Ownershift: Facilitating Overhead Interaction in Virtual Reality with an Ownership-Preserving Hand Space Shift

Tiare Feuchtner
Aarhus University, Denmark

Jörg Müller
University of Bayreuth, Germany

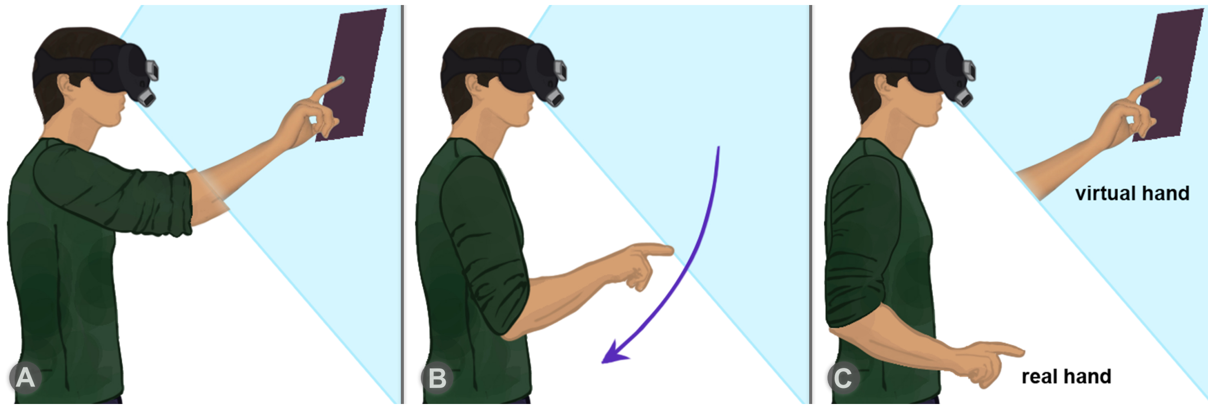

Figure 1. In Ownershift, interaction begins with a 1:1 mapping (A), which allows swiftly reaching towards different virtual targets. If interaction is prolonged, the virtual hand space (VHS) is shifted gradually (B), guiding the user's real hand into a more comfortable position. Overhead interaction can then continue with reduced strain while retaining similar degrees of task performance and body ownership of the virtual hand (C).

CCS Concepts

•Human-centered computing → Virtual reality; Interaction techniques; Empirical studies in HCI;

ABSTRACT

We present Ownershift, an interaction technique for easing overhead manipulation in virtual reality, while preserving the illusion that the virtual hand is the user's own hand. In contrast to previous approaches, this technique does not alter the mapping of the virtual hand position for initial reaching movements towards the target. Instead, the virtual hand space is only shifted gradually if interaction with the overhead target requires an extended amount of time. While users perceive their virtual hand as operating overhead, their physical hand moves gradually to a less strained position at waist level. We evaluated the technique in a user study and show that Ownershift significantly reduces the physical strain of overhead interactions, while only slightly reducing task performance and the sense of body ownership of the virtual hand.

INTRODUCTION

We perform most manipulations with our hands. However, the objects that we manipulate are often not positioned optimally, so that it may be uncomfortable or strainful to reach them; in particular if the manipulation takes a fair amount of time. This is especially true for overhead interaction. Fortunately, virtual reality (VR) allows us to shift virtual hands to the overhead target, while our physical (real) hands remain at a lower and much more comfortable position. Such a shift, or translation, of the virtual hand space (VHS) has previously been considered for bringing distant targets into reach. For instance, the Go-Go interaction technique [37] provides a nonlinear transfer function that allows the user to reach distant objects with his virtual hand by simply extending his physical arm. More recently, Erg-O [33] describes a nonlinear mapping by which the interaction space is subdivided into tetrahedrons, within which the position of the virtual hands is dynamically adjusted to make virtual targets more easily accessible. These two techniques demonstrate the considerable potential of such an approach. However, three aspects in particular are not considered in previous work.

First, interaction with overhead targets is very strenuous and could be alleviated by shifting the virtual hand position. Erg-O has the potential to improve interaction with overhead targets by shifting virtual targets downwards (or the virtual hand upwards). However, the maximum offset explored was limited to 10 cm and the authors indicate that participants did not experience any improvement in terms of comfort. We believe that much more radical hand-space transformations are required to facilitate less strainful overhead interaction.

Second, approaches that shift the VHS rely on movement corrections through eye-hand coordination and do not work well for rapid movements. Reaching movements can be separated roughly into an initial ballistic phase and subsequent corrective movements [40, 41]. During the ballistic phase, visual

UIST '18, October 14-17, 2018, Berlin, Germany

ACM ISBN 978-1-4503-5948-1/18/10 $15.00.
https://doi.org/10.1145/3242587.3242594

feedback is not processed, and thus a hand space shift would be ineffective. For this reason, both Go-Go and Erg-O depend on interaction with slow, controlled movements. To overcome this challenge, our technique begins with a 1:1 mapping, making it easier to reach swiftly for targets during short interactions. We only shift the VHS after a while, since interactions usually become more physically demanding when continued for a prolonged period of time [40].

Third, one of the most important aspects of interaction in VR, besides task performance, is that the users actually perceive their virtual hands as part of their body. This perception is commonly called the body ownership illusion or Virtual Hand Illusion (VHI) and leads to a more natural interaction, a stronger feeling of plausibility and presence [23], and arguably also a lower cognitive load. The work mentioned above did not explore the feeling of body ownership regarding the shifted virtual hands. However, in other non-interactive experiments, the body ownership illusion was reported to break when the artificial hand was located too far away from the physical hand [22, 29, 34]. It remains for us to explore how the proposed VHS transformations affect the illusion of "owning" a virtual hand (in the sense of it being part of one's body) during interaction in immersive VR.

In this paper, we address the three issues listed above. Accordingly, we present Ownershift, an interaction technique for reducing the strain of prolonged overhead tasks in VR. The technique enables users to reach quickly for any target with a 1:1 mapping, which is beneficial for very fast movements (see Fig 1, A). However, if the overhead reaching pose is maintained for extended periods of time, the hand space is shifted slowly; the virtual hand moves upward slowly, gently guiding the user to gradually lower his own hand in order to maintain alignment with the target (Fig 1, B). This leads to a less physically strained pose for prolonged interaction (Fig. 1, C). With our work, we contribute (1) an interaction technique that effectively reduces fatigue during overhead interaction in VR, (2) an evaluation of this technique in a user study comparing it with an instant shift and unaided overhead interaction, (3) evidence of the body ownership illusion, despite a large vertical offset between the real and the virtual hand.

The following are the main lessons learned from our user study: 1. The proposed VHS shift successfully reduces strain during overhead interaction, while task performance and ownership of the virtual hand are only affected slightly. 2. Ownershift is preferable to an instant shift, since, with similar task performance, the gradual shift allows initial ballistic reaching towards the target, is less conspicuous, and perceived as less disorienting and disruptive. 3. The virtual hand illusion seems to be more robust to vertical position offsets between the real and virtual hand than was previously believed.

RELATED WORK

Reducing fatigue during mid-air interaction

Interaction with vertical large screen displays, as well as mid-air interaction, have been found to be quite fatiguing [4, 5], colloquially termed the "Gorilla Arm". With the goal of identifying the optimal regions for interaction and designing low-fatigue interfaces, extensive work on dynamic models has explored this topic. For instance, RULA (rapid upper limb assessment) [32] provides a system for scoring the muscular effort associated with various different postures, based on the orientation of the arms and upper body. According to this method, the least strenuous working posture is one with the hands in front of the body at waist level, the elbows slightly bent, upper arms relaxed and torso straight. Similarly, Hincapié-Ramos et al. [20] identified interactions as least strenuous when hand positions allow bent elbows and are mid-way between the waist and shoulder. Bachynskyi et al. [5] recommended short or medium-length movements in the near and lower part of reachable space.

Hand space transformations

The Go-Go interaction technique [37] is one of the first examples of transformations of the hand space, where users could move the virtual hand beyond their real hand reach so as to access remote virtual objects in immersive VR. The virtual space can also be shifted without the user noticing, for instance, when virtually extending the interaction area by Redirected Walking [25, 38], or using a single haptic proxy for multiple virtual objects through Haptic Retargeting [3, 12]. In this context, Kohli et al. [26] found that performance in a multi-directional tapping task on a haptic proxy was comparable, with and without warping of the virtual space (i.e., same vs. different orientation of the physical and virtual surfaces). Furthermore, Burns et al. [9] indicate that an offset between the real and virtual hand may be readily accepted in order to preserve a believable visualization of the virtual hand, with respect to other virtual objects (e.g., no interpenetration of the virtual hand with other objects). Hence, warping the virtual world and body can enable us to avoid interpenetration of the virtual hand with other virtual objects, or effectively make virtual controls more easily accessible and interaction less tiring, as exemplified by Erg-O [33].

With the aim of making retargeting unnoticeable, most techniques discussed above apply only small shifts (e.g., max. 10 cm [33]). In exploring larger offsets, it has been found that deviations of up to 40° were "bearable" for retargeting [12]. In another experiment, horizontal offsets of up to 76 cm were applied when reaching for a virtual target and its haptic proxy [19]. These researchers found that instantly applying the shift was less disorienting and led to better performance than when interpolating the offset while reaching (i.e., retargeting).

In this paper, we explore the effect of applying a large vertical shift (avg. 65 cm) to the VHS, to ease overhead interaction. In contrast, most related systems apply small horizontal shifts for the purpose of guiding the user's hand to haptic props. Additionally, all approaches discussed above take advantage of the dominance of vision over proprioception, and our natural reliance on visual cues when navigating towards a target (eye-hand coordination). Unfortunately, this does not work well during initial ballistic hand movements towards a target. With our technique, we address this challenge by beginning with a 1:1 mapping and only gradually applying a shift for prolonged interaction. We are not aware of any previous work exploring shifts that are applied gradually over time (vs. interpolation based on the real hand position [3, 12, 37, 33]), and the implications this may have for interaction in VR.

Body ownership illusions

We experience the world with our senses and interpret what we perceive through multisensory integration [10, 31]. However, this sometimes leads to misinterpretation, such as the ventriloquist effect [1]. Another such effect is the body ownership illusion. Body ownership refers to the conviction that your hand, for example, is part of your body, and the illusion of body ownership involves self-attribution of a body-external object. This is probably best known through the rubber hand illusion (RHI) [7]. To elicit this illusion, a rubber hand and a person's hidden real hand are stroked synchronously with a brush. Since the touches felt can only be observed on the rubber hand, this leads to a referral of touch and the interpretation that the rubber hand must be part of the own body. There appears to be some interplay between body ownership and agency [8, 11, 21, 22, 48]. However, it is important to be aware of the distinction between these two terms. Agency, or the sense of control, refers to a feeling of causing a change in the world. For instance, we feel agency when we click something with our mouse cursor, but we will not feel body ownership of the cursor.

Several variations of the RHI experiment have been performed, in order to explore the processes behind this illusion [15, 17]. While the classic RHI experiment relied on synchronous visuo-tactile stimuli, it has been found that the illusion can be achieved through multisensory integration of multiple different senses, such as tactile-proprioceptive [16], visuo-proprioceptive, and visuo-motor [14, 15, 21, 27, 46, 47]. The latter refers to an artificial hand moving in correspondence to the real hand and has been termed the Moving RHI. The RHI has been replicated in VR, as the illusion of owning a virtual hand [43], which is frequently referred to as the virtual hand illusion (VHI) [2, 28].

There is a large body of work exploring the limitations of body ownership illusions: from congruency of stimuli [8, 11, 13, 17, 42, 46], to mismatches in the appearance, morphology, and connectivity of the virtual limb [35, 39, 43, 44, 45]. It has also been found that the body ownership illusion is affected by the distance between the real and artificial hand, with Kalckert and Ehrsson reporting no body ownership beyond a *vertical displacement* of 27.5 cm [22]. Lloyd [29] and Nierula et al. [34] confirm, that body ownership is similarly weakened by *horizontal displacement*. However, while the authors do not discuss absolute ratings, it is clearly evident from their figures, that they observed positive ratings for referral of touch at 67.5 cm [29], as well as some evidence of the VHI at 30 cm displacement [34]. Furthermore, the body ownership illusion proved surprisingly robust to *displacements away* from the user, as explored for connected virtual arms, that were extended up to 3 times their normal length [18, 24]. The latter examples, which provide evidence of ownership, despite displacement of the virtual hand, have in common that they were realized in immersive virtual environments. This supports our hypothesis that users may be more tolerant of discrepancies between the real and the virtual hand in immersive VR, due to the lack of visual cues from the real world and their real body. Hence, this paper takes a step towards exploring how robust the VHI is towards large vertical position offsets and extends the analysis of how this could be leveraged to improve interactions.

OWNERSHIFT

Transformations of the virtual hand space

We define the virtual hand space (VHS) as the interaction space with its origin at the center of the virtual hand representation, which can be transformed with respect to the user. It could for instance be scaled, rotated, or shifted. A shift of the VHS results in a location mismatch between the participant's real and virtual hand, as depicted in Fig. 2. This allows users to access difficult-to-reach targets with their virtual hand representation, while keeping their own hand in a comfortable position. Apart from this shift, the tracking of the user's hand remains unmodified, allowing accurate movement of the virtual hand and fingers.

Our work aims to explore whether transformations can be applied to the virtual hand space, so as to render interaction less tiring, while preserving the illusion of ownership for the virtual hand. The shifts we explore are limited elevation changes of the virtual hand. Our focus on vertical shifts is due to the assumption that when interacting with a target off to one side, we can reorient our torso, or even our whole body, towards it to make interaction more comfortable. For distant objects, we are usually able to walk towards them. However, when manipulating an object above shoulder level, there is no option of repositioning ourselves to make this less strenuous.

Facilitating overhead interaction

We explore a VHS shift to allow the virtual hand to be aligned with an overhead target, while the user holds his physical hand at waist level. This vertical position-offset of magnitude d is the result of a translation of the VHS along a circular path, based on a rotation α around the user's right shoulder (Fig. 2).

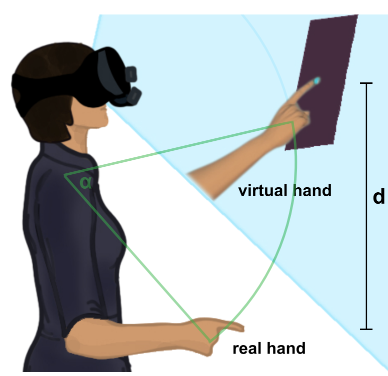

Figure 2. A VHS shift results in a vertical position offset d between the real and virtual hand. We arrive at this offset by translating the virtual hands on a circular path, based on a rotation (α) around the user's shoulder on the sagittal plane. To achieve a more realistic posture, the virtual forearm is always oriented towards the user's elbow.

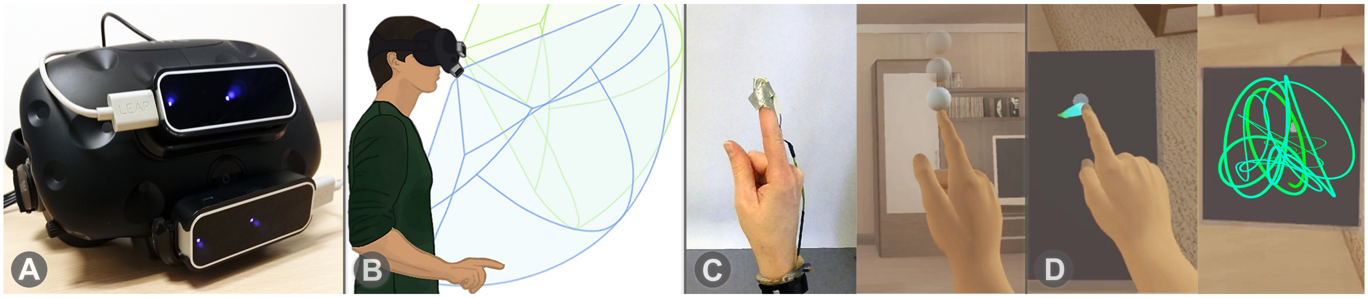

Figure 3. (A) Two Leap Motion sensors were attached to the HMD to support hand tracking, both in the line of sight and in front of the user's body. (B) The resulting tracking volumes are indicated with lines in light green (front-facing sensor) and blue (downward-facing sensor). (C) Haptic feedback was provided through a small vibration motor that was taped to the index finger. (D) A classic pursuit tracking task was used to evaluate task performance; participants followed a target (light circle) of 1 cm radius, which moved across a 30x30 cm panel with quasi-random motion.

Such an arm-rotation in the sagittal plane around the medio-lateral axis (i.e., the axis traversing both shoulders), corresponds to shoulder flexion. Note that this technique ensures a consistent mapping of the hand movements, albeit with the virtual hand translated to a different position.

We propose this shift to be applied gradually, and only during prolonged interaction with an overhead target. At the beginning, the real and virtual hands are collocated (1:1 mapping), allowing the user to reach rapidly for the target. This is important, because when we reach for a target with quick movements, we rely less on eye-hand coordination and would not be capable of correcting for a large shift. However, when interaction with the same target is continued involving smaller hand movements, the VHS can be transformed gradually. While this shift is applied, the user must continuously adjust the position of his real hand, in order to keep the virtual hand aligned with the target, so that his physical hand is guided automatically to a more comfortable posture. If interaction with the target requires a certain degree of hand motion, the shift of the VHS is masked and becomes almost unnoticeable. To reset the shift, our current solution entails detecting when the hand leaves the user's field of view, upon which the system switches back instantly to a 1:1 mapping. This allows the user to reach for other targets in the interaction space, and if interaction is prolonged, a new VHS shift is applied gradually.

SYSTEM DESIGN

To explore the effects of shifting the VHS for overhead interaction, we implemented a prototype in Unity3D[1]. We use a state-of-the-art HMD (HTC Vive[2]) to provide an immersive virtual environment. Furthermore, the system supports full hand tracking and haptic feedback.

Supporting hand tracking in reachable space

For convincing hand and finger tracking, we rely on the Leap Motion[3] sensor. In our design process, we discovered that with the default configuration of using a single Leap Motion sensor attached to the HMD, we could track the hand well along the line of sight. However, this would not support interaction with a shifted VHS, since the participant would then be looking slightly upwards at an overhead target, while moving his physical hand at waist level. Thus, we decided to increase the tracking area with a second sensor. The most stable solution for this proved to be mounting both sensors on the front of the HMD, one centered and the other at the lower edge, as shown in Fig 3 (A). This allows us to additionally track the interaction space in front of the user's body, while looking at an overhead target (Fig 3, B).

Since hand tracking with the LeapMotion sensor relies on the emission of infrared light, multiple, simultaneously active sensors cause interference, which causes the virtual hand to shake. Therefore, it is preferable to have only one sensor active at a time. Hence, the system switched from one sensor to another, when the VHS was shifted. This was based simply on the known location of the interactive target and the user's hand (i.e., when the user's hand was about to leave the tracking area of the front-facing sensor due to the VHS shift, the downward-facing sensor was activated, and as soon as it registered the user's hand, the first was then deactivated). The coordinate systems of both sensors were mapped on top of each other in an initial calibration step, which made the transition smooth and unnoticeable to the user. It remains for future work to devise a more flexible approach for switching dynamically between multiple LeapMotion sensors.

Design of visual and haptic feedback

To make interactions more convincing, visual and tactile feedback is provided whenever the participant's index finger touches a virtual object, e.g., a bouncing ball (Fig 3, C), or an interactive panel (Fig 3, D). A trail of particles follows the finger's path on the object's surface and the intensity of the tactile stimulus on the fingertip varies continuously with the movement speed. Aiming to mimic the feeling of moving your finger lightly over an uneven surface, it vibrates more strongly when moving faster and ceases to vibrate when the finger rests (motionlessly) on the surface. The tactile feedback is provided through a small vibration motor (LRA[4]) that is attached to the tip of the user's index finger. The LRA is controlled through an Arduino Uno[5] and Sparkfun haptic motor driver[6], which receives commands from Unity via serial communication.

[1] `https://unity3d.com`
[2] `https://www.vive.com`
[3] `https://www.leapmotion.com`

[4] `https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras`
[5] `https://store.arduino.cc/arduino-uno-rev3`
[6] `https://www.sparkfun.com/products/14031`

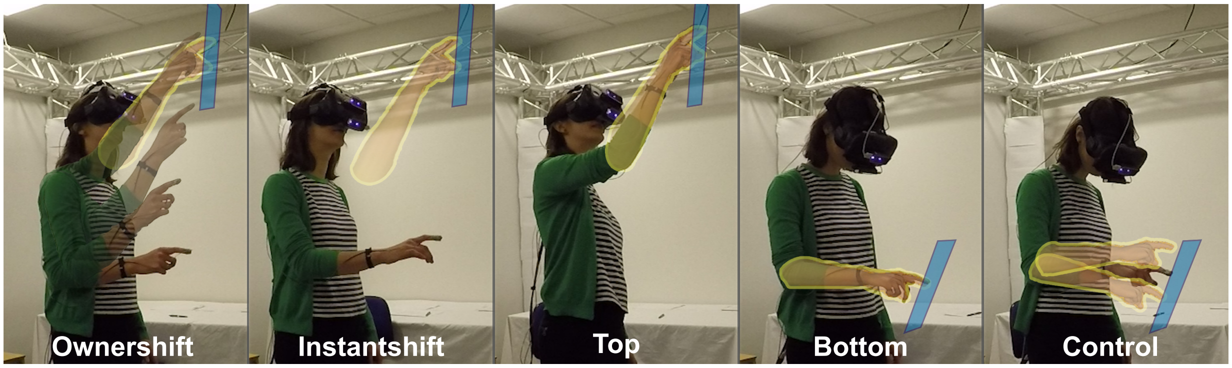

Figure 4. The five conditions varied in panel position, and the type of VHS shift. From left to right: Ownershift condition (O) with gradually applied shift and panel located at the top; Instant shift condition (I) with instantly applied shift and top panel; Top condition (T) with collocated hands and panel at the top; Bottom condition (B) with collocated hands and panel at the bottom; Control condition (C) with quasi-random shifts and bottom panel. The virtual hand is overlaid and highlighted with a yellow outline.

EXPERIMENT

To evaluate the Ownershift interaction technique, we conducted an experiment comparing the linear shift to an instant VHS shift, and to unaided overhead interaction (no shift: collocation of real and virtual hands).

Study Design

We performed a user study to evaluate our interaction technique with respect to the following **dependent variables**: *physical strain*, the *illusion of ownership*, and *task performance*. We designed five conditions varying the **independent variables**: *type of shift* and *panel position* (see Table 1).

	Shift	linear	instant	none	quasi-random
Panel	top	O	I	T	-
	bottom	-	-	B	C

Table 1. The study design consisted of five conditions: Ownershift (O), Instant shift (I), Top (T), Bottom (B), and Control (C). These varied in panel position and the shift type (independent variables).

The conditions are depicted in Fig 4. In the Ownershift condition (O), the user started out reaching overhead to track the target on the top panel (1:1 mapping; collocation of real and virtual hand). The shift was then increased linearly over a duration of 45 seconds, slowly easing the user into a more comfortable position with his hand at waist level. This duration resulted from pilot studies, since this shift speed was found to be barely noticeable and yet allowed the full offset to be reached in less than 1 minute (ensuring 1 minute of interaction with full offset in the 2-minute tracking task explained below). The gradual shift was compared to the Instant shift condition (I), in which the same VHS shift was applied, albeit instantly. This required the user to first locate the virtual hand at its elevated position and adapt to the offset immediately, before being able to interact with the top panel. An instant shift was chosen over an interpolation-based approach (e.g., Go-Go [37], or Haptic Retargeting [3]), since this has been shown to lead to better performance in reaching-tasks with large offsets [19]. Both approaches with shifted VHS were explored in contrast to the Top condition (T), which required unaided overhead interaction with collocated hands (no VHS shift). Furthermore, to collect a baseline, we designed a Bottom condition (B) with 1:1 mapping, for which the panel is easily accessible at waist-level, and an asynchronous variant thereof, the Control condition (C). In the latter, quasi-random shifts were applied to the VHS, with the purpose of disrupting the sense of body ownership and control, and leading to sub-optimal task performance. These quasi-random shifts are explained in more detail in the respective section below.

We conducted the experiment with respect to the following hypotheses: Compared to a collocation of the virtual and real hand (Top condition), shifting the VHS (Ownershift and Instant shift condition) reduces strain in an overhead tracking task (**H1**). The illusion of owning the virtual hand can be maintained, despite the large shift of the VHS (avg. 65 cm) in Ownershift condition (**H2**). Shifting the VHS (Instant shift and Ownershift condition) leads to similar task performance in an overhead tracking task, compared to no shift (Top condition) (**H3**). Based on these hypotheses, we aimed to find out whether it was beneficial to apply a VHS shift gradually, instead of instantly (**RQ1**). Another research question was whether task performance deteriorated while the linear shift was applied, since the user additionally needed to compensate for the adjustment of the VHS while following the target (**RQ2**).

Positioning of interactive panels

The interactive panel measured 30x30 cm and was positioned within comfortable reach in front of the user. Horizontally, the panel was aligned with the user's right shoulder to prevent participants from reaching across their mid-line during interaction. For the panel's vertical placement, we defined a bottom position and a top position. In bottom position, the panel was easily accessible at waist level, while in top position, the panel was centered approximately at eye level. For the latter, the user needed to reach overhead when required to access the panel's upper edge. Panel positions were dynamically adjusted to the user's height (bottom position avg.: 112 cm, top position avg.: 178 cm).

Design of the pursuit tracking task

To evaluate task performance, we chose a classical pursuit tracking task in 2D, with quasi-random target motion. An overview of tracking tasks for interface evaluation is provided by Poulton [36]. In the implemented task, a round target of

1 cm radius moved on the 30x30 cm panel (see Fig 3, D). Quasi-random motion in x and y direction was generated by a sum of 4 sinusoids. Angular frequencies and phase shifts, which were adapted over the course of multiple pilot studies, are provided in Table 1 in the appendix. The user's objective was to keep the tip of his index finger centered on the target at all times.

Quasi-random VHS shift

The quasi-random offsets applied to the virtual hand in the Control condition were calculated similarly as a sum of sinusoids. This was intended to give participants the impression that the virtual hand was uncontrollable. The phase shifts and angular frequencies, in Table 2 of the appendix, were chosen on the basis of a pilot study. In trying to compensate for the movements of the virtual hand, the participants were engaging in a kind of compensatory tracking task, in addition to the pursuit tracking task (following the dot). This has been shown to significantly reduce task performance [36].

Data collection

Data was collected both by logging tracking data for task performance (i.e., the participant's ability to follow the moving target) and through subjective questionnaire ratings for body ownership, agency, and physical strain.

Tracking task error

During the trial, the location of the target and the user's fingertip were recorded in each frame. The position of the index finger was projected onto the panel's surface, so as to cope with the challenge of depth perception and mid-air interaction, which occasionally led participants to lose touch with the panel. The task error was then calculated as the root-mean-squared error ($rmse$) [36].

In order to improve the comparability of our results with related work, we used relative errors, as recommended by Poulton [36]. In other words, we analyzed participant performance by comparing the task error ($rmse$) with the error that would occur if the participant had held his finger in the center of the panel during the entire trial ($refE$).

This results in an error ratio, or percentage, with lower values describing a smaller error and therefore better task performance. For more details, refer to equations (1), (2) and (3) in the appendix.

Questionnaire

After each trial, participants were asked to respond to a questionnaire with nine items (see Table 3 in the appendix). The first four items of the questionnaire (Q1-Q4) aimed at evaluating the participant's feeling of body ownership and agency of the virtual hand. This type of questionnaire is very commonly used to evaluate body ownership, and the items mentioned are based on the original ownership questionnaire [7], as well as later adaptations [21, 24, 43]. Ratings were given on a 7-point Likert scale with values ranging from -3 ('strongly disagree') to 3 ('strongly agree').

The next five questions (Q5-Q9) prompted the participant to indicate the amount of physical strain they felt during the tracking task in their right shoulder, upper arm, forearm, hand and neck. These body parts were chosen, because they were the most affected by the task, since the different conditions influenced neck-tilt and the degree to which the arm needed to be raised. Strain intensity was rated on the Borg-CR10 scale [6], which has been found to correlate strongly with other endurance metrics, such as EMG [20]. Furthermore, we were interested mainly in the participants' perceptions of strain (rather than an objective measure), since this affects their overall experience.

Participants

We recruited 16 right-handed volunteers (4 female) to participate in the experiment. Participants were between 21 and 38 years of age ($mean$ = 28.5, sd = 5.09). All had normal or corrected-to-normal vision and did not suffer from any shoulder injury, or pain when lifting their right arm. Most participants were students or staff at the Department of Computer Science and 12 worked in computer science related fields. Nevertheless, previous VR experience was low ($median$ = 2, sd = 1.05), which translates to "1-3 times" on a scale from 1 ("never") to 5 ("10 or more times"). All participants gave informed consent and were compensated for their time.

Procedure

At the beginning of the experiment, a small vibration motor was attached to the tip of the index finger of the participants' right hand and the experimenter helped them put on the HMD. The participants found themselves in a bright, virtual living room and were asked to look around and familiarize themselves with the virtual environment. Next, they were guided through a short training session in which the pursuit tracking task was introduced. Participants were encouraged to practice the task in each of the conditions, in order to get acquainted with the system and the different types of VHS shift. Once they felt confident that they could perform the task successfully in each of the conditions, the VR equipment was removed and they completed a form with demographic information.

The participants were then again equipped with the VR gear, so as to begin the trials, each of which consisted of 2 phases: In Phase 1, the illusion of ownership was elicited. The virtual and real hand were always collocated in this phase, i.e., the VHS was not shifted. Participants were asked to lift their right hand and follow a set of instructions, e.g., to look carefully at the virtual hand, wriggle their fingers and observe the virtual hand responded to their movements. This provided synchronous visuo-motor stimuli. They were then asked to extend their index finger. Then, pointing upward, a virtual ball appeared to be bouncing up and down on the tip of their index finger. Haptic feedback through the vibration motor enabled them to feel the impacts of this ball. This congruent visuo-tactile stimulation continued for about 20 seconds. Phase 2 consisted of the pursuit tracking task. The experimenter directed the participants' attention to the virtual panel, which they would interact with during the trial. Participants were asked to reach out to the panel with the virtual hand. In the Instant shift condition, this meant that participants needed to first locate the virtual hand, since the VHS space was shifted from the start and the virtual hand was not collocated with their physical hand. In contrast, all other conditions allowed them to rely on proprioception to plan the initial reaching movement. Participants were allowed to step closer to or further away from the panel, to accommodate variations in arm length. When the participants indicated that they were ready to begin tracking the target on the panel, the experimenter activated a 2-minute timer, during which their task performance was recorded. In the Ownershift condition application of the gradual shift was started at this point in time and the maximum offset was reached after 45 seconds. In each trial, the position of the panel and the shift of the VHS varied, depending on the condition (as shown in Table 1). At full VHS shift, the vertical position offset between the real and virtual hand averaged 65 cm, which corresponds to a rotation of 60° around the shoulder.

After each trial, the HMD was again removed and participants answered the questionnaire (see Table 3). This also gave them a short break from VR and permitted any lasting effects to wear off before the following trial. There were 5 trials, one for each condition. The order of conditions was counterbalanced with a Latin square. Each trial (including the questionnaire) took about 5 minutes to complete, 2 minutes of which were spent on the tracking task. This duration was based on earlier studies, which indicate that it may take some time for the ownership illusion to occur and also to wear off. Pilot studies were conducted to ensure that the task was not so long as to be painful.

At the end of the experiment, the participants were asked to rate their own performance in the pursuit tracking task and were invited to talk openly about the different conditions. The experiment took approximately 40-60 minutes.

RESULTS

In summary, we found that the VHS shift reduced strain successfully during interaction with an overhead target (H1). Furthermore, questionnaire responses show that the illusion of body ownership persisted, despite the large offset between the real and virtual hand (H2). The gradual offset in the Ownershift technique was described as more comfortable and less disruptive than the instant offset in the Instant shift condition. Finally, based on agency ratings, we found that participants consistently felt in control, despite a slight decrease in task performance (<4% decrease) in the shifted conditions (Ownershift and Instant shift) compared to the collocated conditions (Top, Bottom) (H3).

Physical strain

The amount of physical strain was evaluated from responses to questions Q5 to Q9 of the trial questionnaire (see Table 3). Responses indicate that the VHS shift successfully reduced physical strain during interactions with an overhead target.

Significant effects of condition on strain were analyzed with one-way repeated-measure ANOVA on questionnaire items, which were rated on the Borg-CR10 scale. Mauchly's test was used to detect any violation of sphericity, and corrections where made when needed. Post-hoc evaluation was performed through a pairwise t-test with Bonferroni correction.

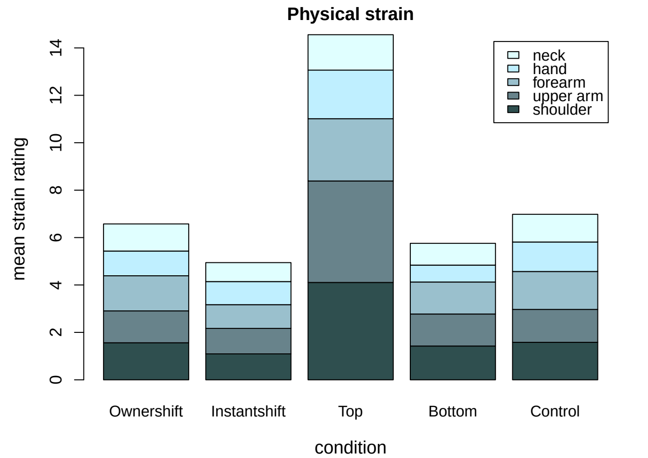

Figure 5. This plot shows the total strain per condition as a sum of mean strain ratings (on Borg-CR10 scale) for each body part. It can clearly be seen that the highest degree of strain was experienced in the Top condition, where the shoulder and upper arm were most strongly affected.

Fig 5 shows averages over all strain items (Q5-Q9), and reveals that the Top condition was more strenuous than all other conditions. Analyzing the questions individually, we find significant effects for all body parts (Q5-shoulder: $F(2.57, 38.50) = 22.83$, $p < 0.01$, partial $\eta^2 = 0.60$; Q6-upper arm: $F(4, 60) = 18.83$, $p < 0.01$, partial $\eta^2 = 0.56$; Q7-forearm: $F(1.90, 28.57) = 6.20$, $p < 0.01$, partial $\eta^2 = 0.29$; Q8-hand: $F(1.60, 24.02) = 4.35$, $p < 0.05$, partial $\eta^2 = 0.22$; Q9-neck: $F(4, 60) = 1.54$, $p < 0.05$, partial $\eta^2 = 0.09$).

Pairwise t-tests show significantly higher shoulder strain in the Top condition than in all other conditions (T vs. all others: $p < 0.01$). Reaching up to the target in the Top condition resulted in an average rating of 4.1 for the shoulder, which, according to the Borg-CR10 scale, corresponds to a perception of strain somewhere between "moderate" and "strong". In all other conditions, average ratings for shoulder strain remained below "weak" (avg. strain <= 1.6). A similar effect was evident for upper arm strain (T vs. all others: $p < 0.01$), which again averaged between "moderate" and "strong" in the Top condition (*mean* = 4.3), but remained between "very weak" and "weak" (avg. strain <= 1.4) in all others. The forearm, hand, and neck were less strongly affected by the overhead tracking task with mean ratings never exceeding 2.6 (below "moderate"). We therefore omit those results from the paper.

Body ownership illusion

Evaluating responses to questionnaire items Q1, Q2, and Q4 (see Table 3), we found evidence of the body ownership illusion, despite the VHS shift in the Ownershift condition. While the findings do show that the body ownership illusion was weakened by the offset between the real and virtual hand, a comparison with the Control condition indicates that participants still perceived a significant connection to the virtual hand in the Ownershift condition.

We performed Friedman rank sum tests on the Likert scale ratings to check for significant effects, followed by post-hoc

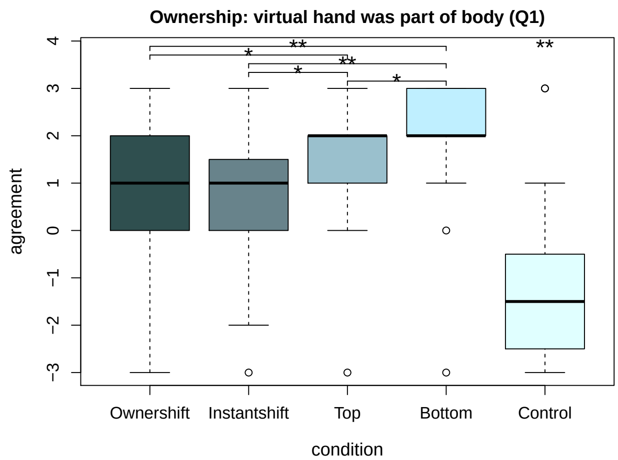

Figure 6. Responses to the primary ownership item (Q1) were highest in the Bottom condition and significantly lower in conditions with VHS shift (Ownershift and Instant shift condition). However, all synchronous conditions yield evidence of body ownership, with only the Control condition prompting mostly disagreement. Significant effects are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

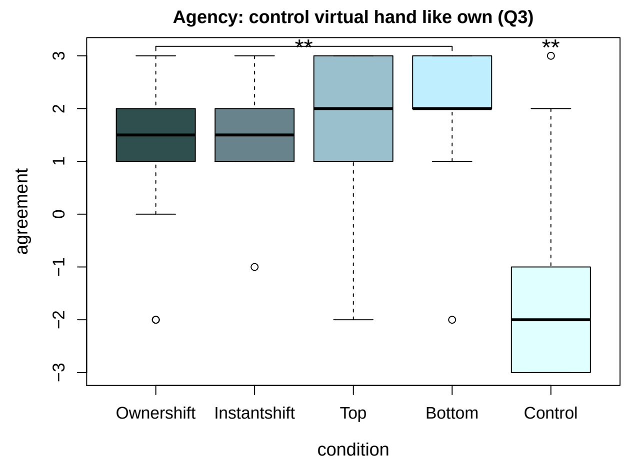

Figure 7. Participants perceived a high degree of control over the collocated virtual hand (Bottom, Top). Agency remained similarly strong, despite a shift of the VHS, as long as the hand motion remained synchronous (Ownershift, Instant shift). As expected, the asynchronous Control disrupted the feeling of agency. Significant effects are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

pairwise Wilcoxon signed-rank tests with continuity correction. For the main ownership question Q1 (“There were times when I felt that the virtual hand was part of my body”), we found a significant effect of condition ($\chi^2(4) = 30.91, p < 0.01$). The ratings for Q1 per condition can be seen in Fig 6.

Post-hoc analysis revealed that ownership was significantly lower in the conditions with VHS shift (Ownershift and Instant shift condition) than in both collocated conditions, Bottom and Top . (O vs. B: $W = 63$, $Z = 2.78$, $p < 0.01$, $r = 0.69$; O vs. T: $W = 50.5$, $Z = 2.54$, $p < 0.05$, $r = 0.64$; I vs. B: $W = 73$, $Z = 2.63$, $p < 0.01$, $r = 0.66$; I vs. T: $W = 42$, $Z = 2.40$, $p < 0.05$, $r = 0.60$). There was also a significant effect between the Bottom and the Top conditions (B vs. T: $W = 32.5$, $Z = 2.16$, $p < 0.05$, $r = 0.54$), indicating that interaction with the panel at top position reduced the body ownership illusion. However, all conditions received predominantly positive ownership ratings apart from the Control condition, for which ownership was significantly lower (C vs. O: $W = 76$, $Z = 2.98$, $p < 0.01$, $r = 0.75$; C vs. I: $W = 89$, $Z = 3.13$, $p < 0.01$, $r = 0.78$; C vs. T: $W = 10.35$, $Z = 3.29$, $p < 0.01$, $r = 0.82$; C vs. B: $W = 104$, $Z = 3.30$, $p < 0.01$, $r = 0.83$).

Responses to Q2 (“There were times when I felt like I had more than one right hand”) revealed a significant effect of condition on the illusion of owning multiple right hands ($\chi^2(4) = 19.63$, $p < 0.01$). Pairwise comparisons show that the feeling of owning multiple hands significantly increased when there was an offset between the real and virtual hand, as previously found by Nierula et al. [34]. However, responses were predominantly negative.

Agency ratings

The feeling of agency over the virtual hand was evaluated from item Q3 (“There were times when I felt I could control the virtual hand as if it were my own.”). As can be seen from Fig 7, participants gave positive ratings in all conditions, apart from the Control condition, indicating that they felt in control, despite the VHS shift.

The results of a Friedman rank sum test show a significant effect of condition on agency ($\chi^2(4) = 34.68$, $p < 0.01$). Post-hoc pairwise Wilcoxon signed-rank tests revealed a significantly weaker feeling of agency in the Ownershift condition compared to the Bottom condition (B vs. O: $W = 73$, $Z = 2.88$, $p < 0.01$, $r = 0.72$). As expected, the Control condition received lowest agency ratings (C vs. O: $W = 100.5$, $Z = 3.14$, $p < 0.01$, $r = 0.78$; C vs. I: $W = 133$, $Z = 3.43$, $p < 0.01$, $r = 0.86$; C vs. T: $W = 120$, $Z = 3.51$, $p < 0.01$, $r = 0.88$; C vs. B: $W = 105$, $Z = 3.47$, $p < 0.01$, $r = 0.87$).

Task performance

Analyzing participant performance during the tracking task, we observed a decrease in task performance in both shift conditions (Ownershift, Instant shift), compared to the Top and Bottom conditions (see Fig 8). Generally, we found that errors were slightly larger when interacting with the panel at the top, even without a shift (Top condition). As expected, the largest errors were recorded in the Control condition.

Mauchly’s test showed a violation of sphericity against Condition ($W(4) = 0.03$, $p < 0.05$). With a corrected one-way repeated-measure ANOVA, we found a significant effect of condition on the error ratio ($F(1.61, 24.1) = 156.86$, $p < 0.01$, partial $\eta^2 = 0.91$).

Post-hoc analysis using a pairwise t-test with Bonferroni correction reveals the following effects: the VHS shift in Ownershift and Instant shift condition led to significantly higher errors than both collocated conditions, Bottom and Top (O,I vs. B,T: $p < 0.01$). However, in interaction with the panel at the top, average errors were similar (O: $avg.error = 0.199$, T: $avg.error = 0.16$) and the increase in error ratio between the Ownershift condition and Top condition amounted to less than 4%. There was no significant difference be-

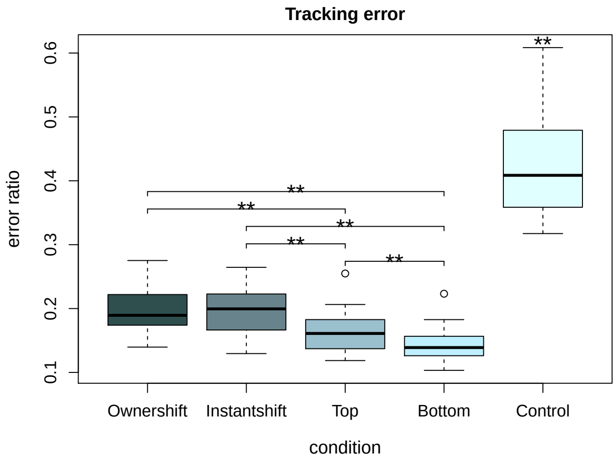

Figure 8. Task performance, measured as the ratio of the root-mean-square error to the target movement, was best in the Bottom condition. Interaction with the top targets led to a higher error rate, in particular when a VHS shift was present (Ownershift, Instant shift). Errors in the Control condition, however, were nearly twice as large and performance was thereby significantly worse than in all other conditions. Significant effects are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

tween Ownershift and Instant shift (I vs. O: $p = 0.75$; O: $avg.error = 0.199$, I: $avg.error = 0.197$). When hands were collocated, interaction with the panel at the top also led to a larger task error than with the panel at the bottom (B vs. T: $p < 0.01$; B: $avg.error = 0.14$, T: $avg.error = 0.16$). Finally, as expected, participants displayed the lowest overall task performance in the Control condition (C vs. all others: $p < 0.01$) with 43% error ($avg.error = 0.43$).

In the Ownershift , the VHS shift was increased linearly over 45 seconds during the first minute of interaction. Earlier research shows evidence that a drifting hand position may lead to reduced performance in pointing tasks [9]. However, we found no significant differences when comparing the error ratios of the first and second minutes of the task, in order to explore whether task performance was diminished when participants needed to compensate for the changing offset.

Post-trial questionnaire and qualitative findings

At the end of the experiment, participants rated their own task performance on a 7-point Likert scale (from -3 'strongly disagree' to 3 'strongly agree'). They were then asked to comment on each of the conditions in a semi-structured interview. Participants were encouraged to say the first thing that came to mind.

Our findings show that overall, participants felt good about their task performance. They felt they could adjust quickly to the VHS shift in the Ownershift and the Instant shift conditions, and that interaction with the panel worked well. While the Instant shift required a short "calibration phase", most participants were not very much aware of the shift in the Ownershift condition. Both shift conditions were perceived as much more comfortable than the Top condition. As expected, the Bottom condition felt most natural, while the Control condition was perceived as annoying and disruptive.

Self-assessment of task performance

Participants felt that they had performed fairly well in the pursuit task. The statement "I did well in the pursuit tracking task (i.e., following the dot on the panel)" received a median rating of 1.5 (on a scale from -3 to 3).

Qualitative findings for interaction conditions

Participants were asked to comment on each of the conditions in the order in which they had experienced them. Note that participants were not aware that the Ownershift condition was the technique we wished to evaluate.

Our interaction technique, Ownershift, was described as "natural" (p5, p7), and participants indicated that hand movements were predictable (p6, p12) and that interaction became more comfortable as the shift occurred (p4, p13). Two participants described the interaction as a little "strange" (p10, p15). The majority of participants (12/16) indicated that they were only slightly or not at all aware of the shift taking place. The adjustment to the offset happened "automatically" (p7, p9) and some recounted that they suddenly became aware of their real hand being much lower than the virtual hand (p3, p10). Only two participants (p2, p13) noticed the shift strongly (p13 - "specially in big circular motions"). The gradual offset in the Ownershift condition was often described as more comfortable and easier to adapt to than the instant offset. The gradual shift was described as requiring less cognitive load and being less disruptive to their connection with the virtual hand (p1, p3, p5, p7, p16). Participants said "it felt more like my own hand than with the instant offset, because I didn't notice the difference as much"(p1), and "[the Ownershift condition] feels a bit more natural than instant. [... there's a] more natural connection." (p7). Another participant added that Ownershift "wasn't as jarring as when my arm was initially up there [referring to the Instant shift condition]" (p16). However, one participant explicitly indicated that she preferred the Instant shift condition, because there "you had a clear idea of what your movement should be [...] when it was gradually offset, you had to adjust all the time and that was a bit difficult" (p2).

The Instant shift condition was described as "nice" and "better", "more convenient", "more comfortable" and "less tiring" than Top (p2, p7, p9, p10, p12, p13, p16). Participants indicated that interaction worked well, did not require much concentration, and that recalibration was automatic (p1, p3, p7, p10, p11, p13, p14, p15, p16). Interestingly, many explicitly described a first calibration phase and said that once they had made the mapping in their brain, it was similar to interacting with collocated hands (p3, p8, p12, p13, p14, p15): "there was a calibration phase but when I got it, it was fine" (p12); "when you learn it, you learn it" (p3).
Others commented that the virtual hand felt more disconnected and less like their own hand (p4, p6) in the Instant shift condition. They described it as "remote controlling" something (p7); "it was (as if) connected with a string or [...] balanced the hand on top of my hand" (p4); "it was like projecting your hand up there [...] like a laser pointer" (p5).

Unsurprisingly, the Top condition, with collocated hands and interaction overhead, was described by all participants as "tiring" , "uncomfortable" , "painful" or "annoying" . For instance p11 said "I couldn't last more than 2 minutes". One participant (p3) said that he felt like time went much faster in the trials with VHS shift, and that the Top condition was the longest trial. But some participants also described it as "good" (p10, p11) in terms of control, "real" (p5) and similar to Bottom (p13, p14, p15).

DISCUSSION

From our findings, we conclude that a vertical shift (65 cm) of the VHS can effectively reduce fatigue during overhead interaction (H1), while maintaining the illusion of owning the virtual hand (H2). Performance is only slightly affected by this shift (less than 4% decrease) and the user feels in control of the virtual hand (H3). The decrease in task performance could be addressed by increasing the size of the moving target; with a target of 3 cm radius, participants would have stayed within the target's bounds 90% of the time (in the Ownershift condition, 90% of measured errors were smaller than 0.03). Additionally, it stands to reason that training could improve task performance [19]. As interpreted by Kohli et al. [26], in a warped virtual space, users are less precise at touching targets, but precise enough. However, it remains to be explored how a gradual shift might affect more delicate manipulations (e.g., drawing a straight horizontal line).

We find that participants performed equally well with the gradual shift in the Ownershift technique, as when interacting with an instantly shifted virtual hand, which has earlier been shown to be more effective than retargeting through interpolation [19]. The qualitative results further suggest that a gradual shift is preferable, since it was described as much less noticeable and less disruptive. Furthermore, it did not require a mental recalibration phase, since the initial 1:1 mapping in Ownershift allows initial ballistic movements toward the target (RQ1). This is in line with earlier work [19], which found that the instant shift was disorienting, when it meant that participants first had to look around to locate the hand, before being able to start interacting. Importantly, we found no evidence that task performance was diminished, while the VHS was gradually being shifted (RQ2).

We can confirm that a position mismatch between the real and the surrogate hand (i.e., rubber hand or virtual hand) leads to lower ratings for the body ownership illusion, as has previously been found by several authors [22, 29, 34]. However, our findings also indicate that under certain circumstances (i.e., realistic hand representation with a combination of visuo-motor and visuo-tactile stimulation), the VHI is much more robust towards such position offsets than was previously believed. It is conceivable that the illusion of owning a virtual hand could occur with even more extreme shifts. However, this remains to be explored. Surprisingly, we observed lower ownership in interaction with the panel at the top, even when hands were collocated (Top condition), compared to interaction with the panel at the bottom (Bottom condition). Presently, we can only surmise about the reasons for this. For instance, it may simply be due to less accurate hand tracking in that condition, since the LeapMotion is not optimized for interaction with elevated hands; or it could even be a side-effect of the discomfort of interacting overhead. More research is required to verify these assumptions.

In future, to make the shift even less noticeable, we recommend applying the gradual shift in proportion to the user's own hand motion. The user's movement could thus completely mask the displacement of the virtual hand, as has been explored in redirected walking [38] and haptic retargeting [3]. Furthermore, it remains for future work to explore the maximum unnoticeable VHS shift speed, as well as to devise better approaches for resetting the shift and dynamic switching between targets.

Apart from the aim of reducing fatigue, a technique based on Ownershift could also pursue support people with reduced mobility. By adjusting the shifts to their specific limitations, it could allow them to access the full reachable space. Furthermore, the principle could be inverted to intentionally increase the difficulty of reaching tasks for rehabilitation purposes.

The pursuit tracking task [36] proved well suited for the evaluation of continuous interaction with a target in VR. It kept participants engaged and required smooth hand movements at moderate speeds, which resembles prolonged direct manipulation of a virtual object. This was a common task for evaluating user interfaces in the 70's, but has largely been replaced by Fitts' law tasks [30] in contemporary HCI research. While tracking tasks do not allow measuring the throughput of a user interface (in bit/s), they evaluate how well users can control a dynamic system. Therefore, we believe that for interaction without a natural delimiter, such as free-hand interaction in immersive VR, the pursuit tracking task provides valuable insights. This is especially true if we wish to evaluate dynamics control, such as the ability to interact with physical simulations, as opposed to mere button clicking. Through this argument, we hope to inspire more researchers in HCI to use tracking tasks for evaluating user interfaces, in addition to Fitts' law tasks.

CONCLUSION

This paper presents Ownershift, an interaction technique that reduces strain during the manipulation of overhead targets, while preserving the illusion of owning the virtual hand. This is achieved by first supporting fast reaching for different targets with a 1:1 mapping, and then gradually shifting the virtual hand space (VHS) upwards, towards an overhead virtual target for prolonged interaction. This gently directs the user to move his hand into a more comfortable position at waist-level. While this leads to a radical offset between the real and the virtual hand, we found that users adjust to this easily, and that the impact on their task performance is limited (less than 4% increase in error). Our user study also provides evidence that a gradual application of VHS shift is preferable to an instant shift, since it allows initial ballistic reaching towards a target, and the offset is easier to adapt to and causes less 'disconnection' from the virtual hand. Furthermore, in contrast to earlier work, we found that the body ownership illusion can be maintained, despite the large vertical position mismatch (avg. 65 cm) between the real and the virtual hand.

REFERENCES

1. David Alais and David Burr. 2004. The ventriloquist effect results from near-optimal bimodal integration. *Current biology* 14, 3 (2004), 257–262.
2. Ferran Argelaguet, Ludovic Hoyet, Michaël Trico, and Anatole Lécuyer. 2016. The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *Virtual Reality (VR), 2016 IEEE*. IEEE, 3–10.
3. Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.
4. Myroslav Bachynskyi, Gregorio Palmas, Antti Oulasvirta, Jürgen Steimle, and Tino Weinkauf. 2015b. Performance and ergonomics of touch surfaces: A comparative study using biomechanical simulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 1817–1826.
5. Myroslav Bachynskyi, Gregorio Palmas, Antti Oulasvirta, and Tino Weinkauf. 2015a. Informing the design of novel input methods with muscle coactivation clustering. *ACM Transactions on Computer-Human Interaction (TOCHI)* 21, 6 (2015), 30.
6. Gunnar Borg. 1998. *Borg's perceived exertion and pain scales.* Human kinetics.
7. Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands feeltouch that eyes see. *Nature* 391, 6669 (1998), 756–756.
8. Niclas Braun, Jeremy D Thorne, Helmut Hildebrandt, and Stefan Debener. 2014. Interplay of Agency and Ownership: The Intentional Binding and Rubber Hand Illusion Paradigm Combined. *PloS one* 9, 11 (2014), e111967.
9. Eric Burns, Sharif Razzaque, Abigail T Panter, Mary C Whitton, Matthew R McCallus, and Frederick P Brooks Jr. 2006. The hand is more easily fooled than the eye: Users are more sensitive to visual interpenetration than to visual-proprioceptive discrepancy. *Presence: teleoperators & virtual environments* 15, 1 (2006), 1–15.
10. Gemma Calvert, Charles Spence, and Barry E Stein. 2004. *The handbook of multisensory processes*. MIT press.
11. Emilie A Caspar, Axel Cleeremans, and Patrick Haggard. 2015. The relationship between human agency and embodiment. *Consciousness and cognition* 33 (2015), 226–236.
12. Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3718–3728.
13. Marcello Costantini and Patrick Haggard. 2007. The rubber hand illusion: sensitivity and reference frame for body ownership. *Consciousness and cognition* 16, 2 (2007), 229–240.
14. Timothy Dummer, Alexandra Picot-Annand, Tristan Neal, and Chris Moore. 2009. Movement and the rubber hand illusion. *Perception* 38, 2 (2009), 271.
15. HH Ehrsson. 2012. The concept of body ownership and its relation to multisensory integration. *The New Handbook of Multisensory Processes - B.E. Stein (Ed.)* (2012), 775–792. MIT Press (Cambridge).
16. H Henrik Ehrsson, Nicholas P Holmes, and Richard E Passingham. 2005. Touching a rubber hand: feeling of body ownership is associated with activity in multisensory brain areas. *The Journal of Neuroscience* 25, 45 (2005), 10564–10573.
17. H Henrik Ehrsson, Charles Spence, and Richard E Passingham. 2004. That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science* 305, 5685 (2004), 875–877.
18. Tiare Feuchtner and Jörg Müller. 2017. Extending the Body for Interaction with Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 5145–5157.
19. Dustin T Han, Mohamed Suhail, and Eric D Ragan. 2018. Evaluating Remapped Physical Reach for Hand Interactions with Passive Haptics in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* (2018).
20. Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. 2014. Consumed endurance: a metric to quantify arm fatigue of mid-air interactions. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 1063–1072.
21. Andreas Kalckert and H Henrik Ehrsson. 2014a. The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and cognition* 26 (2014), 117–132.
22. Andreas Kalckert and H Henrik Ehrsson. 2014b. The spatial distance rule in the moving and classical rubber hand illusions. *Consciousness and cognition* 30 (2014), 118–132.
23. Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012a. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments* 21, 4 (2012), 373–387.
24. Konstantina Kilteni, Jean-Marie Normand, Maria V Sanchez-Vives, and Mel Slater. 2012b. Extending body space in immersive virtual reality: a very long arm illusion. *PloS one* 7, 7 (2012), e40867.

25. Luv Kohli, Eric Burns, Dorian Miller, and Henry Fuchs. 2005. Combining passive haptics with redirected walking. In *Proceedings of the 2005 international conference on Augmented tele-existence*. ACM, 253–254.

26. Luv Kohli, Mary C Whitton, and Frederick P Brooks. 2012. Redirected touching: The effect of warping space on task performance. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 105–112.

27. Elena Kokkinara and Mel Slater. 2014. Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception* 43, 1 (2014), 43–58.

28. Lorraine Lin and Sophie Jörg. 2016. Need a Hand?: How Appearance Affects the Virtual Hand Illusion. In *Proceedings of the ACM Symposium on Applied Perception (SAP '16)*. ACM, New York, NY, USA, 69–76.

29. Donna M Lloyd. 2007. Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and cognition* 64, 1 (2007), 104–109.

30. I Scott MacKenzie. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction* 7, 1 (1992), 91–139.

31. Angelo Maravita, Charles Spence, and Jon Driver. 2003. Multisensory integration and the body schema: close to hand and within reach. *Current Biology* 13, 13 (2003), R531–R539.

32. Lynn McAtamney and E Nigel Corlett. 1993. RULA: a survey method for the investigation of work-related upper limb disorders. *Applied ergonomics* 24, 2 (1993), 91–99.

33. Roberto A Montano Murillo, Sriram Subramanian, and Diego Martinez Plasencia. 2017. Erg-O: ergonomic optimization of immersive virtual environments. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. ACM, 759–771.

34. Birgit Nierula, Matteo Martini, Marta Matamala-Gomez, Mel Slater, and Maria V Sanchez-Vives. 2017. Seeing an embodied virtual hand is analgesic contingent on colocation. *The Journal of Pain* 18, 6 (2017), 645–655.

35. Valeria I Petkova and H Henrik Ehrsson. 2008. If I were you: perceptual illusion of body swapping. *PloS one* 3, 12 (2008), e3832.

36. Eustace Christopher Poulton. 1974. *Tracking skill and manual control*. Academic press.

37. Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*. ACM, 79–80.

38. Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. 2001. Redirected walking. In *Proceedings of EUROGRAPHICS*, Vol. 9. Citeseer, 105–106.

39. Martin Riemer, Xaver Fuchs, Florian Bublatzky, Dieter Kleinböhl, Rupert Hölzl, and Jörg Trojan. 2014. The rubber hand illusion depends on a congruent mapping between real and artificial fingers. *Acta psychologica* 152 (2014), 34–41.

40. Richard A Schmidt, Tim Lee, Carolee Winstein, Gabriele Wulf, and Howard Zelaznik. 2018. *Motor Control and Learning, 6E*. Human kinetics.

41. Reza Shadmehr and Steven P Wise. 2005. *The computational neurobiology of reaching and pointing: a foundation for motor learning*. MIT press.

42. Sotaro Shimada, Kensuke Fukuda, and Kazuo Hiraki. 2009. Rubber hand illusion under delayed visual feedback. *PloS one* 4, 7 (2009), e6185.

43. Mel Slater, Daniel Perez-Marcos, H Henrik Ehrsson, and Maria V Sanchez-Vives. 2008. Towards a digital body: the virtual arm illusion. *Frontiers in human neuroscience* 2 (2008).

44. G Tieri, E Tidoni, EF Pavone, and SM Aglioti. 2015. Mere observation of body discontinuity affects perceived ownership and vicarious agency over a virtual hand. *Experimental brain research* 233, 4 (2015), 1247–1259.

45. Manos Tsakiris, Lewis Carpenter, Dafydd James, and Aikaterini Fotopoulou. 2010. Hands only illusion: multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research* 204, 3 (2010), 343–352.

46. Manos Tsakiris, Gita Prabhu, and Patrick Haggard. 2006. Having a body versus moving your body: How agency structures body-ownership. *Consciousness and cognition* 15, 2 (2006), 423–432.

47. Lee D Walsh, G Lorimer Moseley, Janet L Taylor, and Simon C Gandevia. 2011. Proprioceptive signals contribute to the sense of body ownership. *The Journal of physiology* 589, 12 (2011), 3009–3021.

48. Jing Zhang, Wei Chen, Hengwei Li, Bernhard Hommel, and Tifei Yuan. 2014. *Disentangling the sense of agency and the sense of ownership in the virtual hand illusion paradigm*. Technical Report. PeerJ PrePrints.

Ownershift: Facilitating Overhead Interaction in Virtual Reality with an Ownership-Preserving Hand Space Shift

APPENDIX

Design of the pursuit tracking task

In the user study, task performance was evaluated with a pursuit tracking task [36] in which the participant was instructed to follow a moving target with his finger as closely as possible. The quasi-random movement of the target results from the sum of 4 sinusoids for both the x and y directions. Table 1 contains the angular frequency and phase shift for each sinusoid.

axis	sin1	sin2	sin3	sin4
x	$2.07t$	$1.65t$	$0.23t$	$0.37t$
y	$2.07t + 0.5\pi$	$0.96t + 0.5\pi$	$1.98t$	$1.08t$

Table 1. Angular frequency and phase shift of the quasi-random target motion in the pursuit task. The amplitude was 1.2 and *t* denotes the time in seconds.

Quasi-random VHS shift

The purpose of the Control condition was to break the body ownership illusion, reduce the feeling of agency and provide a benchmark for unacceptable task performance. Therefore, a quasi-random VHS shift was applied, which resulted in a constantly changing offset between the virtual hand and real hand positions, consequently rendering the hand uncontrollable for the user. The quasi-random shift was calculated as a sum of sinusoids, as presented in Table 2.

axis	sin1	sin2	sin3	sin4
x	$2.51t$	$2.4t$	$0.28t$	$0.44t$
y	$2.51t$	$0.12t + 0.25\pi$	$2t$	$2.51t + 0.5\pi$
z	$1.31t$	$1.16t + 0.5\pi$	$2.4t$	0

Table 2. Angular frequencies and phase shifts of the quasi-random hand offsets applied in Control condition. (*t* is time in seconds)

Tracking task error

During the pursuit tracking task, the task error was calculated as the root-mean-squared error ($rmse$) [36]:

$$rmse = \sqrt{\frac{\sum_{t=1}^{n} \left|P_{F(t)} - P_{T(t)}\right|^2}{n}}, \quad (1)$$

where P_F is the position of the participant's fingertip and P_T is the target position at time t.

The participant's task performance was then computed as the ratio of task error ($rmse$) to a reference error ($refE$) that would occur if the participant's finger had remained in the center of the panel during the entire trial:

$$taskperformance = \frac{rmse}{refE} \quad (2)$$

with

$$refE = \sqrt{\frac{\sum_{t=1}^{n} \left|C - P_{T(t)}\right|^2}{n}}, \quad (3)$$

where C is the center of the panel.

Questionnaire

After each trial in the user study, participants were asked to respond to the questionnaire items in Table 3. The questionnaire was completed on paper.

Body ownership & agency

Q1 There were times when I felt that the virtual hand was part of my body.
Q2 There were times when I felt like I had more than one right hand.
Q3 There were times when I felt I could control the virtual hand as if it was my own.
Q4 I never felt that the virtual hand was part of my body.

Physical strain

Q5 How much strain did you feel in your right shoulder?
Q6 How much strain did you feel in your right upper arm?
Q7 How much strain did you feel in your right forearm?
Q8 How much strain did you feel in your right hand?
Q9 How much strain did you feel in your neck?

Table 3. Participants responded to this questionnaire after each trial, indicating their degree of ownership (Q1, Q2, Q4), agency (Q3) and physical strain (Q5-Q9) for each condition.