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Body Warping Versus Change Blindness Remapping: A Comparison of Two Approaches to Repurposing Haptic Proxies for Virtual Reality

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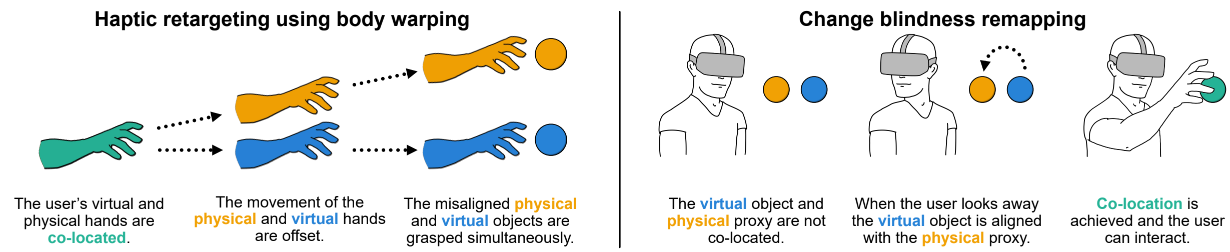

Figure 1: Illustration of haptic retargeting based on body warping (left) and change blindness remapping (right) adapted from [33].

Abstract

When using tangible props as proxies for virtual objects, it is important that these haptic proxies are similar to and co-located with their virtual counterparts. This makes it challenging to scale virtual scenarios because more proxies are needed as scenarios grow more complex. Haptic retargeting, or virtual remapping, makes it possible to repurpose the same physical prop as a proxy for multiple virtual objects. This paper details a user study comparing two techniques for repurposing haptic proxies; namely haptic retargeting based on body warping and change blindness remapping. Participants performed a simple button-pressing task, and 24 virtual buttons were mapped onto four haptic proxies with varying degrees of misalignment. Body warping and change blindness remapping were used to realign the real and virtual buttons, and the results indicate that users failed to reliably detect realignment of up to 7.9 cm for body warping and up to 9.7 cm for change blindness remapping. Moreover, change blindness remapping yielded significantly higher self-reported agency, and marginally higher ownership. Taken together these results suggest that this less explored technique has potential when it comes to repurposing haptic proxies for virtual reality.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality;

1 Introduction

The recent proliferation of consumer-grade virtual reality (VR) has made impressive audio-visual virtual environments (VEs) widely accessible. However, the ability to touch virtual objects is still out of reach to most consumers.

Haptic proxies—that is, physical props serving as proxies for virtual objects—offer a cheap, convenient, and compelling approach to supporting touch in VEs. Haptic proxies do by definition provide passive haptic feedback (i.e., haptic feedback generated from users' physical interaction with tangible objects). However, passive haptic feedback does not necessarily involve haptic proxies, as evidenced by prior work that rely on elastic interface to deliver passive haptic feedback during virtual interactions [1, 2]. The primary advantage of haptic proxies is that the user experiences actual kinesthetic and cutaneous sensations; thus, eliminating the need for simulation. Contrary to most body-referenced interfaces (e.g., exoskeletons [27]), haptic proxies support kinesthetic perception of properties such as weight, and haptic proxies allow users greater freedom of movement compared to ground-referenced devices (e.g., the Phantom Omni [30]). Nevertheless, it becomes increasingly challenging to use haptic proxies as virtual scenarios grow more complex. Particularly, it has been argued that successful use of haptix proxies in VR is contingent upon at least two criteria being met [28, 33, 54]:

- *Similarity:* The haptic proxies and virtual objects should be sufficiently similar in regards to both material properties (e.g., texture, compliance, and thermal quality) and geometric properties (e.g., shape and size). This limits the utility of haptic proxies because a haptic proxy with different properties is needed whenever the user touches a new virtual object.
- *Co-location:* The virtual objects should be co-located with haptic proxies whenever the user attempts to interact with them (i.e., the two should be aligned with respect to both position and rotation). This makes it impractical to rely on haptic proxies, if the virtual scenario demands interaction with a large number of virtual objects.

To address both criteria, haptic proxies can be combined with active haptic feedback (i.e., feedback produced by actuators exerting forces on the user); thus delivering mixed haptic feedback [50]. For example, similarity can be achieved using mechanical or human actuation affecting properties such as objects' internal weight distribution [50] and shape [51], or the external forces acting on grasped objects [9]. Mixed haptic feedback can also be used to ensure co-location. For example, haptic proxies can be physically aligned with with their virtual counterparts by robotic arms [3], robotic vehicles [45], drones [21], or human confederates [11].

A growing body of research focuses on fulfilling the two criteria through purely virtual manipulation. These techniques leverage the limitations of the human perceptual system to distort users' sensation of touch in VR. For example, by manipulating the movement of users' virtual bodies, it is possible to create a sensation of similarity with respect to properties such as shape [5, 23], size [7], weight [37], mass distribution [48], and contact forces [41]. Similar forms of virtual manipulation have been used to fulfill the criterion of co-location. These approaches to *haptic retargeting* [4], or *virtual*

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remapping [32], distort the mapping between real and virtual movements and objects to ensure that users physically encounter haptic proxies whenever they interact with virtual objects.

Body warping [4] is a form of haptic retargeting that has garnered a lot of attention in recent years. To ensure that the haptic proxy and virtual object are touched simultaneously, body warping introduces an offset between the user's real and virtual hand, as shown in Figure 1 (left). For that reason, it seems likely that the noticeability of the manipulation is proportional to the distance between the virtual object and the haptic proxy. Moreover, it seems likely that offsets between the real and virtual hands may reduce the user's sense of embodiment towards the virtual body (i.e., the sense of being co-located with, controlling, and owning the virtual body [22]).

Change blindness remapping [28] is a less explored approach to ensuring co-location that masks realignment of virtual objects with their haptic proxies by leveraging change blindness—a perceptual phenomenon that occurs when individuals fail to detect visual changes [42]. Particularly, change blindness remapping aligns virtual objects with haptic proxies, when the virtual objects are not visible to the user, such as when users are looking away, as illustrated in Figure 1 (right). Because the technique does not involve manipulation of the user's virtual hands, it should be less detrimental to the sense of embodiment, and change blindness should ensure that the technique can be deployed imperceptibly.

In this paper, we present a within-subjects study exploring these empirical claims by comparing haptic retargeting based on body warping to change blindness remapping. The results indicate that subtle remapping over higher distances may be possible with change blindness remapping, and we found some indication that change blindness remapping may be less detrimental to users' sense of embodiment.

2 Related Work

Inspired by the haptic retargeting framework proposed by Azmandian et al. [4], we can categorize techniques that allow physical props to be reused as proxies for multiple virtual objects based on whether they (1) change the mapping between users' real and virtual hands, (2) change the mapping between haptic proxies and their virtual counterparts, or (3) a combination of the two. To avoid confusion with the specific prototypes described by Azmandian et al. [4], we use the labels *hand remapping*, *world remapping*, and *hybrid remapping*, when referring to these general categories.

2.1 Hand remapping

Hand remapping techniques decouple the movement of users' real and virtual hands to ensure that they grasp misaligned physical and virtual objects simultaneously; thus creating the impression that the two objects are co-located. Because hand remapping techniques depend on the ability to offset virtual hand movements while the user is reaching for objects, they are generally limited to ensuring co-location of objects in *peripersonal space* (i.e., the space within reach [14]).

Azmandian et al. [4] were the first to describe this form of hand remapping, dubbed *body warping* (Figure 1, left), and a related approach was proposed by Carvalheiro et al. [8]. Benda, Esmaeili, and Ragan [6] highlight that several different approaches to hand remapping have been proposed, including rotations along specific axes [17], gain-based warping [52], and scaled body movements [16]. Moreover, Cheng et al. [10] combined hand remapping with prediction of intended targets from gaze and hand motions, to allow interaction with multiple virtual objects based on a single haptic proxy; and Clarence et al. [13] developed a reach prediction algorithm aimed at enabling unscripted remapping, which can predict targets with 81% accuracy after approximately 65% of the reaching movement. Han et al. [19] explored habituation to hand remapping and different configurations of offset magnitudes, offset directions, and object locations; and recently, Zenner, Ullmann, and Krüger [54] combined dynamic haptic retargeting based on hand remapping with the *Shifty* [50] (a weight shifting proxy) to simultaneously address the criteria of similarity and co-location.

Ideally hand remapping is imperceptible to users. For that reason, prior work has focused on identifying detection thresholds for different types of remapping at varying magnitudes, and under different conditions. Zenner and Krüger [52] provided estimates of the extent to which body warping can be performed without the user noticing it. Specifically, they estimate that the virtual hand can be subtly displaced vertically or horizontally by up to 4.5° and forward physical grasping movements can be scaled by a factor between 0.88 and 1.07, corresponding to amplification by up to 13.75% and compression by up to 6.18%. Esmaeili, Benda, and Ragan [16] explored the effects of task complexity and motion direction on detection thresholds. They found no significant effect of task complexity but provide estimates of detection thresholds for downscaling and upscaling hand movements in the horizontal plane (0.809, 1.310), the vertical plane (0.869, 1.520), the depth plane (0.779, 1.380), and for compound movement (0.758, 1.430). Gonzalez and Follmer [17] explored detection thresholds for bimanual haptic retargeting and found that compared to single hand remapping (right: -16.4°, 17.1°; left: -16.2°, 18.5°), bimanual remapping in the same direction led to slightly higher thresholds (-19.5°, 21.4°). However, bimanual remapping in opposite directions led to lower detection thresholds (-12.3°, 14.3°). Contrary to most previous work, which focused on dynamically changing offsets, Benda, Esmaeili, and Ragan [6] explored users' ability to detect fixed positional offsets. They found that thresholds varied significantly based on direction, and offsets below detection thresholds did not impair performance compared to conditions with no offset. Ogawa et al. [34] explored the effects of hand representation on detection thresholds and present evidence indicating that users may be less likely to notice remapping of hands with realistic, rather than abstract appearance. Finally, Zenner, Regitz, and Krüger [53] showed that hand remapping can also be masked by blink-induced visual suppression and the corresponding change blindness. That is, instantaneous offsets between users' real and virtual hands can be introduced during blinks without users noticing it. Moreover, the authors demonstrated that this approach can be combined with continuous body warping to decrease the likelihood of detection.

2.2 World remapping

World remapping techniques ensure that virtual objects are aligned with haptic proxies when the user attempts to grasp the objects. Because world remapping techniques rely on moving the VE relative to the user, rather than distorting the users' hand movements, these techniques can also be applied in *extrapersonal space* (i.e., the space that is out of reach and cannot be directly acted upon [14]).

The earliest attempts at repurposing haptic proxies relied on *redirected walking*—a collection of techniques that aim to give users an experience of walking freely in VEs that are larger than the physical walking area [32]. Redirected walking can be accomplished by continuously amplifying or reducing users' translational and rotational motion in the VE; thus changing their physical path. Kohli et al. [24] were the first to demonstrate that such manipulations can repeatedly steer users back to a single physical cylindrical stand, and thereby give them the impression that they are interacting with a larger number of virtual cylenders. However, if applied in isolation, this approach demands use of haptic proxies that are perceptually invariant to rotation, which greatly limits generalizability [43]. A similar approach was described by Steinicke et al. [40] who used a physical table as a proxy for multiple virtual objects, and Langbehn et al. [26] who used redirected walking to reuse a physical table as a proxy for two virtual tables in adjacent rooms. Moreover, Thomas, Pospick, and Rosenberg [46] recently proposed a framework for reactive alignment of real and virtual environments based on redirected walking. Suma et al. [42] proposed a radically different approach to redirecting users based on impossible overlapping virtual architecture, which is masked using change blindness. That is, the location of rooms, hallways, and doors could be discretely changed behind users' backs. Moreover, the authors showed that this form of manipulation could be used to steer users across the same patch of physical gravel whenever they encountered that surface in the VE [43]. World remapping using redirected walking do by definition require the user to walk in order to ensure that virtual objects and haptic proxies become co-located. However, world remapping can also be performed when users are stationary or seated.

Azmandian et al. [4] proposed *world warping*, which continuously rotates the VE around stationary users to align virtual objects with and haptic proxies. To help mask the rotation the manipulation is performed during users' head rotations. Because this approach involves rotation of the entire VE, it risks introducing misalignment in other areas of the environment (e.g., alignment of objects on a table may cause the virtual and the physical table to become misaligned). More recently, Matthews et al. [31] proposed *interface warp*, which can be applied individually, or in combination with body warping, to ensure co-location during interaction with virtual interfaces. For example, the technique can be used to continuously shift virtual buttons to match the position of corresponding haptic proxies. The warping is not designed to be unnoticeable as it is performed continuously inside the user's visual field, but it can reduce the amount of body warping needed to ensure co-location between real and virtual interface elements.

Inspired by previous work on redirected walking [42], which showed that change blindness can be used to mask large changes in the VE, Lohse et al. [28] proposed *change blindness remapping* (see Figure 1, right). This technique instantly aligns virtual objects with suitable haptic proxies when the virtual objects are outside the users' field-of-view or when their view of the scene is occluded. Thus, it is not necessary to manipulate the entire VE, but only the transformation of the virtual object that needs to be aligned with a haptic proxy. Notably, Marwecki et al. [29] explored a similar idea. However, they did not perform the remapping when the virtual object is occluded or behind the users' backs. Instead, they used eye-tracking to determine the focus of the users' visual attention and combined this information with visual masking, to subtly realign haptic proxies inside users' field of view (FOV). Research on change blindness remapping is scarce compared to work on hand remapping. Nevertheless, the approach seems worthy of further scrutiny, especially considering the promising results related to change blindness redirection (i.e., Suma et al. [42] found that only one in 77 participants noticed that the location of doors and corridors were changed behind their backs).

2.3 Hybrid remapping

When first introducing body and world warping, Azmandian et al. [4] also proposed that the two approaches can be combined. Particularly, *hybrid warping* both decouples the user's real and virtual hands and rotates VE around the user to ensure that the virtual and physical objects become co-located. Even though research on hybrid remapping is limited, the approach is promising. Azmandian et al. [4] present a user study comparing body, world, and hybrid warping, which indicate that all three variations elicited higher self-reported presence than wand-based interaction, but hybrid warping yielded the highest presence and satisfaction. Notably, Zenner, Kriegler, and Krüger, [49] recently introduced the *Virtual Reality Hand Redirection Toolkit* (HaRT), which supports all three approaches.

3 Method and Materials

Haptic retargeting based on body warping introduces an offset between users' real and virtual hands, and previous work has shown that there is a limit to how great the offset can be before users notice the manipulation [52]. Moreover, it seems likely that users' sense of embodiment towards their virtual hands will decrease as the offset increases. Contrarily, change blindness remapping relies on transformations of virtual objects, rather than users' virtual bodies, and previous work has show that change blindness can mask rather dramatic changes in the VE [43]. For these reasons, we hypothesized that change blindness remapping can be used to ensure co-location of virtual and physical objects that are further apart compared to body warping, and change blindness remapping will also lead to a stronger sense of virtual embodiment compared to body warping. To explore these general hypotheses, we performed a within-subjects study comparing the two approaches to repurposing haptic proxies for VR (body warping and change blindness remapping) in terms of noticeablity and embodiment.

3.1 Participants and Setting

A total of 20 participants took part in the study. They were aged between 23 and 46 years (M=26.4, SD=5.1), and 15 identified as male and 5 as female. When asked about their prior experience with VR, 15 reported having experienced VR before. All participants had normal or corrected-to-normal vision and gave informed consent.

The study was performed during the final stages of the gradual reopening after a society-wide lock down aimed at minimizing spread of COVID-19. To avoid forcing participants to enter the potentially crowded campus of Aalborg University Copenhagen, we performed the study in the private residence of one of the authors, and participants were recruited from the authors' personal networks. To minimize response bias (e.g., courtesy bias), we did not inform the participants of our hypotheses, and we emphasized that the aim of the study was not to provide evidence favoring a specific remapping technique, but rather to help us explore the advantages and disadvantages of the two techniques.

3.2 Virtual Scenario and Environment

During exposure to the two conditions, the participants were tasked with performing a simple button-pressing task. Particularly, they were seated in front of a table located in a futuristic virtual space station. On the table, they saw 24 red buttons that were numbered and organized into four groups of six buttons (Figure 2, left). To complete the scenario the participants had to click the buttons one by one. This process involved six steps (S1-S6):

- *S1* The participants looked at the virtual screen above them (highlighted with blue on Figure 2, right), which asked them to check the status indicator on the table.
- *S2* The participants looked at the table waiting for the status indicator to turn green (Figure 2, left).
- *S3* When the status indicator on the table turned green, the participants would direct their gaze toward the virtual screen on their right (highlighted with orange on Figure 2, right).

Figure 2: Top-down view of the virtual table including the 24 labelled buttons and the green status indicator (left). Overview of the VE including the two screens, highlighted with blue and orange (right).

S4 When looking at the screen to the right, the participants could see what button to press next. These instructions included the name of the group of buttons (e.g., "Unity" or "Quest") as well as the number of the specific button (1-6).

S5 The participants reached out and pressed the button.

S6 Finally, the participants once again directed their gaze at the screen above them, which asked them to answer a question, before the cycle repeated itself.

We chose this simple task because button-pressing is likely to occur in many VR scenarios, and it is a familiar and fast interaction that can be repeated multiple times within a limited period of time; thus reducing exposure times and cognitive load. Moreover, interface buttons are static. This was desirable because change blindness remapping involves movement of virtual objects, and we wanted to ensure that movements observed by participants were attributed to the remapping and not discounted as naturally occurring movement.

The VE was created using AutoDesk Maya and Unity, and it was displayed using an Oculus Quest 2. The participants' hands were tracked using the Quest 2's native hand-tracking, and they were represented in the VE using a simple black hand model (Figure 3, left). Previous work has show that the Oculus Quest offers significantly higher spatial accuracy with respect to finger tracking compared to the HTC Vive [38].

3.3 Remapping Techniques

The physical environments included four circular buttons buttons, with a diameter of 2 cm (Figure 3, right), which served as proxies for the 24 virtual buttons. The physical buttons were only included to provide passive haptic feedback during interactions, and button presses were detected by registering when the virtual hand collided with the virtual button. We manually aligned the physical and virtual buttons before the study was run with help of the Oculus Passthrough, which permits users to see a real-time view of their surroundings while wearing the display. Figure 4 shows the horizontal distribution of both virtual and physical buttons.

All remapping was performed horizontally (i.e., the manipulation of the virtual objects or the users' virtual hand were either left or rightward). In relation to both remapping techniques, all six virtual buttons in a each of the four groups were mapped onto a single physical button, as shown on Figure 4. Thus, interaction based on two of the physical buttons involved leftward remapping (A and C in Figure 4) and interaction with the other two involved rightward remapping (B and D in Figure 4). Body warping and change blindness remapping were performed as follows.

Body warping: Body warping was performed while the participants were reaching for the button during S5. That is, the remapping was applied when they reached through an invisible plane located between them and the rows of buttons. Inspired by the original work of Azmandian et al. [4], we incrementally warped the virtual hand's horizontal position. Particularly, the magnitude of the left or rightward offset between the users' real and virtual hands was linearly mapped to the distance to the row of virtual buttons. This ensured that the virtual hand touched the virtual buttons as the users' real hands pressed the physical buttons.

Change blindness remapping: Change blindness remapping was performed during S4, when the participants were reading the instructions on the screen to their right dictating what button to press next. That is, while the users were looking away, all virtual buttons were instantaneously shifted left or rightward to ensure that the correct virtual button was aligned with a physical button. As such, the manipulation bears some semblance of the one performed during *interface warp* [31], which overtly shifts the virtual buttons to match the physical button's position as the hand approaches. However, change blindness remapping is designed to be unnoticeable, by deploying the manipulation discretely outside the users' FOV. To ensure that the starting position of the buttons were always the same, they were returned to their original position during S1, and S2 was included to ensure that the participants used these positions as a visual reference before the remapping was performed.

3.4 Procedure and measures

Initially, the participants filled a questionnaire asking about demographic information (age, gender, and prior VR experience). Then they were introduced to the two remapping techniques, the task, and the scenario. Subsequently, the participants were exposed to the two conditions, which required them to performed a series button clicks with their right hand. Co-location between the real and virtual buttons was ensured using either change blindness remapping or body warping. Six different distances between the real and virtual buttons were used (0 cm, 3 cm, 6 cm, 9 cm, 12 cm, and 15 cm) and each distance was repeated four times for each of the two remapping techniques, yielding a total of 48 trials (24 per condition). After exposure to each condition the participants were asked to fill out a questionnaire. The order of the two conditions was randomized between participants and the trial order was also randomized for each participant. The study lasted about 15 minutes per participant.

To quantify the *noticeability* of change blindness remapping and body warping, we adopted a psychophysical approach that previously has been used to quantify perceptual detection thresholds in relation to a different types of virtual interactions, including redirected walking [18, 39, 44] and hand remapping [6, 16, 52]. For both change blindness remapping and body warping, the participants were exposed to remapping at six different distances between the virtual and real buttons: 0 cm (no remapping), 3 cm, 6 cm, 9 cm, 12 cm, and 15 cm. After exposure to each trial, the participants performed an adapted two-alternative forced-choice (2AFC) task, which required them to judge whether or not their hand or the environment was manipulated for each of the two conditions. In line with previous work on noticeability of body warping [52], we refer to this task as a pseudo-2AFC task because it, contrary to the established definition used in the psychometric literature, does not involve a choice between two distinct stimulus levels [18].

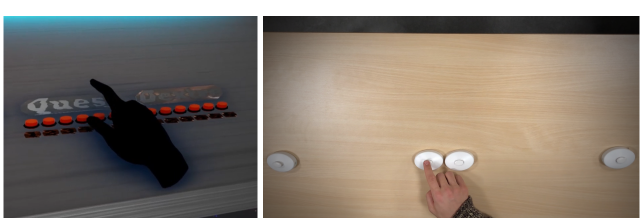

Figure 3: The virtual hand as seen from the user's perspective (left) and a top-down view of the physical table and the four buttons serving as haptic proxies (right).

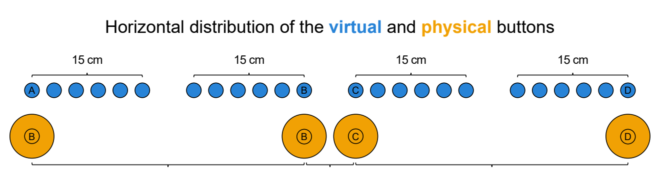

Figure 4: Illustration of the horizontal distribution of the virtual and physical buttons. Each of the four physical buttons served as a proxy for six virtual buttons. Virtual buttons labelled with A, B, C, and D did not require any remapping.

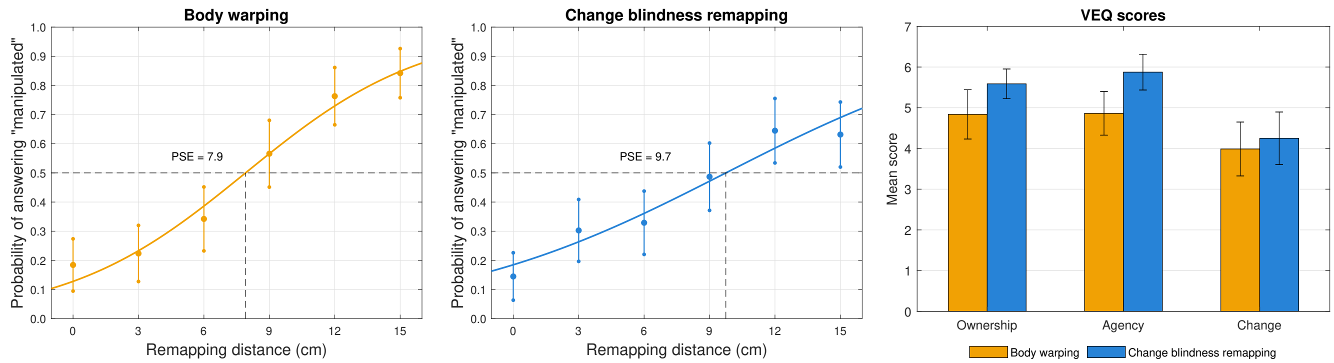

Figure 5: Left and middle: Detection results, standard errors, and fitted psychometric functions for body warping and change blindness remapping. The x-axes show magnitude of the remapping in cm and the y-axes represent the probability that participants responded that the hand movement or the VE had been manipulated. The horizontal dotted lines show points on the curves where the participants on average responded "manipulated" half of the time (i.e., random chance), and the corresponding vertical dotted line identify the point of subjective equality (PSE), which we consider the detection threshold. Right: Mean scores of the VEQ sub-scales (ownership, agency, and change) for the two remapping techniques. Error bars indicate 95% CIs.

To determine if the participants' sense of *embodiment* was affected by the two remapping techniques, we administered the *virtual embodiment questionnaire* (VEQ) [36] after exposure to each condition. The VEQ assesses embodiment in terms of three sub-scales related to the extent to which users experienced a sense of *ownership* of the virtual body, a sense of *agency* over the virtual body, and a *change* in the perceived body schema. Each sub-scale includes four items answered using 7-point Likert-type rating scales where 1 indicates strong disagreement and 7 indicates strong agreement. Each sub-scale is scored by taking the mean of the four items. Because the participants' hands were the only body parts visualized in the VE, we adapted the questionnaire by replacing all instances of the word "body" with "hand."

4 Results

In this section we summarize the results pertaining to noticeablity and embodiment.

Noticeablity Due to a logging error, we lost data for one participant, and the analysis of the results pertaining to noticeability is based on data collected from 19 participants. For each of the six remapping distances we derived the pooled probability that participants reported that manipulation was occurring, and fitted separate psychometric functions for the body warping and change blindness remapping. Figure 5 (left and middle) shows the pooled response probabilities and standard errors across participants, and fitted psychometric functions of the form $f(x) = \frac{1}{1+e^{a*x+b}}$ where a and b are real numbers. The detection thresholds for each psychometric function were defined as the remapping distances at which the participants were equally likely to report that manipulation was occurring or not on the pseudo-2AFC task. That is, the thresholds corresponded to the points of subjective equality (PSEs) where the probability of responding "manipulated" was 0.5 (chance level). The dashed lines on Figure 5 (left and middle) shows the PSEs and indicate that the detection threshold for body warping was 7.9 cm and for the change blindness remapping it was at 9.7 cm.

Embodiment Paired-samples t-tests were used to determine whether there was a statistically significant mean differences between body warping and change blindness remapping in regard of the scores obtained from the three sub-scales of the VEQ (ownership, agency, and change). There were no outliers in the data, as assessed by inspection of boxplots. The difference scores for the two remapping techniques were normally distributed in regards to all three subscales, as assessed by inspection of Normal Q-Q Plots, and Shapiro-Wilk's tests (ownership, p = 0.855; agency, p = 0.791; change, p = 0.470). As apparent from Figure 5 (right) the mean scores were higher for change blindness remapping compared to body warping with respect to all three VEQ sub-scales. For the agency score, we found a statistically significant increase of 1.013 (95% CI, 0.286 to 1.739), t(19) = 2.916, p = 0.009, d = 0.652). However, for the ownership score, the increase of 0.750 (95% CI, -0.063 to 1.563) was only marginally significant ($t(19) = 1.390, p = 0.069, d = 0.432$); and for the change score, the increase of 0.263 (95% CI, -0.703 to 1.228) was not statistically significant ($t(19) = 0.569, p = 0.576, d = 0.127$).

5 Discussion

Below we present a discussion of the results, some limitations of the current study, potential future work, and broader reflections on how body warping and change blindness remapping compare.

5.1 What technique is least noticeable?

The results indicate that participants were unable to reliably detect remapping of real and virtual objects at distances of up to 7.9 cm for body warping and up to 9.7 cm for change blindness remapping (i.e., an increase of 1.8 cm or 23%). This may suggest that users are less likely to notice change blindness remapping than body warping, when the two techniques are used for remapping in peripersonal space. Moreover, this may imply that change blindness remapping can be used to ensure co-location of real and virtual objects that are further apart. It is possible to offer at least one likely explanation for the difference in noticablity; namely, that body warping relies a gradually increasing offset between the position of the user's real and virtual hands. This introduces a growing discrepancy between the visual and proprioceptive information about the location of the user's hand, which is sustained until the hand is retracted. Contrarily, change blindness remapping introduces a discrete change to the VE that ensures instant alignment of the real and virtual objects.

5.2 What technique yields the most embodiment?

The results pertaining to the three factors of embodiment (sense of ownership, sense of agency, and change in body schema) revealed that change blindness remapping on average scored higher than body warping with respect to all three factors. However, the difference in scores was only statistically significant with respect to agency, and marginally significant for ownership. No difference was found with respect to the change in body schema. Notably, the items forming the basis for this sub-scale asks explicitly about whether users felt that their bodies changed in terms of properties such as appearance and weight [36]. Thus, it is possible that the limited or absent difference between change blindness remapping and body warping can be attributed to the virtual hands being identical between conditions. Nevertheless, the results provide some indication that change blindness remapping may elicit a stronger sense of agency, and possibly ownership, compared to body warping. This indication is in line with previous work suggesting that discrepancies between the position and movement of the real and virtual limbs can impair both the sense of virtual ownership [25] and agency [47].

5.3 Limitations and Future Work

Despite the interesting indications yielded by the current study, a number of limitations suggest the need for future work.

Like some previous work on threshold estimation for haptic retargeting [52], we deliberately reduced the number of repetitions per remapping distance (i.e. we only used four repetitions). This was done to prevent fatigue on behalf of the participants. However, the low number of repetitions also prevents us from deriving detection thresholds for individual participants, which can be subjected to statistical analysis. This represents a major limitation of the current work, and future studies should include more repetitions, as well as a wider range of remapping distances. In addition to enabling statistical comparison, a larger number of repetitions will also increase the accuracy of the identified thresholds.

Even if the identified detection thresholds are accurate for horizontal remapping in peripersonal space and change blindness remapping is less noticeable than body warping, we cannot be certain that the results will generalize to other types of interactions, scenarios, and objects. For example, they might not apply to remapping in other directions (e.g., vertical, forward, or backward), and the current study did not explore whether thresholds vary between leftward and rightward remapping or between unimanual and bimanual remapping. Similarly, it seems possible that noticeability will be affected by factors such as the number and arrangement of virtual objects, the size and shape of the objects, the complexity of the scenario, and individual differences. Furthermore, the current study focused on change blindness remapping involving simultaneous transformation of several virtual objects (i.e., four groups of buttons were all moved during remapping). However, it also seems possible to only transform a selection of objects, and it may be possible to swap virtual objects when performing remapping [28]. Moreover, the current study only compared change blindness remapping to haptic retargeting based on body warping, and it is relevant for future work to explore how the technique compares to world warping and hybrid warping [4], as these approaches probably will be less detrimental to embodiment. Finally, because the participants were aware of the manipulation, the identified detection thresholds may represent conservative estimates.

In addition to the future work suggested by the limitations of the current study, it is worth pointing to other unexplored directions for research. While different hand remapping techniques have been explored extensively, the same cannot be said of change blindness remapping. The current work focused on remapping in peripersonal space, but given the impressive results related to change blindness redirection [42], it seems likely that the technique can also be used to perform remapping in extrapersonal space. Moreover, it is necessary to explore non-intrusive interventions that prevent users from interacting with virtual objects that have not been remapped to a haptic proxy yet [28]. The current work explored change blindness remapping deployed when users were facing away. However, it also seems possible that environmental manipulations can be performed inside users' FOV, when visual attention is not focused on the manipulated object [29], or by masking the manipulation using blinks and saccades, as has been done in relation to hand remapping [53]. On the topic of masking, previous work on redirected walking indicates that both passive [35] and active [15] distractors can be used to mask warping of users' movements; and challenge-based distractors, imposing additional cognitive load, may make users less like to notice manipulations of virtual architecture [12]. Thus, it seems relevant for future work to explore how interaction and distraction can be used to mask both body warping and change blindness remapping. Furthermore, just as research on redirected walking has explored so-called *redirection controllers* [20], it is relevant to develop remapping controllers that can manage the deployment of individual remapping techniques and dynamically match virtual objects and haptic proxies in order to handle spontaneous user behaviours.

5.4 Body warping versus change blindness remapping

The current study gives us reason to suspect that change blindness remapping may be harder to notice than body warping; and change blindness remapping may also be less detrimental to embodiment. These benefits of change blindness remapping can presumably be attributed to the continuous alignment of the users' real and virtual hands. Even though it is possible that the results will apply to other virtual scenarios, tasks, and environments, it is unlikely that change blindness remapping always will be favorable or even feasible. Particularly, our implementation of change blindness remapping, as well as the original work by Lohse et al. [28], both require the user to look away before realignment can be performed. This greatly limits the number of scenarios that change blindness remapping can be applied to, as the scenario either has to involve scripted or dynamic diversions encouraging the user to look away. Furthermore, this implies that the system needs information about future targets when the user is looking away. Because body warping is deployed inside users' FOV it does not impose such limitations and information about intended targets can be predicted from gaze and hand motions [10] and even after the reaching moment has been instigated [13]. Notably, it may be possible to deploy change blindness remapping inside users' visual field during opportune moments, such as when visual attention is focused elsewhere [29], if the relevant part of the scene is momentarily occluded, or during blinks and saccades [53]. However, future work is needed to determine if these types of remapping are possible.

6 Conclusion

In this paper we presented a user study comparing a popular approach to repurposing physical props as proxies for multiple virtual objects (haptic retargeting based on body warping [4]) to a less explored approach (change blindness remapping [28]). Our results indicate that participants were unable to reliably detect change blindness remapping of real and virtual objects at distances of 9.7 cm, whereas the threshold associated with body warping was 7.9 cm. Moreover, we found that participants on average rated change blindness remapping higher on all three sub-scales of the virtual embodiment questionnaire (embodiment, agency, and change), but a statistically significant difference was only found for agency, and a marginally significant difference was found for embodiment. Taken together, we believe these results indicate that change blindness remapping has potential as an approach to repurposing haptic proxies for VR. Change blindness remapping is simple to implement; it is computationally inexpensive; it does not involve offsets between users' real and virtual hands; it can be deployed in both peripersonal and extrapersonal space; it does not require remapped objects to be in view; blink-induced visual suppression and intentional blindness may enable use of the technique inside users' FOV; and the current study gives us reason to suspect that change blindness remapping sometimes may be less noticeable and yield a stronger sense of embodiment, compared to haptic retargeting based on body warping.

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