Investigating the Detection of Bimanual Haptic Retargeting in Virtual Reality

Eric J. Gonzalez
Stanford University
Stanford, USA
ejgonz@stanford.edu

Sean Follmer
Stanford University
Stanford, USA
sfollmer@stanford.edu

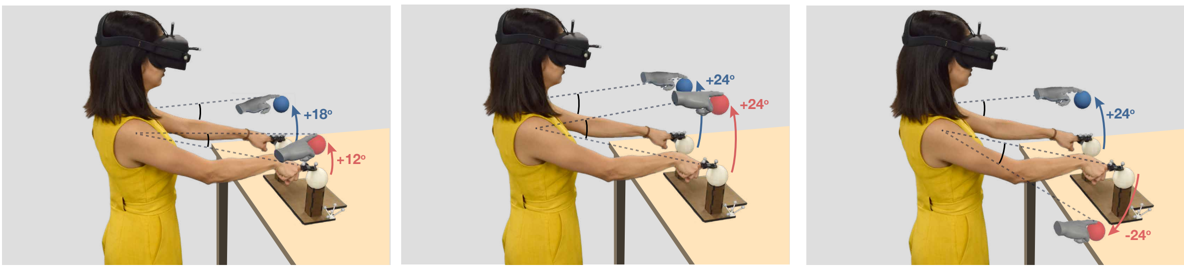

Figure 1: A user touches two spheres in virtual reality with three examples of bimanual haptic retargeting. The virtual hands (grey) and spheres (red and blue) are offset sagittally about the shoulder from a physical proxy by the angles shown.

ABSTRACT

Haptic retargeting is a virtual reality (VR) interaction technique enabling virtual objects to be "remapped" to different haptic proxies by offsetting the user's virtual hand from their physical hand. While researchers have investigated single-hand retargeting, the effects of bimanual interaction in the context of haptic retargeting have been less explored. In this study, we present an evaluation of perceptual detection rates for bimanual haptic retargeting in VR. We tested 64 combinations of simultaneous left- and right-hand retargeting ranging from -24° to $+24^\circ$ offsets and found that bimanual retargeting can be more noticeable to users when the hands are redirected in different directions as opposed to the same direction.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

KEYWORDS

Haptic retargeting, bimanual, visuo-haptic illusion, virtual reality.

ACM Reference Format:

Eric J. Gonzalez and Sean Follmer. 2019. Investigating the Detection of Bimanual Haptic Retargeting in Virtual Reality. In *25th ACM Symposium on Virtual Reality Software and Technology (VRST '19), November 12–15, 2019, Parramatta, NSW, Australia.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3359996.3364248

VRST '19, November 12–15, 2019, Parramatta, NSW, Australia

ACM ISBN 978-1-4503-7001-1/19/11...$15.00
https://doi.org/10.1145/3359996.3364248

1 INTRODUCTION

Virtual Reality (VR) affords users the opportunity to immerse themselves in new environments that can differ greatly from their own. Beyond audiovisuals, however, physical feedback through haptics is needed to create a truly immersive experience [Hoffman 1998].

One way to address this is through the use of *active* haptic devices, which use robotic elements to provide force feedback [Massie et al. 1994] or modify their shape [McNeely 1993; Siu et al. 2018]. This allows for rich physical feedback, but introduces new challenges such as increased cost and computational complexity.

A parallel approach has been to explore the use of passive props, or *haptic proxies*, to physically embody spatially-aligned virtual objects in VR [Insko 2001; Simeone et al. 2015; Stoakley et al. 1995]. This approach is simple and low-cost, but on its own is inherently inflexible as proxies are limited to representing a single object of similar shape and location. It also quickly becomes inefficient, as larger-scale interactions would require complex arrangements of proxies specific to each virtual environment.

To address this, more recently researchers have looked at leveraging *visual dominance* – the tendency for vision to dominate sensory conflicts [Gibson 1933] – to extend the perceived properties of passive props. Techniques such as haptic retargeting [Azmandian et al. 2016] and redirection [Kohli 2013] introduce offsets between the user's physical and virtual hand to modify the perceived position [Cheng et al. 2017], orientation [Kohli 2010], or shape [Abtahi and Follmer 2018; Zhao and Follmer 2018] of passive props, such that they can be repurposed within the same virtual environment.

While these techniques have been well-investigated for single-hand interactions [Azmandian et al. 2016; Burns et al. 2005; Cheng et al. 2017; Han et al. 2018; Kohli 2013; Zenner and Krüger 2019], retargeted interactions with both hands have been less explored. Since bimanual actions are often a core part of one's interactions with the physical world [Kantak et al. 2017], enabling easier manipulation of objects and tools, retargeting techniques aimed at making

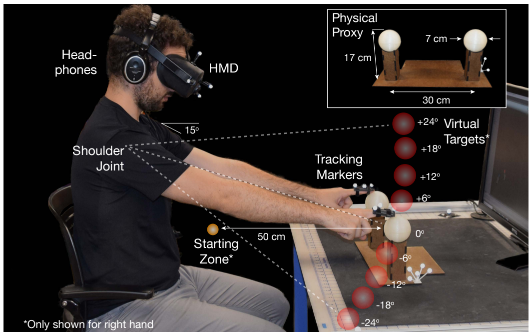

Figure 2: Experimental setup. All possible virtual targets shown for right hand, offset sagittally about the shoulder.

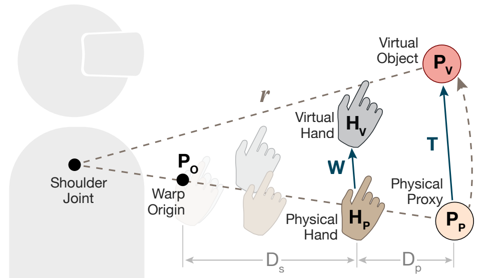

Figure 3: Diagram of single-hand haptic retargeting. The user's arm length is given by r, and the angular retargeting offset is given by α.

the virtual world more immersive should ultimately support bimanual interaction. Research has shown that visual feedback continues to play an important role in bimanual movements [de Oliveira and Barthélémy 2005; Diedrichsen et al. 2004; Neely et al. 2005], suggesting haptic retargeting may be effective in redirecting of both hands simultaneously. However, it is unclear how the additional visuo-proprioceptive cues afforded by the user's second hand affects their perception of retargeting. Matthews et al. reported minimal differences in perceived manipulation between unimanual and bimanual retargeting in the context of two-handed interfaces [Matthews et al. 2019], but the perceptual effects of retargeting during general bimanual reach remain less explored.

In this study, we present an evaluation of perceptual detection rates for bimanual haptic retargeting during two-handed reach in VR. We tested 8 angular offsets per hand ($-24°$, $-18°$, $-12°$, $-6°$, $+6°$, $+12°$, $+18°$, $+24°$ measured about the shoulder in the sagittal plane) during simultaneous reach, for a total of 64 bimanual combinations. Comparing detection rates across all combinations, our results reveal significant interaction effects between left- and right-hand offset on the detection of bimanual retargeting. Furthermore, retargeting both hands equally in opposite directions (e.g., Figure 1, Right) yielded lower detection thresholds than equal magnitude same-direction retargeting (e.g., Figure 1, Middle).

2 METHODOLOGY

2.1 Overview

We conducted an experiment investigating the effects of both simultaneous and individual left- and right-hand redirection on the detection of haptic retargeting. Participants reached to a pair of virtual targets embodied by a static physical proxy. Each target was rotationally offset from the proxy in the sagittal (vertical) plane, about the participant's shoulder, by one of 8 angles ranging from $-24°$ to $+24°$ (see Figure 2). Each bimanual trial consisted of a two-handed reach, where each hand was independently retargeted based on one of the above offsets. We also tested unimanual reaches using the left and right hands individually at the same retargeting offsets. Following the method of constant stimuli [Simpson 1988], participants experienced each of the $(8\times8)+8+8 = 80$ randomized conditions over multiple trials and stated whether they detected any offset on either hand. The results provide insight into how both the *absolute* retargeting of each hand and the *relative* retargeting between hands impact the detectability of bimanual retargeting.

2.2 Participants

We recruited 14 right-handed participants (6M, 8F), ages 20-42 (μ=27, σ=5). Participants received a $15 gift card for their time.

2.3 Apparatus

The experimental setup is shown in Figure 2. Participants wore an Oculus Rift [ocu [n.d.]] head-mounted display (HMD), noise-cancelling headphones, and retro-reflective markers mounted on both index fingers. An OptiTrack Prime 13 [opt [n.d.]] system was used to stream fingertip and head motion data into a Unity virtual environment. A passive prop with two 3D-printed spheres (7 cm diameter) mounted 30 cm apart and 17 cm above a base platform provided haptic feedback during the study. Participants sat in a chair at a height-adjustable table, at arm's length from the prop.

2.4 Procedure

2.4.1 Haptic Retargeting Implementation. We follow the haptic retargeting approach defined by Azmandian et al. [Azmandian et al. 2016]. Figure 3 illustrates the approach for a single hand/object, which is performed identically for each hand. The virtual sphere is offset from the physical proxy by $\alpha°$, measured about the participant's shoulder in the sagittal plane. Beginning with their fingertip at the warping origin ($\mathbf{P_o}$), the participant reaches forward towards the virtual sphere ($\mathbf{P_v}$). Based on the physical hand's position ($\mathbf{H_p}$) relative to the origin and physical prop ($\mathbf{P_p}$), a vector offset ($\mathbf{W}$) is added between the physical and virtual hand:

$$\mathbf{W} = \left(\frac{D_s}{D_s + D_p}\right)(\mathbf{P_v} - \mathbf{P_p}) \tag{1}$$

where $D_s = ||\mathbf{H_p} - \mathbf{P_o}||$ and $D_p = ||\mathbf{H_p} - \mathbf{P_p}||$. By gradually offsetting the virtual hand linearly, the participant's physical hand arrives at the proxy when the virtual hand arrives at the sphere.

2.4.2 Calibration & Training. Prior to starting, participants' arm lengths were measured from shoulder to index fingertip. Participants sat with the physical proxy centered in front of them. The seat and table were adjusted such that their arms were 15^o below horizontal when touching the tops of the proxy spheres (see Figure 2). This was selected based on reported comfort during pilot studies.

Participants completed a brief training session prior to beginning the study. Here they explored two conditions, one with no retargeting and one with a large degree of upward retargeting on the left hand. During this session, the right sphere was swapped with an identical sphere mounted 5 cm lower. This was done to avoid biasing the participant with the exact proxy setup as the study.

Participants were not shown the physical proxy at any point, and were told that the physical spheres could be moved to different heights that may or may not match the virtual spheres they see. In reality, the physical spheres were not moved during the study.

2.4.3 Task. Both bimanual and unimanual reaches were tested. Each bimanual trial consisted of a two-handed target acquisition task. Two virtual spheres were displayed at the participant's measured arm's length, one red and one blue. Each virtual sphere was offset from a static physical proxy sphere by one of the the following angles, measured about the shoulder in the sagittal plane: $-24°$, $-18°$, $-12°$, $-6°$, $+6°$, $+12°$, $+18°$, or $+24°$. Beginning with each hand 50 cm from of their corresponding proxy, the participant reached with both hands to touch the tops of the virtual spheres – red with their right index finger, blue with their left – while each hand was retargeted to the corresponding physical sphere. No warping was applied prior to reaching, and warping was applied linearly as described in Section 2.4.1 during the reach. Participants had up to 10 seconds to repeatedly reach to the spheres before answering the following question, completing the trial: "Did you perceive an offset between your physical and virtual hands? Yes or no." Upon answering verbally, the targets disappeared, the participant retracted their hands to the starting zones, and the next trial began.

During the single-hand reaching tasks only one hand/target was displayed. Participants reached only with the visible hand and answered the same question above for these trials. Overall, each participant completed 240 randomized trials: $8 \times 8 = 64$ bimanual conditions, $8 \times 2 = 16$ single-hand conditions, 3 trials per condition.

2.5 Analysis

2.5.1 Data Processing. For each condition, we compute an overall detection rate. Due to the large number of conditions (80), each participant experienced a limited number of repeated trials per condition (3); thus, data was pooled between participants to provide a general overview of detection trends [Abtahi and Follmer 2018; Zenner and Krüger 2019]. We divide the data into bimanual, left-only, and right-only retargeting conditions and treat each as an independent experiment.

2.5.2 Experimental Design. The method of constant stimuli (MCS) is a repeated measures within-subjects experiment design. For bimanual retargeting, we consider left hand offset (i.e., retargeting magnitude) and right hand offset to be independent variables, and detection (as described above) as a binary response variable.

2.5.3 Statistical Modeling. To examine the combined effects of left and right hand offsets on the detection of bimanual haptic retargeting, we use a mixed effects logistic regression model with left offset, right offset, and their interaction as fixed effects, and participant as a random effect. As detection is expected to increase both when (1) positive (i.e., upward) offsets increase and (2) negative (i.e., downward) offsets decrease, we partition the data into quadrants (e.g., left hand upward/right hand downward) in which detection response is monotonic and fit a separate model to each quadrant.

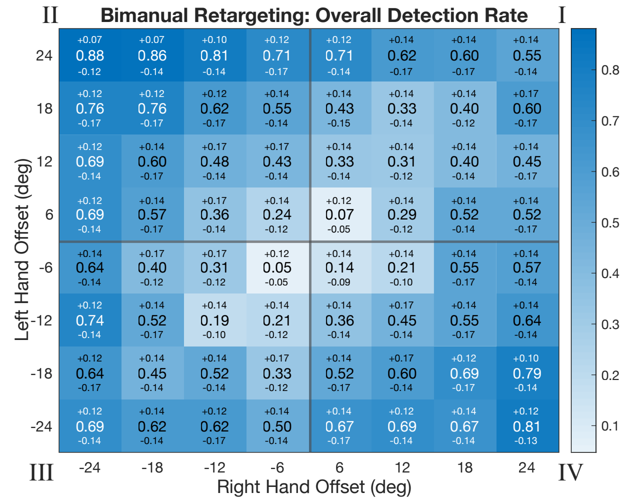

Figure 4: Mean detection rates of bimanual retargeting for each left/right offset combination. 95% bootstrap CIs shown.

2.5.4 Detection Threshold Estimation. We also estimate detection thresholds for two informative cases of bimanual retargeting, where both hands are offset by the same amount in (1) the same direction or (2) opposite directions from a level reference. In the former case, the virtual hand configuration matches the physical hands (i.e., level with each other), while in the latter it does not. We refer to these simply as "same" and "opposite" direction bimanual retargeting, but emphasize that we refer to the special case when left and right hand offsets are equal in magnitude but may vary in direction. Thresholds are found by fitting a psychometric function (i.e., logit) to the mean detection rates [Abtahi and Follmer 2018]; the offset predicted to yield a 50% detection rate is considered the detection threshold (DT) [Ehrenstein and Ehrenstein 1999]. Thresholds are also found for the single-hand reaches for comparison.

3 RESULTS & DISCUSSION

The overall detection rates for each bimanual retargeting combination are shown in Figure 4. As expected, we see that conditions with minimal retargeting of either hand (Figure 4, center of heatmap) yielded the lowest rates of detection. When retargeting is applied in opposite directions to either hand (Figure 4, quadrants II & IV), detection rate increases more sharply compared to same-direction retargeting (Figure 4, quadrants I & III).

The results of a mixed effects logistic regression analysis (described in Section 2.5.3) are given in Table 1, grouped by directionality of retargeting. Wald tests indicated both left offset (L) and right offset (R) were found to significantly influence detection in all four directional combinations ($p < 0.001$). Significant interaction effects (L×R) were found in all directional combinations ($p < 0.03$). The prevalence of significant interactions suggests that the *relative* retargeting between the hands plays an important role in detection. This is visualized in Figure 4, which shows that the effect of right hand offset (columns) tends to depend on the value of left hand offset (row) and vice versa.

Figure 5 shows the psychometric plots and detection thresholds (DT) for the four cases described in Section 2.5.4. 95% confidence intervals were computed for each DT using the bias-corrected and

Table 1: Summary statistics for mixed effects logisitic regression models fit to each directional combination of bimanual retargeting. Parameters include left and right hand offsets (L, R) and their interaction (L×R). Model coefficients β represent change in log-odds of detection per parameter unit.

		Right Down (-)			Right Up (+)		
		L	R	L×R	L	R	L×R
Left Up (+)	z	5.08	4.05	-1.55	6.77	6.02	-5.18
	p	**<0.001**	**<0.001**	**0.025**	**<0.001**	**<0.001**	**<0.001**
	β	0.24	0.21	-0.006	0.28	0.24	-0.012
Left Down (-)	z	5.97	6.89	-4.37	5.92	5.46	-3.11
	p	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.002**
	β	0.25	0.29	-0.010	0.26	0.23	-0.007

accelereated (BCa) bootstrapping method with 1000 repeated samples [Wichmann and Hill 2001]. Note that the detection rates for "opposite" and "same" direction bimanual retargeting correspond to the diagonal and anti-diagonal of Figure 4, respectively. In the case of opposite bimanual retargeting, the offset in Figure 5 is given for the right hand alone; the relative angle between the retargeted virtual hands is 2×offset. Note there is no relative angular difference between hands in the same-direction case. Compared to single-hand retargeting (Right DTs: $-16.4°$, $17.1°$; Left DTs: $-16.2°$, $18.5°$), same-direction bimanual retargeting yielded slightly larger DTs ($-19.5°$, $21.4°$). In contrast, opposite-direction bimanual retargeting yielded smaller DTs ($-12.3°$, $14.3°$).

This difference in estimated DTs highlights the impact of including both hands on users' perception of haptic retargeting. In single-hand retargeting, users have only one point of reference relative to their body (i.e., their hand), and therefore one potential source of visuo-proprioceptive discrepancy. In bimanual retargeting, the additional point of reference leads to three potential sources of discrepancy: the absolute positions of the left and right hands in space, as well as the *relative position* between them. In general, this creates more opportunities for the illusion to be broken by body semantic violation [Padrao et al. 2016]; this is evidenced by the higher detection rates observed for conditions with large relative differences in retargeting between hands (Figure 4, quadrants II & IV). However, the slightly larger DTs observed for same-direction bimanual retargeting suggest that when the relative positioning between virtual hands is consistent with that of the physical hands (i.e, via equivalent retargeting), the additional reference point may help strengthen the illusion.

4 LIMITATIONS & FUTURE WORK

Pooling participant data provided more data points per condition (42, as opposed to 3), allowing for more robust psychometric fitting and greater insight into overall trends; however, individual differences in participants' DTs may have been hidden as a result. Future work is needed to determine how DTs vary between individuals.

Additionally, the detection rates and thresholds observed in this study are likely affected by the position of the physical targets, as target location is thought to influence proprioceptive acuity [King and Karduna 2014]. We expect the observed detection trends, to hold across physical target positions, though further investigation is needed. Our study also only examined the overall detection of retargeting. If participants were asked to explicitly report detection of offsets for each hand independently, more detailed trends may become apparent.

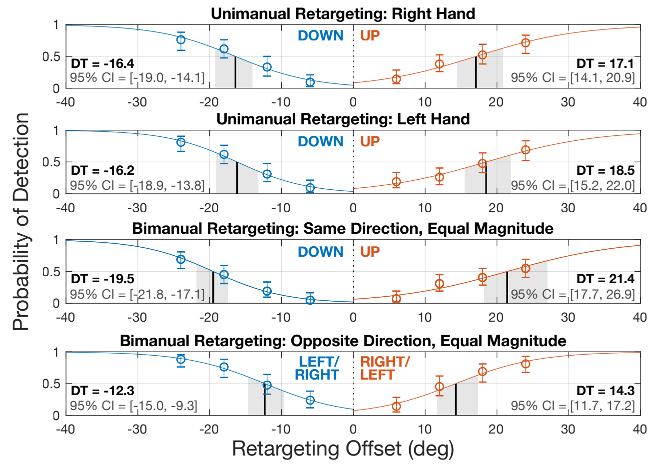

Figure 5: Psychometric curves and estimated detection thresholds with 95% confidence intervals shown (gray). For bimanual cases, only right hand offset is shown (for "Same": left = right offset; for "Opposite", left = -1×right offset).

Furthermore, this study examined bimanual retargeting only in a single dimension – angular offsets in the sagittal plane – but in practice haptic retargeting can be applied in any direction to remap a prop to a virtual object. Further research on multi-directional bimanual haptic retargeting (e.g., retargeting both hands in orthogonal directions) should be conducted to better understand how bimanual haptic retargeting may be perceived in practical contexts.

Lastly, haptic retargeting is built on the theory that users continually correct their reaching motion through visual feedback. Thus, to some degree, the extent of visual attention given to the virtual hand influences the illusion's success. Bimanual actions however, inherently split a user's attention between hands [Riek et al. 2003] – potentially unevenly, as in the case of reaching for something in one's periphery while the other hand completes a separate task (e.g., shifting gears). Future work should explore the effects of visual attention on the effectiveness of haptic retargeting, and how this translates to retargeted bimanual interactions.

5 CONCLUSION

In this study, we present an initial investigation of the detection of bimanual haptic retargeting during a two-handed reaching task. We report the overall detection rates found for 64 combinations of left- and right-hand retargeting ranging from $-24°$ to $+24°$ (measured about the shoulder), and estimate detection thresholds in the cases of equivalent bimanual retargeting in the same and opposite directions. Our results suggest that retargeting both hands equally in opposite directions may yield lower detection thresholds than same-direction bimanual retargeting. These findings highlight the significant interaction effects between left- and right-hand retargeting on users' perception of bimanual haptic retargeting.

6 ACKNOWLEDGMENTS

The authors would like to thank Parastoo Abtahi and other members of the SHAPE Lab for their valuable feedback and discussions.

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