Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences

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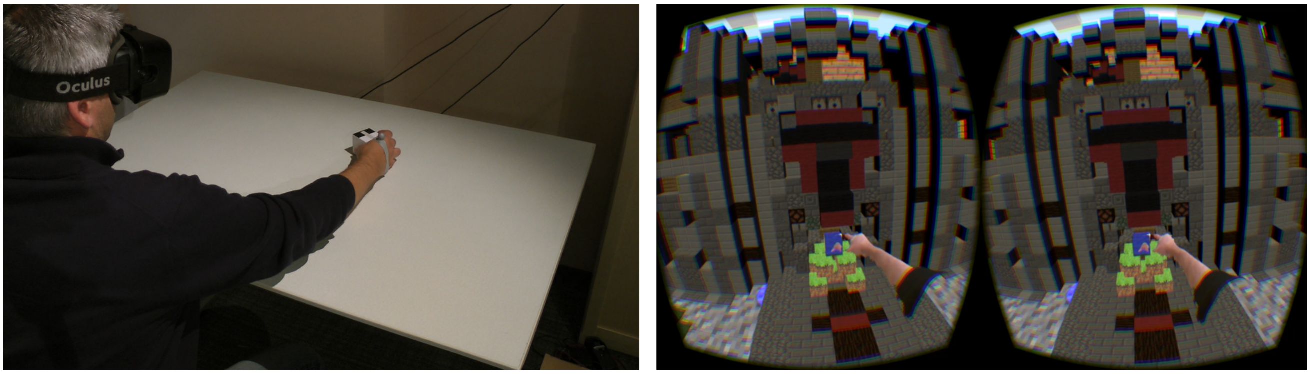

Figure 1. User building a virtual castle by arranging and stacking multiple virtual cubes mapped to a single physical cube.

ABSTRACT

Manipulating a virtual object with appropriate passive haptic cues provides a satisfying sense of presence in virtual reality. However, scaling such experiences to support multiple virtual objects is a challenge as each one needs to be accompanied with a precisely-located haptic proxy object. We propose a solution that overcomes this limitation by hacking human perception. We have created a framework for repurposing passive haptics, called *haptic retargeting,* that leverages the dominance of vision when our senses conflict. With haptic retargeting, a single physical prop can provide passive haptics for multiple virtual objects. We introduce three approaches for dynamically aligning physical and virtual objects: world manipulation, body manipulation and a hybrid technique which combines both world and body manipulation. Our study results indicate that all our haptic retargeting techniques improve the sense of presence when compared to typical wand-based 3D control of virtual objects. Furthermore, our hybrid haptic retargeting achieved the highest satisfaction and presence scores while limiting the visible side-effects during interaction.

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INTRODUCTION

Over the past few years, virtual reality (VR) has experienced a resurgence. With the proliferation of consumer-level head-mounted displays and motion tracking devices, an unprecedented quantity of immersive experiences have been created. Though optics, rendering, and audio technologies have improved substantially, a component that has remained underdeveloped is haptics—the sense of touch expected when reaching out and grabbing virtual objects.

A key objective in virtual reality is establishing a sense of presence. When shown an environment with photorealistic rendering, people can be convinced by the illusion of reality, and describe the experience as immersive [37], but when reaching out to touch a virtual object, the illusion can be shattered when one's hand unexpectedly passes through the rendered visuals.

One method for adding a sense of touch to virtual objects is through *passive haptics* [17], where physical props are placed around the environment to match their virtual counterparts. The result can be a compelling tactile sensation when reaching and touching an object. However, this technique requires each virtual object to have a physical prop of the same size and shape, in the correct position, to create this illusion. Furthermore, each time the virtual scene is changed, the infrastructure must be modified and possibly rebuilt. This limits the ability to develop complex virtual environments with passive haptics.

In this paper, we explore a solution that overcomes these limitations by hacking human perception. We have created a framework for repurposing passive haptics, called *haptic retargeting,* that leverages the dominance of vision when our senses conflict. In essence, our approach repurposes a single physical prop to provide a passive haptic sensation for a variety of virtual world objects thus increasing the user's sense of presence and improving the overall quality of the experience (Figure 1).

We do this by dynamically aligning physical and virtual objects as the person is interacting in the environment. Specifically, we investigate three approaches: a) world manipulation, where the virtual world surrounding the person is moved to better align with a passive haptic prop, b) body manipulation, where the virtual representation of the person's body is warped to meet up with the passive haptic prop, and c) a hybrid technique which combines both world and body manipulation. This work improves upon *redirected touching* [25] by adding dynamic detection and remapping within the same experience for the whole hand instead of one finger, and also introducing a hybrid continuum, allowing retargeting in limited-movement situations. Our user study results confirmed that our haptic retargeting techniques improved the sense of presence when compared to typical wand-based 3D control of virtual objects.

Specific contributions of our work include:

- The concept and detailed analysis of haptic retargeting as a method for repurposing passive haptics from the same physical object over multiple virtual objects.
- The implementation and analysis of 3 specific haptic retargeting approaches: world, body and hybrid warping.
- The results of a user study evaluation of our three haptic retargeting approaches in comparison with typical wand-based virtual manipulation.

RELATED WORK

There are several areas of related work that are relevant to our current design: haptic redirection, dominance of visual perception, and repurposing physical props.

Haptic Redirection

Perhaps the most closely related work to our own is *redirected touching* [25], which addresses the inflexibility of passive haptic displays by warping the virtual space, introducing a discrepancy between a person's real and virtual hand motion. As a result, a physical display can be mapped to a virtual display rotated about the vertical axis by up to 18 degrees, without being noticed. In contrast to our approach, this work explored world warping along a single dimension (rotation along a single vertical axis) and was limited to a one-finger touch interaction without solving the problem of representing a full body under a variety of warped space conditions.

The inflexibility of passive haptics can be overcome with the aid of robotics using *active haptics*. In the case of Robotic Shape Displays [28]: when a user reaches for a virtual object, a robotic arm places a real object correctly in front of the user's hand. One such robot has a Shape Approximation Device as its end-effector, which has several corners with curved and flat edges to approximate different shapes [35]. While impressive, these haptic displays are expensive, require sophisticated control mechanisms, and miscalculations and latency could be dangerous to users.

Studies have shown that using haptics can lead to significantly increased presence and spatial knowledge training transfer [17]. Though haptics are traditionally implemented using a one-to-one mapping between the real and virtual world, in *redirected touching* [25] spatial warping is used to generate mappings between the real and virtual space, such that a single real object can provide haptic feedback for virtual objects of various shapes. This results in discrepancies between a person's real and virtual hand motions so that they reach the real and virtual objects simultaneously. Studies have shown that people can adapt to spatial warping [24] and perform tasks as effectively under non-warped conditions [23].

In the context of walking, a single physical prop can be used to provide haptics for multiple virtual objects [22]. This is achieved by using *redirected walking* [30], a technique that injects additional translations and rotations to the user's head movements, causing users to walk on a physical path that is different from the perceived virtual path. By having the user walk back to the same physical object when moving from one virtual target to the next, the object provides haptic feedback for multiple virtual targets. Though for an imperceptible execution of this method, large tracking spaces are required [34].

Dominance of Visual Perception

Some of these haptic redirection techniques are based on the key idea that when senses conflict, vision often dominates. A person moving their hand along a straight surface while wearing distorting glasses feels the straight surface as curved [10]. In Rock and Victor's study [31], participants holding an object through a cloth while viewing the same object through a distorting lens believed the object was most similar to the distorted visual image, rather than the shape that they felt. Lécuyer et al. [26] had participants push with their thumb on a piston mounted on a passive isometric input device. Simultaneously, participants were visually shown a virtual spring that compressed as force was applied to the piston. Even though the piston did not physically move, perception of spring stiffness was influenced by the virtual spring.

Vision is also found to dominate proprioception [5]. This finding is exploited in a technique to allow visually correct hand-object collisions in the virtual world when there is no collision in the real world (since there is no real object). Upon "collision", the virtual and real hand positions can differ. Burns' technique exploits visual dominance over proprioception to bring the two hands back to the same position without the user noticing they were ever apart. Visual dominance is not always complete; during sensory conflict, sensory signals are weighted by their reliability [13]. When mixed-reality users are presented with real haptic and virtual cube-shaped objects with discrepant edge curvatures, they perceive the curvature to be intermediate [20]. Using a video see-through system, users' hand displacements were manipulated to perceive visual angles that were incongruent with physical edges up to 30 degrees. This phenomenon has also been leveraged to enable fine-controlled selection [16] and extend users' reach and selection abilities [1,6].

Vision can also dominate vestibular cues [21], which allows head rotations and translations to be scaled up or down in *redirected walking* [30]. This discrepancy causes a decoupling between the user's path in the real and virtual world.

Spatial warping not only affects hand motions, but also how the user's body is represented (virtual body). Experimental findings from body ownership illusions [33] show that under specific multisensory conditions, we can experience artificial body parts or fake bodies as our own body parts or body, respectively [19]. For instance, in one study, when the entire scene including the body was rotated by 15 degrees upwards, perceived ownership of the virtual body was only slightly diminished [4]. Scaling the body proportions has also been investigated by creating a long arm illusion, extending the length of the user's virtual hand by a factor of 3 while still sustaining high ownership levels [18].

Repurposing Physical Props

While reusing physical props has seen little attention in virtual reality environments, other research has extensively explored the use of physical props to provide haptic feedback in other domains [32]. Specifically, Hinckley et al. [15] introduced the notion of using physical models to control 3D virtual models on a separate screen, which led to many others extending this work to provide 3D interaction of objects in virtual environments in general [5,8,6,29], though the problem of providing a one-to-one mapping of physical controls in one's immediate surroundings is not considered.

Corston et al. [7] extend this idea by providing the ability to recognize these physical props through recognition via a Kinect sensor, however they too do not superimpose this control in a virtual reality environment so that the physical controls and digital artifacts coincide. In an augmented reality environment, Henderson and Feiner [14] provide opportunistic controls, which do connect the digital display environment to physical surfaces which are repurposed to provide a haptic response to specific widget-like digital controls, such as sliders and buttons. Our work builds upon these ideas by extending the notion of mapping digital objects in a virtual reality scene to physical props in a person's surroundings to provide a haptic response, but we focus on providing a seamless transition between these spaces, so that a person wearing the head-mounted display is largely unaware that these props are being repurposed.

HAPTIC RETARGETING

Our vision of haptic retargeting is to create a design space where we may reuse the physical objects in a person's vicinity to provide a sense of touch when reaching, grabbing, lifting, or otherwise manipulating artifacts in a virtual reality scene, but to not be limited by what specific objects are around and whether they are located in the "right" place.

We define the term *haptic retargeting* to encompass the general notion of *reusing the passive haptics of the same real physical objects across multiple virtual objects*. This can be generalized to finding a mapping between the virtual and real coordinate systems. Note that the mapping could be more complex than a simple affine transformation.

In addition to the core mapping requirement, we stipulate that good haptic retargeting solutions will also accomplish the following two requirements:

- The mapping is dynamic; i.e., the solution should support interactive manipulations and not require careful placement of objects or pre-computed solutions;
- The mapping is minimally noticeable (or unnoticeable) and therefore minimally disturbing to the person.

Implementation Environment

To investigate the capabilities of haptic retargeting, we have created a virtual Minecraft world (Figure 1), where a person seated at a desk, wearing a VR headset, constructs complex virtual shapes out of virtual cubes by lifting and placing them on top of one another. We focus on a specific alignment problem that involves manipulating cubes and constructing models out of them, similar to the basic premise of the Minecraft game (http://www.minecraft.net).

We used the Oculus Rift DK2 headset, tracked by the Oculus camera in combination with an overhead Microsoft Kinect v2.0 camera. The Kinect camera is used to capture the geometry and the appearance of the person's body, track the position of the person's hand, as well as track the passive haptic proxy object on the tabletop (Figure 2). Depth and color images from the Kinect are used to render realistic 3D views of the user's own body.

While there are many possible VR configurations, we had the user seated at the desk for three reasons: a) this arrangement provides the person with an interactive surface (desk) on top of which the manipulations can be easily performed, b) the person's overall movements are restricted in space, thus making our hand/object tracking easier, and c) we expect many people using VR technology for work or play in

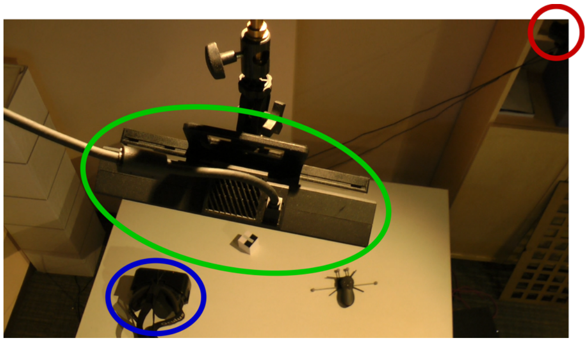

Figure 2. Top-down view of our setup with Kinect (green), Oculus HMD (blue) and Oculus DK2 Camera (red).

longer durations would prefer to be seated rather than walking around a room. In addition, many leading VR products (e.g., Oculus Rift, Sony Playstation VR) appear to be designed for the seated configuration.

Haptic Retargeting Mappings

We explore three mapping techniques to accomplish haptic retargeting:

- **Body Warping** – Manipulating the virtual representation of the person's body (e.g., arms) such that, at the point of contact with the real object, the body part also appears to be at the virtual object;
- **World Warping** – Manipulating the virtual world's coordinate system to align virtual and physical objects;
- **Hybrid Warping** – A dynamic combination of Body and World Warping.

We now detail each of these methods.

BODY WARPING

As an illustrative example, consider a simple arrangement with a real cube A positioned on the desk in front of the user, and the virtual cube A' shifted slightly to the right. In this case, as the user reaches for the cube, to ensure that the virtual hand meets the real cube, a translation to the right must be applied. A straightforward way of achieving this is to shift the entire rendering of the body to the right, effectively translating the user's hands and arms to the right.

Incremental vs. Instantaneous Warp

Applying an overall shift, the user's virtual representation of their hands and arms may be noticeable and possibly disruptive. To avoid this, we apply the warp *incrementally* to respect the hands' position at the beginning of the warp, yet still align the cubes once the hand reaches the physical cube. To define an incremental warp, we first measure the position P_H of the user's hand (the hand used to grab the object) when Body warping is activated and define it as the *warping origin* W_O. The *warping end* W_T is then set to hand position P_A at the time of Body Warping activation.

The *warping ratio* α is then:

$$\alpha = \min\left(0, \max\left(1, \frac{(W_T - W_O).(P_H - W_O)}{(W_T - W_O)^2}\right)\right)$$

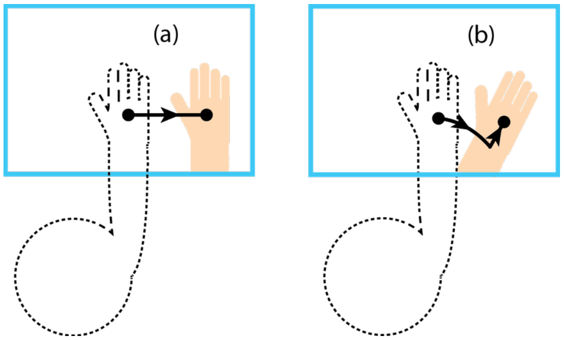

Figure 3. Body-friendly adjustment - Original approach (a) causes hand to drift away from expected body position, but with a body-friendly warp (b), alignment can be achieved without drastically separating hand from body.

The warping ratio quantifies the hand's progression towards A and determines the amount of warp applied to the hand's position. By applying the warp incrementally, when the user's hand reaches the physical cube, the representation of the hand will meet the virtual representation of the cube; and as the user's hand is retracted, the warp is "undone".

Body-Friendly Adjustment

Consider the case where the user reaches with their right hand and body warping effects a translation to the right. The greater the translation, the more separated the arm appears from the body. Similarly, a large translation to the left will cause the arm to appear very close to the body. Large mismatches between the visual and proprioceptive cues can be disturbing, particularly when the arm appears to be obviously detached from the user's torso, or protrudes unnaturally from the torso. Such mismatches can be disruptive and distracting to the user.

Our solution employs a combination of translation and rotation about the user's body position (Figure 3). This method does not guarantee that hand rotation matches that of the object (except in the case of a sphere). One way to resolve this discrepancy would be to rotate the user's rendering around the wrist, to match the orientation of the object. Such non-affine transforms were not investigated in this study. In an informal proof-of-concept study, none of the 8 users that experienced the body-friendly-warp reported the discrepancy in orientation, suggesting that in some cases *convincing* the user that the physical and virtual cubes are aligned may not always require perfect alignment.

Target Prediction

A successful remapping needs to be timely in addition to accurate. This requires determining the user's intent early on to ensure alignment when the hand reaches the virtual target. Adopting a heuristic similar to drag-and-pop [3], we compare the hand's velocity with the direct path to candidate targets and thus predict the next virtual target. A remapping is then calculated and incremental warping is begun.

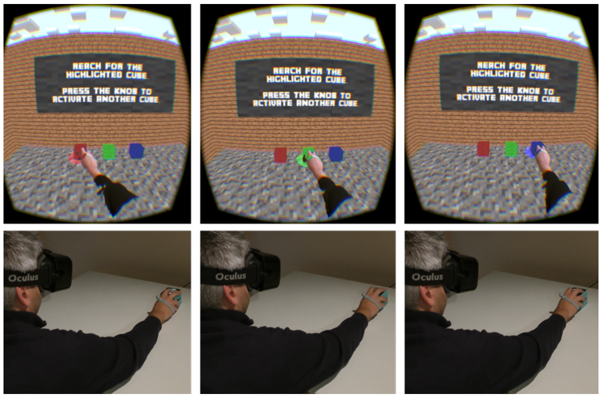

Figure 4. 1 for 3 Illusion - User touches 3 different virtual cubes while in reality the same cube is touched each time.

1 for 3 Illusion

We developed a demonstration task that involves reaching to touch one of three static virtual cubes aligned horizontally on the desk before the user (Figure 4). At each phase, the user is instructed to tap a button placed in front of them on the desk. After the button is pressed, an instruction appears directing them to reach for and touch one of the cubes. Before the demo, they would see three cubes placed on the desk, leading them to believe that the three virtual cubes corresponded to the same three physical cubes (Figure 5). Once the user puts on the HMD, unbeknownst to them, the left and right cubes were removed from the desk, leaving only the center cube on the table. In each phase, pressing the button initiates a new trial, mapping the single physical cube to one of the three virtual cubes using Body Warping.

Users report that as they performed the task, they were uncertain what the purpose of the demonstration was and found it repetitive; but once they were instructed to take off the HMD, they realized what had happened. Observing the users' behavior, we noticed that as they reached to grab a cube, the virtual hand would start warping and they would—perhaps subconsciously—correct the hand trajectory, effectively countering the warp to meet the real cube.

Cube Stacking with Body Warping

In the current proposed implementation of Body Warping, the warping factor is at its maximum when the user's hand is in contact with the cube and no further warping is applied while the user moves the cube. Though Body Warping was originally intended to align the user's virtual hand with the real object, it can be extended to accomplish other illusions.

For example, we explored stacking virtual cubes on a table. The task is to grab a virtual cube resting on the table, and place it on top of another cube, also sitting on the table. Under normal circumstances, if the user were to perform this task with the tracked cube, when the user brings the cube above the bottom virtual cube, not only would there be no haptic feedback indicating the cube's placement on the lower cube, the cube would fall to the table once released. To properly simulate the haptics of stacking the cube, the idea is to add an upward translation to the body warp, so that when the user attempts to place the upper cube, the user sees the virtual cube resting on the lower cube. Meanwhile, haptic feedback indicating that the upper cube is stacked on the lower cube is provided by the table's surface. This creates the illusion that the cubes are being stacked.

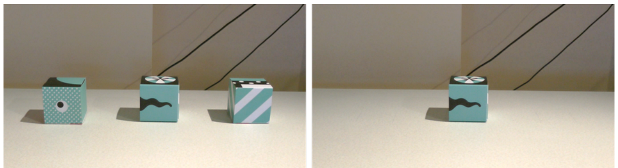

Figure 5. Arrangement of three cubes before the demonstration task begins (left) and with two cubes removed once the HMD is put on (right). The user handles only a single physical cube.

WORLD WARPING

World warping involves manipulating the virtual world to align virtual objects with the real. In the cube alignment example, where physical cube A is placed on the table, and the virtual cube A' is positioned to the right of A, alignment using World Warping involves translating the entire virtual world to the left, so that A' meets A. Users would likely find this change jarring if applied instantaneously. However, from the redirected walking literature we know that a user's head motions can be scaled by certain factors without user noticing. For instance, if the user performs a 90 degree rotation to the right, the virtual world can also rotate with/against the user's head rotation, resulting in a rightward/leftward 10 degree rotation about the user's head position. From previous studies [34], when walking, translations can be scaled up by 26% or scaled down by 14% without being noticed. Similarly, rotations can be imperceptibly scaled up by 49% and down by 20% (note that the scaling factors are not symmetric and may be different if seated).

Implementation

In a redirected walking implementation [30], translations and rotations in the virtual world are injected at each simulation frame. Our implementation follows a similar approach. We calculate the user's instantaneous change in position and orientation, and scale the desired translation and rotation proportionally. Such translations and rotations are applied continually, frame to frame, until alignment is achieved.

In a seated virtual reality experience, head rotations are more common than head translations. In our implementation of world warping, we exclusively employ rotations. This approach can be sufficient to accomplish large displacements especially for farther targets.

Towards Ensuring Alignment

When a large amount of head rotation is expected, as when the user faces away from the virtual target, we can assume a minimal amount of head rotation to face the target. Given the existing rotation-scaling factors, the user's head rotations may not be sufficient to guarantee alignment by the time the

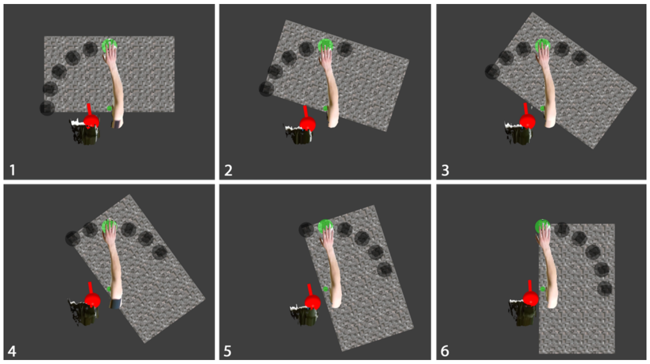

Figure 6. Ring of Cubes Illusion - World warping progressively maps a single physical cube to different virtual cubes arranged in an arc around the button, and within the user's reach.

user faces the target. To ensure alignment, we developed a mechanism to calculate the required scale factor for alignment, which may result in applying a potentially higher scale factor to ensure alignment. In this case, ensuring alignment can come at the cost of being noticed by the user, and even possibly inducing additional simulator sickness. Furthermore, rotations were injected about the position of the button as opposed to the exact position of the head to guarantee perfect alignment.

The Ring of Cubes Illusion

To demonstrate the functionality of world warping, we created a demonstration similar to the 1 for 3 Illusion. In this task, the user is instructed to look to their right to view a billboard to trigger the next instruction (Figure 6). The user sees an arrangement of cubes forming a quarter of a circle and in each phase, one of the cubes is deactivated and the adjacent cube is activated. As before, the user is instructed to touch the active cube in each trial.

The cubes are arranged so that mapping one cube to the other can be accomplished by rotating the world around the button placed in front of the user. Each time the user looks to the board and looks back, the required scale factor is calculated and applied. The rotations are applied about the position of the button in the scene since the button is always the starting location of the manipulating hand. Since the button itself was cylindrical, its own rotation during the warp was not easily detectable.

This Ring of Cubes Illusion demonstrates how World Warping manipulations can be compounded and extended as long as there are sufficient head motions. This contrasts with Body Warping, where manipulations are constrained by physical limitations of the body.

HYBRID WARPING

Both Body Warping and World Warping can produce a noticeable distortion of the user's sense of space if the magnitude of the warp is large. To minimize artifacts of each approach and thereby improve the user's overall sense of presence, we propose a Hybrid Warping technique which distributes the alignment task between both Body Warping and World Warping techniques simultaneously.

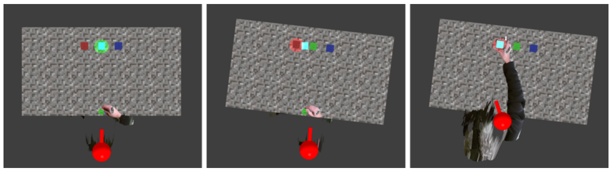

Figure 7. Hybrid Warping - The real cube first aligned with the green cube (left) moves towards the red cube with World Warping while the user looks around (middle) and the alignment is completed with Body Warping as they reach for it (right).

Implementation

In this hybrid remapping, the user's head translation and rotation enables our World Warping technique to inject some small amounts of translations and rotations that assist in the alignment. The algorithm also simultaneously employs Body Warping to aid in task completion: the required warp is calculated based on the current hand position and the difference between positions of the target object and its virtual representation. Scaling factors are set so that users are typically unable to detect either of the warping.

In essence, Hybrid Warping works by World Warping improving the alignment as much as it can, while the remaining warp is accommodated by Body Warping. In theory, if enough head motions are observed, the alignment may be completed entirely by World Warping, and no manipulation will be applied by Body Warping.

The Hybrid Warping approach combines Body and World Warping such that head motions activate World Warping, and hand motions activate Body Warping. In typical use, Hybrid Warping alternates regularly between World and Body Warping as head and body motions occur. Note that in Figure 7, since head motions occur first as the user looks at the target, World Warping is applied before hand motions enable Body Warping, but the algorithm does not require this order.

EVALUATION

We designed an experiment to compare Body Warping, World Warping, and Hybrid Warping. We used a variant of Hybrid Warping which combines Body and World Warping such that each is responsible for exactly half of the alignment task. These three mechanisms were compared to a control condition where the user interacts with a wand (no haptic feedback). As target prediction was only possible in Body and Hybrid Warping techniques, we removed this functionality in all conditions in order to create a comparable task and investigate the question of which technique most effectively creates a haptic illusion.

Participants

Twenty participants (17 male, 3 female, aged 23-52, *Mdn*= 29) took part in our study and were compensated with $10 gift cards to a local restaurant. Participants were screened using the Titmus Fly Stereotest to ensure all users could identify disparities as low as 100 seconds of an arc. All participants self-reported as being right-handed.

Apparatus

We used a Kinect 2.0 mounted on the ceiling facing downward for rendering and tracking the participant's body. Hand tracking was assisted by requiring participants to wear a Velcro-fastened 1cm-wide strap with a retro-reflective marker positioned on the back of the hand. A 5cm-sided cube was tracked by a strip of retro-reflective tape placed on the top, providing three degrees of freedom (3DOF) of positional tracking and 1DOF of rotation. The Kinect also tracked a "Virtual Wand" comprised of a wireless presenter with four rods attached, each with a retro-reflective marker on one end. This provided 3DOF positional tracking and 1DOF of rotation (similar to the cube) (Figure 8). A Griffin PowerMate knob was also used as a virtual button. Participants wore an Oculus Rift DK 2 head-mounted display (HMD) with tracking provided by the Oculus Camera (in addition to IMUs). The experience was developed on the Unity3D game engine.

Procedure

After screening, participants were told about the series of tasks they were to perform and questionnaires to answer. This was followed by the Miles Ocular Dominance test [29]. They were then asked to complete a questionnaire for demographic information (age, gender, handedness, ocular dominance, eyewear usage). Next was Witmer and Singer's Immersive Tendencies Questionnaire [37]. Finally, they answered three *Visualization of Rotations* and three *Visualization of Views* questions from the Purdue Spatial Visualization Test [12].

After gathering this preliminary information, participants were asked to perform a task once for each of the four conditions. At the end of each condition, participants completed Witmer and Singer's Presence Questionnaire [37] with two added questions: "*How stable did the world seem?*" and "*How easy was it to reach and grab objects*?" Participants' hand positions were also logged for analysis.

Conditions

Participants completed the following four conditions:

- *Wand*: Participants used a virtual wand with grab and release functionality to interact with a virtual cube (no haptic feedback).
- *Body*: Participants interacted with a tracked cube using our Body Warping technique.

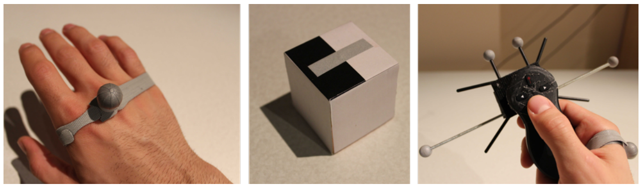

Figure 9. The hand, cube, and virtual wand are tracked with retroreflective markers.

- *World*: Participants interacted with a tracked cube using our World Warping technique.
- *Hybrid*: Participants interacted with a tracked cube using our Hybrid Warping technique.

We used a within-participants design, and conditions were counterbalanced using a Latin Square.

Task

The primary task performed in each of the conditions was a block-stacking task, where participants were asked to place a cube (blue) in a target location (indicated in red). The basic progression of the task was (a) tap a button to begin, (b) look up and to the left to receive instructions, (c) look back at the table to see the target cube (blue) and destination (red), (d) reach and grab the blue cube, (e) place it "inside" the destination marker, and (f) return to the button to end the task. In total, each participant completed 9 repetitions, in the form of three horizontally stacked rows, for each condition. They used only their right (dominant) hand.

To begin each condition, the participant put on the HMD to see a virtual world with a desk (aligned with a physical desk) with a button (aligned with the knob) near them on the desk, as well as three virtual brick walls. The wall in front of the participant contained a billboard with instructions. A second billboard was placed up and to the left (Figure 9), for step (b), and was intentionally placed out of the HMD's forward-facing view to be able to invoke world-centric and hybrid haptic responses, and to maintain consistency in the other two conditions. Participants were asked to look at this board with the instruction to inspect the next stacking operation, which was described graphically in 2D.

Participants were given a chance to practice examining (moving and rotating) the blue cube with their hands at the beginning of each condition to familiarize themselves with the technique before each set of trials for as long as they needed. Participants practiced for one minute on average.

A trial was considered complete when the blue cube was placed such that it had 75% overlap with the destination (red) "ghost" cube. At this point the blue cube turned yellow. Once

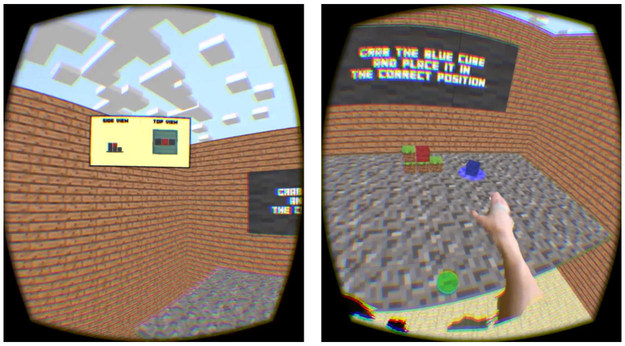

Figure 8. Participants first studied arrangement instructions (left) and then grabbed the blue cube and placed it in the target position indicated as a red cube (right).

the button had been pressed to end the trial, the yellow cube would "solidify" and change texture, and the virtual blue cube would disappear. The blue cube then would reappear in step (c) of the next trial and, despite having just been placed elsewhere in a previous trial, the haptic remapping technique was used to match it to the same physical cube. The respawning of the blue cube was done by taking the actual position of the cube and rotating it by 16 degrees around the position of the button, alternating between clockwise and counter clockwise. In *Wand* condition, this did not require haptic feedback, but in the other three cases, the haptic remapping was solved by the appropriate warping technique. *Hybrid* condition split the warping evenly between Body Warping and World Warping (8 degrees each). Note that with *Body*, when the hand is retracted, the warp is undone, but in the case of *World*, when a new remapping was required, the previous warp was first undone, requiring a total of 32 degrees of rotation (and 16 degrees in *Hybrid*). We required the participant to look at the upper left instruction board to ensure that they performed some head rotations. The scaling factors for *World* were dynamically adjusted to guarantee alignment by the time the user looked back at the cube.

To provide the illusion of stacking, the table itself was used to provide a haptic response when placing the cube, and so the base of the target (i.e., the top of the previous layer) was positioned to align with the physical table surface. The Body Warping technique could handle this directly as the cube was lifted, however World Warping could not. To address for this, the blue cube would appear in step (c) on a virtual pedestal at the same height as the destination. The *Hybrid* technique used Body Warping manipulation for 50% of height adjustment, and so started on a pedestal half-way between the table and the bottom layer. *Wand* did not require any adjustment, as no haptic response was provided. Only 1 of the 20 participants reported noticing that the table had been "lowered."

RESULTS

The following results are based on the data collected from our user study via questionnaires and hand tracking data.

Presence Analysis

We measured the sense of presence and the perceived effectiveness of the haptic response using Witmer and Singer's 21-question Presence Questionnaire [37], including questions relating to the realism, control, interface quality, ability to examine, performance, and haptic subscales. Participant responses to these questions were reliable (Kronbach's $\alpha = .972$). To analyze presence and these subscales, we used a one-way RM-ANOVA on the remapping technique factor (4 levels), a common statistical method for robustly analyzing Likert-scale responses [27]. Significant effects were found for the overall presence scale, as well as the realism, quality of interface, and haptic subscales (Table 1). Each question was asked on a 7-point scale, which has been normalized to -3 (lowest), 0 (neutral), 3 (highest).

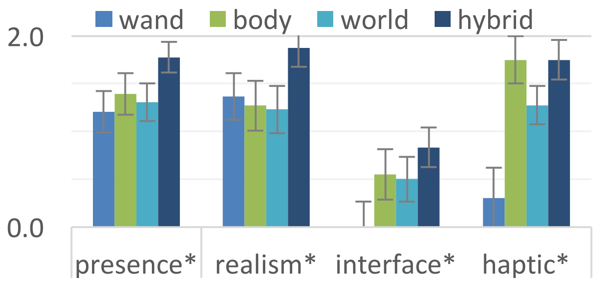

Figure 10. Results of the Presence Questionnaire. Error bars represented standard error (SE).

	$F_{3,27}$	*P*
Presence (overall):	**3.1**	**.03***
Realism	**2.9**	**.04***
Control	1.9	.14
Quality of Interface	**3.2**	**.03***
Ability to Examine	1.2	.32
Performance	1.3	.29
Haptic	**13.9**	**< .001****

***Table 1*. Results of RM-ANOVA for Presence and its six subscales. * = *p* < .05 or ** = *p* < .001.**

Overall Presence

Post-hoc analysis revealed that participants rated *Hybrid* significantly higher than the *Wand* baseline ($p = .01$), and marginally higher than *World* ($p = .06$) on our measure of presence. All other pairwise differences were not significant ($p > .05$). Figure 10 shows that *Hybrid* received the highest average score for all 21 questions on a 7-point scale ($M = 1.8$, $SE = 0.2$).

Realism

Post-hoc analysis revealed that participants rated *Hybrid* significantly higher than *Body* ($p = .02$), and marginally higher than *World* ($p = .054$) on the realism subscale. All other pairwise differences were not significant ($p > .05$). This subscale included seven questions, such as "how natural was the mechanism which controlled movement through the environment?" and "how compelling was your sense of objects moving through space?"

Quality of Interface

Post-hoc analysis revealed that participants rated *Hybrid* significantly higher than the *Wand* ($p = .01$) on the quality of interface subscale, and all other pairwise differences were not significant ($p > .05$). This subscale included three questions: "how much delay did you experience between your actions and expected outcomes?", "how much did the visual display quality interfere or distract you from performing assigned tasks or required activities?", and "how much did the control devices interfere with the performance of assigned tasks or with other activities?"

Perceived Effectiveness of Haptic Response

The Presence Questionnaire includes two optional questions in a haptic (sense of touch) subscale: "how well could you actively survey or search the virtual environment using

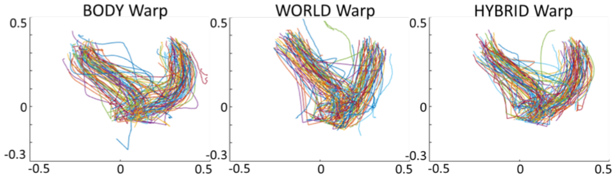

Figure 11. Horizontal paths (in meters) of our 20 participants when reaching for the target cube. Note: while the paths differ, the target and user locations are similar across conditions.

touch?" and "how well could you move or manipulate objects in the virtual environment?" Post-hoc analysis revealed that participants rated all warping techniques higher than *Wand* (*World*: p = .001; *Body*: p = .03; *Hybrid*: p < .001).

Path Analysis

To further understand the participant's experience, we analyzed the paths of the participants' hands when reaching for the passive haptic target cube. We logged hand position from the moment the participant pressed on the button, until they acquired the target cube. We excluded paths that had any missing data due to noise in hand tracking (~10%) and we dropped the *Wand* condition from our analysis, since we were primarily interested in the effect that our various warping conditions had on the paths.

We assume that if the user has a good agreement between their visually-perceived virtual world and their physical reality, then their reaching paths should be direct, straight, and without any corrective movements.

When plotting all paths taken by 20 participants over 3 conditions (Figure 11), it is clear that the paths are substantially different across conditions. The paths are the straightest in the *World* condition, which we expect, since there is a perfect match between the physical and the virtual world. The paths are progressively more curved in *Hybrid* and *Body* conditions, likely indicating that the users adapted their movements more to match their expectations.

We also noticed that some of the paths had an explicit "kink" near the end of the movement (Figure 12). These 'last moment corrections' indicate that the participant missed the target and adjusted their movement to find the cube. Two independent scorers manually inspected the paths to count these correction events. We observed very high agreement between scores (Krippendorff's α= .904).

Counts of corrections were statistically significantly different across conditions (Friedman Test χ^2= 25.9, p < .001). Post-hoc Wilcoxon Signed Ranks tests revealed *Hybrid* and *World* both did very well with only 7.5% and 8.75% of paths exhibiting last moment correction (Z = 0.6, p = .53, *n.s.*). *Body* had 31.25% of such corrections which was significantly different than both *World* (Z = 3.7, p < .001) and *Hybrid* (Z = 3.5, p = .001).

DISCUSSION

The main findings of our evaluation are as follows:

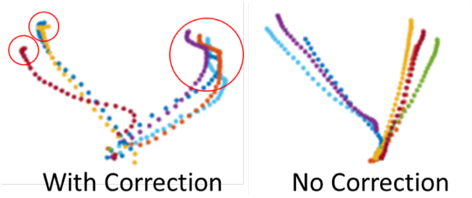

Figure 12. Examples of paths shown that exhibit a last moment correction (a kink) in the movement (left) vs. no correction (right).

- Participants reported the highest sense of presence when using *Hybrid*, and this difference was significant compared to *Wand* and *World* techniques.
- *Hybrid* also had advantages in terms of realism and quality of interface, and all three of the retargeting techniques provided a better sense of haptics than the *Wand* condition.
- Our path analysis revealed that *World* had the most direct paths to targets.
- *Body* led to more corrections near the target object than both *World* and *Hybrid*, suggesting that combining techniques can help reduce the need for path correction.

Given these findings, we recommend designers use the Hybrid Warping approach when applying haptic retargeting, in order to achieve an appropriate balance between providing a greater sense of presence and avoiding the need for path correction, thus enhancing the illusion by making these path corrections less noticeable. Participants generally reacted to the experience of using haptic retargeting with enthusiasm and surprise, making comments such as "knowing that the cube was just placed there and it appeared somewhere else freaked me out", "this is surreal; it's definitely messing with me", and "my mind is blown".

Based on these results, as well as our experience with designing and implementing these retargeting techniques, we can also provide additional advice.

Reduce the Need for Virtual World Adjustment

Our path analysis confirms that when the participant's actions match their expectations, they are able to perform direct movements without errors. While the paths are slightly more curved in the *Hybrid* condition, our analysis confirms that participants did not perform significantly more corrections than in the *World* condition. This is very encouraging, since World Warping requires a significant amount of manipulation of the virtual world around the user. This manipulation must be masked during head movement or it will be noticed by the user. Hybrid Warping is a good compromise: the amount of world movement can be kept to a minimum, while few mistakes are made when reaching for the target. In addition, as our presence analysis shows, this combination of low world and low body movement achieved the highest presence score of all conditions.

Make Use of Visual Dominance

It appears that users are proficient at accurately performing the required set of muscular actions to initially reach for an observed object, though they often rely on visual feedback to make fine adjustments towards the end of the movement. Therefore, it may seem natural to be slightly off when initially reaching for an object. The tendency to tolerate initial errors in movement, corrected in the last phase by visual feedback, argues for the use of Body Warping to retarget haptics. But the dominance of visuals over proprioceptive cues probably has a limit, and beyond a certain point, the user will question the magnitude of their error.

Encourage Slow Movements When Possible

The more slowly the hand moves, the more likely it is for the user to gradually correct the trajectory with visual feedback. In the these cases, the user is less likely to notice the smaller errors over the length of the reach. This suggests the possibility of extending the limits of Body Warping when users are more likely move their hands more slowly. In our experience, the applied warp is more noticeable when people perform quick ballistic motions to reach the target, and as a result, they see their hand *miss* the target. We hypothesize that the visual angular difference between the physical and visual targets is the key element in limiting Body Warping efficacy. In the *Body* condition this difference was higher than the *Hybrid* condition, increasing the odds of the user noticing the warp and decreasing performance.

Avoid Enforcing Head Motions by using Body or Hybrid

World Warping exploits the user's head translations and rotations, and therefore alignment cannot be guaranteed if head motions are not required. Even if some type of head motions are performed, they must be relevant to the necessary manipulation. For example, the motion of the user's head left and right will not help alignment when a forward translation is required. Furthermore, the magnitude of these motions must be sufficient to achieve the desired alignment. For example, if the alignment requires a 5cm translation and the maximum permitted translation-scaling factor is 25%, then the user must move at least 20cm forward. Magnifying the scale factors to guarantee alignment increases the likelihood of the user noticing the injected motions. Hybrid Warping may be less noticeable than World Warping in part because it works to minimize the scaling factor over time.

Limitations & Future Work

Tasks presented in our study have been deterministic in nature: in each case the virtual target is designated by the system rather than determined by the user. We previously described a method for path prediction that can be used in both the Body and Hybrid Warping approaches. Path prediction is more difficult with the World Warping technique, as it performed when the user is likely already looking at the object, reducing the chances that there would be sufficient head movements to effect alignment. *Redirected walking* [30] has similar a similar limitation. We thus removed path prediction from our study. Even with this omission, the Hybrid Warping technique was shown to provide a greater sense of presence, and we thus recommend using it.

In our design, each warp has been followed by an unwarp. This was enforced in the *Body* condition by retracting the hand to press a button, and in *World* by requiring the user to look back at a sign. Our remapping mechanism cannot support releasing a virtual object and immediately grabbing another object using the same physical object, though by using multiple physical cubes (e.g., two), this may be possible.

In our experiments, a single cube is mapped to multiple virtual cubes of identical dimensions. While using a physical cube may not be effective for other virtual shapes, our focus has been on the illusion of a prop's location, rather than its other material properties. Nonetheless, we can still effectively "fool" users into believing a real object is at the position of the virtual object, despite shape mismatch. For example, if a VR experience requires object movement or building, it may not be essential for material properties to match. Rather, it may be more important to simulate the physical movement of a prop. Moreover, recent work [2] suggests that some geometric substitutions could further improve this experience. Exploration of what constitutes appropriate substitutions, and their effectiveness in whole-hand contexts, are areas of potentially fruitful future work.

In the current implementation, we have only considered simple translations and rotations of the body and world representations in the virtual environment. We would like to explore more complex, perhaps non-linear mappings and test whether they provide a more compelling illusion. We would also like to explore incorporating our technique into a more completely developed environment, such as a video game, and evaluate the experience of using our technique in combination with other design constraints. Lastly, our techniques currently map virtual objects to similarly shaped physical ones, and we would like to explore more complex shapes and sizes and larger discrepancies between the two.

CONCLUSION

In this paper, we present a system for providing haptic feedback in a virtual reality environment by warping the virtual space to match the location of a physical prop in a person's immediate surroundings. We provide three alternative methods for achieving this warping: Body Warping and World Warping, which can be combined into a Hybrid Warping technique that uses both. These techniques allow a person to experience passive haptics in a virtual environment that differs from the physical one in potentially dramatic ways, allowing the designer to consider more complex virtual scenes and experiences, while still providing a sense of touch. We also present the results of a user study which shows that people experience a greater sense of presence when these techniques are combined, and we provide valuable insights into how to design virtual worlds that make use of haptic retargeting. Through haptic retargeting, designers of virtual worlds can consider a wider range of scenarios where passive haptics can be used.

REFERENCE

1. Merwan Achibet, Adrien Girard, Anthony Talvas, Maud Marchal, and Anatole Lecuyer. 2015. Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. *Virtual Reality (VR), 2015 IEEE*, 63–68.
2. Yuki Ban, Takashi Kajinami, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2012. Modifying an identified angle of edged shapes using pseudo-haptic effects. *Haptics: Perception, Devices, Mobility, and Communication.* Springer Berlin Heidelberg, *2012. 25-36.*. http://doi.org/10.1007/978-3-642-31401-8_3
3. Patrick Baudisch, Edward Cutrell, Dan Robbins, et al. 2003. Drag-and-pop and drag-and-pick: Techniques for accessing remote screen content on touch-and pen-operated systems. *Proceedings of INTERACT*, 57–64.
4. Kristopher J. Blom, Jorge Arroyo-Palacios, and Mel Slater. 2014. The effects of rotating the self out of the body in the full virtual body ownership illusion. *Perception* 43, 4: 275–294. http://doi.org/10.1068/p7618
5. Eric Burns, Sharif Razzaque, Mary C. Whitton, and Frederick P. Brooks. 2007. MACBETH: The avatar which I see before me and its movement toward my hand. *Proceedings - IEEE Virtual Reality*: 295–296. http://doi.org/10.1109/VR.2007.352509
6. François Conti and Oussama Khatib. 2005. Spanning large workspaces using small haptic devices. *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*: 183–188. http://doi.org/10.1109/WHC.2005.118
7. Christian Corsten, Ignacio Avellino, Max Möllers, and Jan Borchers. 2013. Instant User Interfaces: Repurposing Everyday Objects as Input Devices. *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces - ITS '13*, 71–80. http://doi.org/10.1145/2512349.2512799
8. George W. Fitzmaurice, Hiroshi Ishii, and William A.S. Buxton. 1995. Bricks: laying the foundations for graspable user interfaces. *Proceedings of the SIGCHI conference on Human factors in computing systems*: 442–449. http://doi.org/10.1145/223904.223964
9. Bernd Frohlich and John Plate. 2000. The cubic mouse: a new device for three-dimensional input. *Conference on Human Factors in Computing Systems: Proceedings of the SIGCHI conference on Human factors in computing systems* 1, 06: 526–531. http://doi.org/10.1145/332040.332491
10. James J. Gibson. 1933. Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology* 16, 1: 1–31. http://doi.org/10.1037/h0074626
11. John C. Goble, Ken Hinckley, Randy Pausch, John W. Snell, and Neal P. Kassell. 1995. Two-handed spatial interface tools for neurosurgical planning. *Computer* 28, 7: 20–26. http://doi.org/10.1109/2.391037
12. Roland Guay. 1977. Purdue Spatial Visualization Test-Visualization of Views. *Purdue Research Foundation, West Lafayette, IN.*
13. Hannah B. Helbig and Marc O. Ernst. 2007. Optimal integration of shape information from vision and touch. *Experimental Brain Research* 179, 4: 595–606. http://doi.org/10.1007/s00221-006-0814-y
14. Steven J Henderson and Steven Feiner. 2008. Opportunistic Controls: Leveraging Natural Affordances as Tangible User Interfaces for Augmented Reality. *Proceedings of the 2008 ACM symposium on Virtual reality software and technology - VRST '08*, 211–218. http://doi.org/10.1145/1450579.1450625
15. Ken Hinckley, Randy Pausch, John C Goble, and Neal F Kassell. 1994. Passive Real-world Interface Props for Neurosurgical Visualization. *Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI '94*, 452–458. http://doi.org/10.1145/191666.191821
16. Ralph L. Hollis, Septimiu E. Salcudean, and A. Peter Allan. 1991. A six-degree-of-freedom magnetically levitated variable compliance fine-motion wrist: Design, modeling, and control. *IEEE Transactions on Robotics and Automation* 7, 3: 320–332. http://doi.org/10.1109/70.88141
17. Brent E. Insko. 2001. Passive haptics significantly enhances virtual environments. *Computer*: 100.
18. Konstantina Kilteni, Jean Marie Normand, Maria V. Sanchez-Vives, and Mel Slater. 2012. Extending body space in immersive virtual reality: A very long arm illusion. *PLoS ONE* 7, 7. http://doi.org/10.1371/journal.pone.0040867
19. Konstantina Kilteni. 2015. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in Human Neuroscience* 9, March. http://doi.org/10.3389/fnhum.2015.00141
20. Itaru Kitahara, Morio Nakahara, and Yuichi Ohta. 2010. Sensory Properties in Fusion of Visual / Haptic Stimuli Using Mixed Reality. In *Advances in Haptics.* InTech. 565–583.
21. Roberta L. Klatzky, Jack M. Loomis, Andrew C. Beall, Sarah S. Chance, and Reginald G. Golledge. 1998. Spatial Updating of Self-Position and Orientation During Real, Imagined, and Virtual Locomotion. *Psychological Science* 9, 4: 293–298. http://doi.org/10.1111/1467-9280.00058

22. Luv Kohli, Eric Burns, Dorian Miller, and Henry Fuchs. 2005. Combining passive haptics with redirected walking. *Proceedings of the 2005 International Conference on Augmented Teleexistence* 57, 4: 253–254. http://doi.org/10.1145/1152399.1152451
23. Luv Kohli, Mary C. Whitton, and Frederick P. Brooks. 2012. Redirected touching: The effect of warping space on task performance. *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012 - Proceedings*: 105–112. http://doi.org/10.1109/3DUI.2012.6184193
24. Luv Kohli, Mary C. Whitton, and Frederick P. Brooks. 2013. Redirected Touching: Training and adaptation in warped virtual spaces. *IEEE Symposium on 3D User Interface 2013, 3DUI 2013 - Proceedings*: 79–86. http://doi.org/10.1109/3DUI.2013.6550201
25. Luv Kohli. 2010. Redirected touching: Warping space to remap passive haptics. *3DUI 2010 - IEEE Symposium on 3D User Interfaces 2010, Proceedings*: 129–130. http://doi.org/10.1109/3DUI.2010.5444703
26. Anatole Lécuyer, Sabine Coquillart, Aberrahmane Kheddar, Paul Richard, and Phillipe Coiffet. 2000. Pseudo-haptic feedback: can isometric input devices simulate forcefeedback? *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. http://doi.org/10.1109/VR.2000.840369
27. Rensis Likert. 1932. A technique for the measurement of attitudes. *Archives of Psychology* 22 140: 55. http://doi.org/2731047
28. William A. McNeely. 1993. Robotic graphics: a new approach to force feedback for virtual reality. *Proceedings of IEEE Virtual Reality Annual International Symposium*. http://doi.org/10.1109/VRAIS.1993.380761
29. Walter R Miles. 1930. Ocular dominance in human adults. *Journal of General Psychology* 3: 412–430.
30. Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. 2001. Redirected Walking. *Proceedings of EUROGRAPHICS*: 289–294.
31. Irvin Rock and Jack Victor. 1964. Vision and Touch: An Experimentally Created Confilict Between The Two Senses. *Science (New York, N.Y.)* 143: 594–596. http://doi.org/10.1126/science.143.3606.594
32. Adalberto L Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 3307–3316. http://doi.org/10.1145/2702123.2702389
33. Bernhard Spanlang, Jean-Marie Normand, David Borland, et al. 2014. How to Build an Embodiment Lab: Achieving Body Representation Illusions in Virtual Reality. *Frontiers in Robotics and AI* 1: 1–22. http://doi.org/10.3389/frobt.2014.00009
34. Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2010. Estimation of Detection Thresholds for Redirected Walking Thechniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1: 17–27. http://doi.org/10.1109/TVCG.2009.62
35. Susumu Tachi, Taro Maeda, Ryokichi Hirata, and Hiroshi Hoshino. 1994. A Construction Method of Virtual Haptic Space. *Proceedings of the 4th International Conference on Artificial Reality and Tele-Existence (ICAT'94)*.
36. Colin Ware and Jeff Rose. 1999. Rotating virtual objects with real handles. *ACM Transactions on Computer-Human Interaction 6*, 162–180. http://doi.org/10.1145/319091.319102
37. Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 7, 3: 225–240. http://doi.org/10.1162/105474698565686