues provided by the real robot or VR. In Study 1, we confirm that VR offers no advantage in this simple viewing condition but also show that it does offer an advantage in a more challenging viewing condition. In Study 2, we show that stereo viewing available in VR, not parallax due to head movement, is the cause of this advantage. Together, our studies suggest a role for VR in robot simulation, especially in situations where the improved visual cues are useful in the task.

O. Liu, D. Rakita, B. Mutlu, and M. Gleicher are with the Department of Computer Sciences, University of Wisconsin–Madison, 1210 West Dayton Street, Madison, WI 53706, USA, dliu62@wisc.edu, rakita@cs.wisc.edu, bilge@cs.wisc.edu, gleicher@cs.wisc.edu. This work was supported by National Science Foundation Award #1208632.

Fig. 1. In this work, we are assessing how virtual reality compares to an on-screen condition in a human-robot collaboration task. Here, a user is seen interacting with the simulated robot in our study task using the Oculus Rift VR headset.

II. Related Work

A. VR in Robotics

Prior work in robotics includes various explorations of the value of VR for robot simulation. Burdea [2] provides a survey of the applications of VR in robotics. Tang and Yamada [3] developed a robotics system for a construction robot using virtual reality. They then conducted experiments which confirmed that their method was superior in operability, safety and reduction of stress than the conventional visual display. Belousov et al. [4] created a virtual control environment for robot teleoperation via internet. Having the working environment of the robot and the robot itself displayed in a dynamic, 3D virtual environment instead of the physical environment allowed suppressed time delay inherent in IP networks and accelerated work efficiency for the operator. Safaric et al. [5] developed a training system involving usage of virtual robots to provide an inexpensive and safe method for enterprises to train their employees. They then conducted experiments and confirmed the method to be viable, cheap and efficient. Kawasaki et al. [6] proposed a virtual robot teaching method based on hand manipulability for multi-fingered robots, and demonstrated its effectiveness through a pick-and-place experiment. Our work further supports the value of VR by showing that VR provides task advantages over on-screen in certain human-robot collaboration tasks. We also assess the contribution of individual VR components to these advantages.

B. Physical vs. Simulated HRI

While in person studies with a real robot may have advantages [7], the use of simulation has proven to be a valid platform for some robot studies [1], [8], [9]. Other studies have shown differences between on-screen robots and real ones for human robot interaction. For example, Bainbridge et al. [10] suggest that the participants are more willing to fulfill an unusual request and to afford greater personal space with a physical interaction with a robot than an on-screen presentation. Seo et al. [11] showed that people may empathize more with a physical robot than a simulated one. Wainer et al. [12] demonstrated that participants saw embodied robots as more helpful, watchful and enjoyable compared to a remote or the simulated robot in a coaching scenario. While these studies suggest advantages to real robots over on-screen ones, they do not assess VR presentations of robots that can provide cues more similar to the physical condition.

C. Perception in VR

Attempts to quantify the benefits of VR over other viewing techniques began with the work of Pausch et al. [13] who measured the advantages of VR for a visual search task. Later work continued to quantify benefits of VR. For example, Barfield et al. [14] investigated performance in a desktop virtual environment as a function of stereopsis, i.e., depth perception, and head tracking, showing that the use of head tracking significantly improved task accuracy, while the use of stereopsis had a tendency to improve it. The study of Kulshreshth and LaViola [15] investigated user performance benefits of using head tracking in modern video games. Their findings indicate that head tracking provides a significant performance benefit for expert gamers. There are many other studies which support the benefits of these VR functionalities, such as the study of Ragan et al. [16] on small-scale spatial judgments, where they separately tested the effect of the three functionalities by toggling them on and off and found all three of them bringing significant advantages in spatial judgment tasks. Our work extends the prior work by exploring the role of VR for simulated human-robot collaborations.

The early work of Pausch et al. [13] also established the paradigm of simulating reduced display environments within VR as a mechanism to reduce experimental confounds. The work of Slater et al. [17] extended and validated this paradigm. We make use of this strategy in our studies, simulating the on-screen condition within VR to reduce confounds, as described in Section III-B.

III. Overview of Studies

The two studies presented here followed the same high-level study design. We describe the shared elements here and the specific details of each study in subsequent sections.

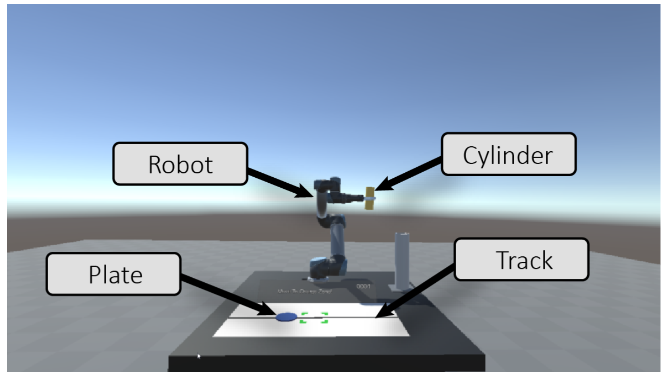

Fig. 2. In our studies, the task involves the participants moving the circular plate on the linear track to the position just under where the robot is about to place the cylinder. The participants are asked to make this prediction as early as possible and continually update their guess throughout the motion. We evaluate user performance based on our task manipulations.

A. Study Design

Both studies followed a 2 $\times$ 2 within-subjects design. The independent variables for Study 1 included viewing direction and whether VR was enabled. In Study 2, we manipulated whether stereo and head tracking were enabled. In all conditions, participants viewed the simulation on an Oculus Rift[1] DK2 VR headset. The "non-VR" condition was simulated by disabling head tracking and stereo viewing in the VR headset. This strategy of simulating simpler viewing conditions within VR has been established in prior work (e.g., in work by Pausch et al. [13] and Slater et al. [17]) and offers a number of advantages over using a different display (e.g., a regular monitor for "on-screen" conditions). First, it controls for a number of factors such as resolution and field of view. Even the inability of a VR participant to see their hands can cause differences in their use of the input device. Second, it avoids any preconceived advantages that participants may expect, such as hearing that "VR is better." Third, it allows us to create a range of viewing conditions by enabling and disabling features independently, which will enable the experiment of Study 2 to identify which features of VR contribute to performance differences.

B. Study Task

Participants in both studies interacted with a simulated robot performing a collaborative task, shown in Figures 2, 3, and 4. In the task, the robot picks up a sequence of cylinders one at a time and places them anywhere on a linear track. The user must move a plate along the track using the mouse so that the plate is under the cylinder as the robot sets it down. Participants are told to continually make their best guess while the robot is moving, such that the speed and accuracy with which they place the plate at the goal position serves as a measure of task performance.

Each prediction the participant makes is associated with a "score" metric. This score is calculated by dividing the arc length of the whole robot motion by the arc length of

[1]Oculus Rift: https://www.oculus.com/rift/

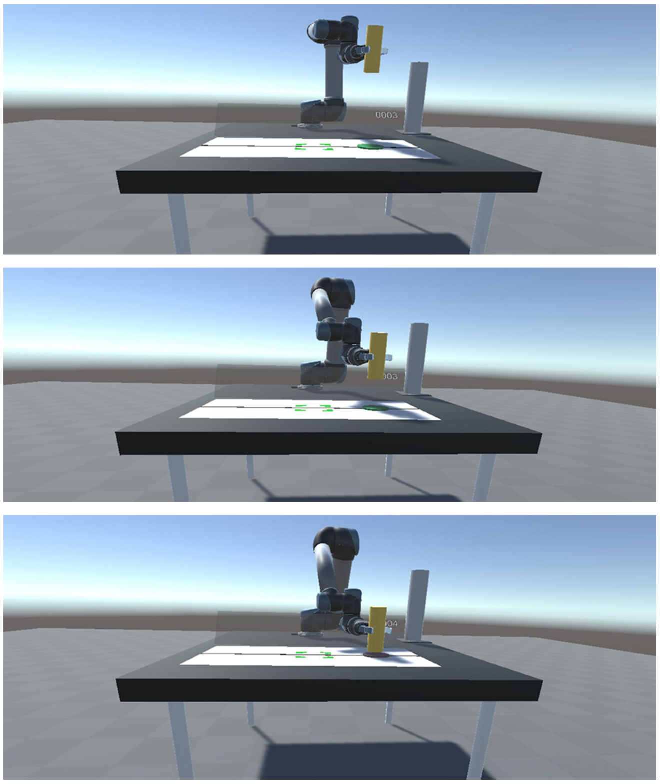

Fig. 3. The task in our studies involves the participant inferring as soon as possible where the robot will place a cylinder on a linear track. The three images here (from top to bottom) depicts the robot placing a single cylinder on the track. Our studies evaluate user performance on this task depending on the user's viewing condition and the configuration of the track.

the partial trajectory the robot has traversed at the time the participant first reaches the goal position. A 3 cm error (approximately the radius of the cylinder) on both sides of the goal is allowed. In addition, a prediction will be registered only if the plate is still for at least 0.2 seconds. This requirement prevents the goal from being registered if the user is simply passing through the goal en route to an incorrect prediction. This score metric establishes a proportional relationship between the score of a prediction and its timeliness and accuracy, thus providing a fair reflection of the participant's perception ability in the task condition.

This experimental task was originally introduced by Bodden et al. [1] as a way to assess how well participants could predict a robot's movements for various robot designs and movement synthesis algorithms. In our studies, the same robot (a simulated Universal Robots UR5) and same movement synthesis strategy is used in all conditions. Conditions vary aspects of viewing, either changing the viewpoint or the VR features.

C. Study Procedure

The participants sat at a table where the VR headset was set up (a picture of our experimental setup can be seen in Figure 1). After providing consent, the experimenter administered a standard TNO stereo blindness test [18] to ensure all participants had good stereo vision. The TNO test involved participants looking at three pictures while wearing a pair of red-blue glasses. Each picture contained figures which can only be seen when both eyes cooperate to give stereoscopic vision. The experimenter asked the participants a set of questions to see if they could see the hidden figures. Two participants were excluded for failing the test. To familiarize participants with VR viewing, they were then asked to watch a standard virtual reality demonstration[2] and to turn and look around as well as to lean their upper body in different directions.

After VR familiarization, the participants started the four study sets. Each study set consisted of training trials to familiarize the users with the new task condition, followed by the actual study trials. The training trials consisted of test motions from the current task condition. Sets 2–4 contained three training motions, while the first study set consisted of five training trials to allow for additional practice.

Each participant performed the tasks in the four conditions of the study. The conditions were blocked and presented in a random order. Each condition consisted of 12 trials sampled from positions along the track. The order of the trials within each block was randomized. Between each condition, participants were asked to remove the headset and complete a questionnaire. At the end of the four conditions, the participant was asked to fill out a demographic questionnaire.

D. Participants

For both studies, participants were recruited from the University of Wisconsin–Madison campus community by a posting on an electronic jobs bulletin board. The study took approximately 45 minutes. Participants received \$8 USD for their time. Participant demographics for each study are detailed separately in the following sections.

IV. Study 1: VR vs. On-screen Viewing

Our first study aimed to assess the impact of VR in robotic tasks by testing the differences between VR-based and on-screen interactions in a human-robot collaboration task.

A. Study Design

The study followed the common 2×2 within-participants design described in Section III. The independent variables included *viewing condition* (virtual reality vs. on-screen) and *track configuration* (horizontal vs. vertical).

The *track configuration* manipulation varies the orientation at which the user views the track in order to provide an understanding of whether or not the effects viewing condition has in the collaboration task is related to task conditions. For instance, if the track runs toward and away from the user (which we call the "vertical" track configuration), the task involves sensing the depth of the robot's motion in order to accurately place the plate under the goal position on the track. In this track configuration, we would expect the extra features afforded by VR to help infer the goal position, thus correlating to improved task performance. However, if the track runs left to right with respect to the user (which we

[2] Oculus Rift Dreamdeck: https://www.oculus.com/experiences/rift/

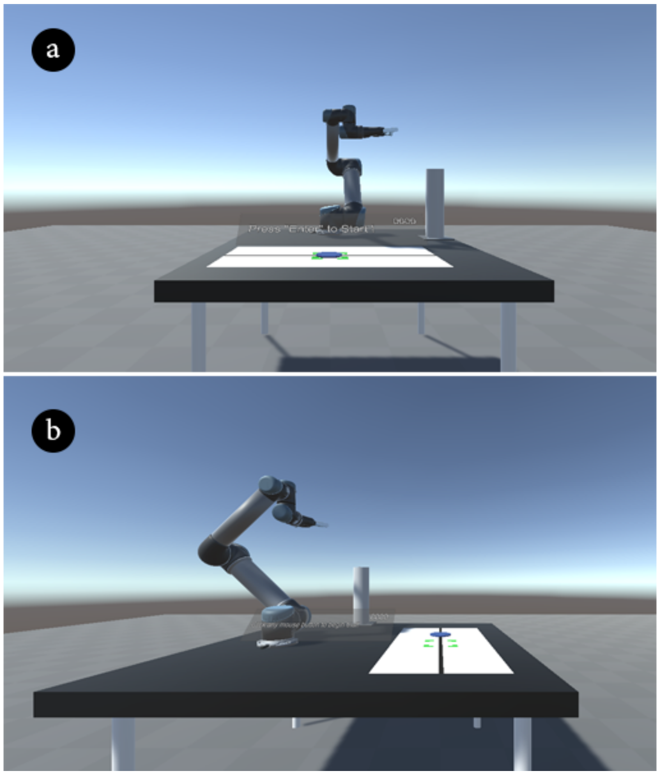

Fig. 4. In this study, we manipulate the track configuration to test the effects virtual reality has under different task conditions. (a) The "horizontal" track runs from left to right, and (b) the "vertical" track runs toward and away from the user.

call the "horizontal" track configuration), there is less depth sensing required from the user as all goal points on the linear track are equidistant from the user's frame of view. In this condition, we would expect the on-screen condition to perform similarly to VR as the extra features may not provide as many benefits. The two track configurations used in the study can be seen in Figure 4.

The *viewing condition* variable manipulates how the user sees the simulated environment. In the "virtual reality" condition, the user experienced the interaction using the full set of VR features, including stereopsis and head tracking. The "on-screen" condition, as explained in Section III, was approximated in the virtual reality environment by turning off the stereopsis and head tracking features. These manipulations are meant to assess if VR and on-screen have differing user performance under different task conditions.

B. Hypotheses

We developed two hypotheses based on prior work, particularly findings by Bodden et al. [1] that on-screen presentation of the robot provides similar results to a real robot in cases where the perception of the robot was easy.

H1. In the vertical track scenario, on-screen viewing will reduce participant performance compared to VR viewing. This prediction is based on the expectation that the vertical track scenario will require depth sensing, with which we expect VR features to help.

H2. In the horizontal track scenario, there will be no performance differences between on-screen and VR viewing. The basis of this hypothesis is the expectation that the horizontal track scenario will not present particular viewing challenges, such as depth sensing, and that the experience between the two conditions will be similar.

C. Participants

We recruited 26 participants, two of which were excluded from the study for stereo blindness, yielding 24 tested participants (14 male, 10 female). Participant ages averaged 21.78 ($SD = 5.90$).

D. Results

All descriptive and inferential statistics for data from Study 1 are shown in Figures 5 and 6 and are excluded from text to improve readability. Participant data was analyzed using a two-way repeated measures analysis of variance (ANOVA). All pairwise comparisons were made using Tukey's HSD Post Hoc tests. There was a significant interaction effect between the two independent variables, track configuration and viewing condition. H1 predicted that using on-screen viewing would reduce participant performance in the vertical track scenario compared to VR viewing. Our results support H1, as participants scored worse in the on-screen condition compared to the VR condition on the vertical track condition. H2 predicted that there would be no differences between on-screen and VR viewing in the horizontal track scenario. Our results also support H2; in the horizontal track scenario, performance scores between on-screen and VR were equivalent based on an equivalence margin of $p > .50$, following guidelines suggested by Walker and Nowacki [19].

E. Discussion

The results of Study 1 support our hypotheses and indicate that virtual reality does present a difference in a robot interaction task when such a difference would be expected.

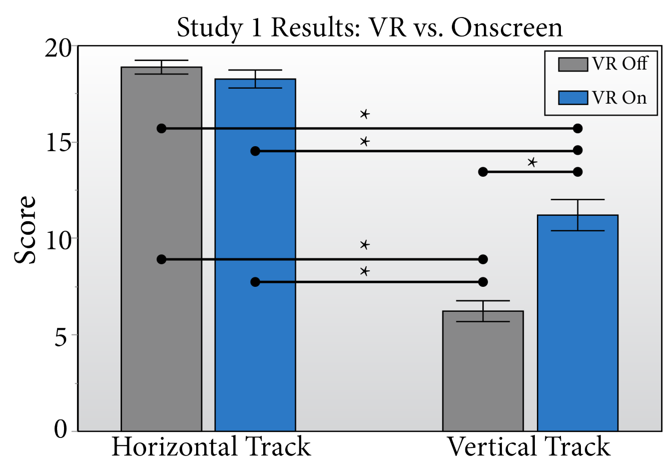

Fig. 5. Results from our first user study evaluating the effect VR has on task scenarios compared to an on-screen condition. *Error bars represent standard error. * denotes pairwise comparison* $p < .0001$.

Track configuration	Horizontal		Vertical	
Viewing condition	**VR On**	**VR Off**	**VR On**	**VR Off**
Mean	18.27	18.88	11.21	6.23
St Dev	2.24	1.71	3.67	2.59

Variables	DF	R^2	f	p
Track config. × viewing	1	0.911	42.48	$< .0001$

TC	VR		TC	VR	p
Horizontal	*Off*	*vs.*	*Vertical*	*Off*	$< .0001$
Horizontal	*On*	*vs.*	*Vertical*	*Off*	$< .0001$
Horizontal	*Off*	*vs.*	*Vertical*	*On*	$< .0001$
Horizontal	*On*	*vs.*	*Vertical*	*On*	$< .0001$
Vertical	*On*	*vs.*	*Vertical*	*Off*	$< .0001$
Horizontal	*Off*	*vs.*	*Horizontal*	*On*	$= .71$

Fig. 6. Descriptive statistics (top), inferential statistics (middle), and pairwise comparisons (bottom) from Study 1.

For instance, when depth cues are not an important part of the task, e.g., when the linear track is horizontal with respect to the user, the virtual reality features of stereopsis and head tracking do not improve performance. However, when depth cues are an integral part of the task, such as when the linear track is in a configuration that runs toward and away from the user, the tested virtual reality features improve performance compared to when these features were not present in the on-screen condition.

We note that the decreased scores when the track is configured vertically cannot be attributed to any ambiguity in the robot's motion as the trajectory synthesis method was controlled between the horizontal and vertical conditions. Both conditions consisted of evenly spaced, straight-line interpolated paths in joint angle space.

These results not only indicates that virtual reality can provide task benefits in certain scenarios, but the effects found are task dependent. Thus, when considering using either an on-screen interface or virtual reality for a robot interaction task, it is worth considering the task at hand and assessing whether virtual reality may offer benefits in such a situation.

V. Study 2: Effects of individual VR components

Our second study assessed the individual impact of VR features (head tracking and stereopsis) on user performance. In this section, we outline our experimental setup and results.

A. Study Design

This study also followed a 2 × 2 (*stereopsis*: on vs. off; *head tracking*: on vs. off) within-participants design. These manipulations were chosen to include key VR features that we expected to have a significant perceptual impact.

Stereopsis determined whether or not the user could see separate images from each eye using the VR headset. When stereopsis was off, the user saw the scene using monoscopic vision, which we administered using the monoscopic option provided by the Oculus SDK.

Head tracking determined whether the virtual camera moved in the scene along with the user's head motion. When head tracking was turned off, the user's view was set to be at a static position in space. This static camera configuration was pre-set to ensure consistency between participants as well as a consistently clear view of the track. When both stereopsis and head tracking were turned off, participants experienced the on-screen condition from Study 1.

B. Hypotheses

H1. Participants will perform better with both stereopsis and head tracking turned on than both stereopsis and head tracking turned off and only head tracking or stereopsis is present. This prediction is based on our speculation that both stereopsis and head tracking contribute to task performance.

H2. Participants will perform better with only head tracking or stereopsis than both stereopsis and head tracking turned off. We believe that having one form of depth cue will be better than having none.

C. Study Task and Procedure

The study task and procedure for our second study was similar to the first. The track in this study was always in the "vertical" configuration (as seen in the bottom of Figure 4). We used this track configuration to measure the contribution of different VR features because Study 1 showed that only this vertical case caused significant differences between VR and on-screen conditions.

We also changed the stereo-blindness test in the second study. We prepared a scene in the VR headset consisting of a segmented picture, where certain pieces were placed closer or further from the user's point of view. The participant viewed the segmented picture from a straight on viewing direction and was asked to identify which pieces were closer to him/her. This setup allowed us to specifically check for stereo-blindness in the VR environment rather than relying on red-blue glasses, which can also be affected by color acuity.

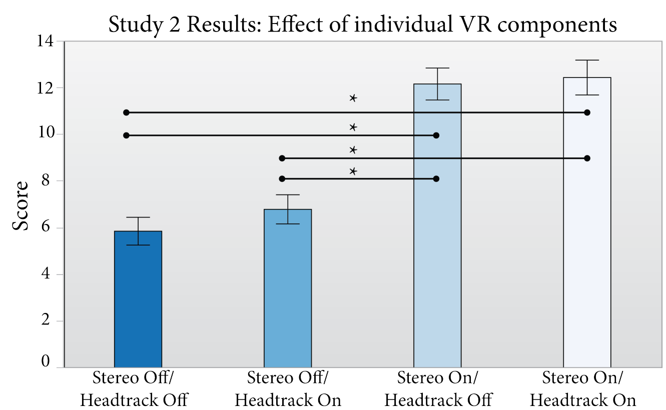

Fig. 7. Results from our second user study evaluating the relative effect of VR features on user performance. *Error bars represent standard error. * denotes pairwise comparison* $p < .0001$.

Stereopsis	**On**		**Off**	
Head tracking	**On**	**Off**	**On**	**Off**
Mean	12.44	12.16	6.79	5.85
St Dev	3.65	3.35	3.67	2.59

Variables	**DF**	**R^2**	**f**	**p**
Stereo. × head tracking	1	0.705	0.373	= .547

Stereo	**HT**		**Stereo**	**HT**	**p**
On	*On*	*vs.*	*Off*	*Off*	< .0001
On	*Off*	*vs.*	*Off*	*Off*	< .0001
On	*On*	*vs.*	*Off*	*On*	< .0001
On	*Off*	*vs.*	*Off*	*On*	< .0001
Off	*On*	*vs.*	*Off*	*Off*	= .580
On	*On*	*vs.*	*On*	*Off*	= .981

Fig. 8. Descriptive statistics (top), inferential statistics (middle), and pairwise comparisons (bottom) from Study 2.

D. Participants

We recruited 24 participants in total (14 male, 10 female). Participant ages averaged 20.82 ($SD = 2.25$). Participants were tested for stereo-blindness prior to running the study, and using this criterion, no participants were excluded.

E. Results

All descriptive and inferential statistics on the data from Study 2 can be seen in Figures 7 and 8. Participant data was analyzed in the same manner as Study 1, using a two-way repeated measures analysis of variance (ANOVA), and all pairwise comparisons involved Tukey's HSD Post Hoc tests. We did not observe any interaction effects in Study 2. H1 predicted that both stereopsis and head tracking turned on would lead to better performance than all other conditions. Our results partially support H1; participants performed better when both stereopsis and head tracking were turned on over head tracking turned on and stereopsis off and both turned off, but not better than stereopsis on and head tracking off. H2 predicted that participants would perform better with either head tracking or stereopsis turned on over both turned off. Our results also partially support H2; participants performed better when stereopsis was turned on and head tracking was off over both off, but head tracking on / stereopsis off did not outperform both off.

F. Discussion

The results of Study 2 show that, for this task, VR display leads to significantly different task performance, and that most of this difference can be attributed to the presence of stereo display. The implication of this finding is that, for at least some human robot interactions, stereo cues are important. Recent literature in perceptual science suggests that stereo cues are useful even at long distances [20].

Our hypothesis that head tracking would be helpful was not supported; head-movement parallax provided only a marginal difference. This result is consistent with the results obtained by Barfield et al. [14] that stereo has a much stronger effect on task performance than head-tracking cues do.

VI. Limitations and Future Work

Our studies show that virtual reality viewing can have a significant effect on how robots are perceived in a human-robot interaction task, and that in at least one case, this difference can be attributed to the existence of stereo cues. Our results also suggest that VR is different than on-screen viewing. We have not considered whether it is more similar to being physically present with the robot. While both the real robot and VR provide more depth cues (e.g., stereo and head motion parallax) than a standard on-screen presentation, it is possible that VR viewing exaggerates these cues [21], [22].

The studies presented here focused on the advantages of VR for depth perception in a collaborative task where perception is a critical factor. For other tasks, clear perception of the robot may not be as important. Conversely, it is possible that VR viewing offers advantages beyond providing depth perception, and that these advantages mitigate some of the observed differences between on-screen and in-person human robot interaction (as described in Section II).

We considered a specific collaborative task with specific short term outcomes. While we believe that the importance of perception transfers to other scenarios, such as remote tele-operation, it is possible that the immersive experience afforded by VR is closer to true interactions with a real robot and that training, experiments, or interactions in VR more reliably transfer to skills with the real robot. Understanding if VR is a better way to bridge the gap between simulated and real robot interactions is left as exciting future work.

Our results provide an *ad hoc* guideline; VR viewing (or at least stereo) makes a difference in situations where depth perception of the robot and its movements is important. In the future, we would like to better quantify the situations where these benefits occur to better inform when different viewing strategies are appropriate.

Visual simulation is important in a number of robotics applications, such as prototyping and studying human-robot interactions and training users for situations where direct experience is impractical. In our studies, we have shown that the way such simulations are viewed can have a significant effect. Specifically, in a collaborative human-robot interaction task, virtual reality displays can yield better performance in certain situations, and the majority of this effect is due to providing stereo viewing cues. These results suggest that the type of display should be considered in robot simulations and that VR displays may offer a way to mitigate some of the known issues in using visual simulation for robotics applications.

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