Improving Virtual Reality Overhead Interaction Through Non-Linear Hand Space Shift

Haichen Gao
HCI-E MSc Final Project Report 2020
UCL Interaction Centre, University College London
Supervisors: David Swapp, Felix Thiel

ABSTRACT

Interacting with targets that are position at the mid-air could bring users a strenuous experience. This project presents Non-linear shift interaction technique that is further developed based on the previous Ownershift technique. Instead of actively shifting the user's virtual hand with a constant speed, Non-linear shift applies the hand shift speed in proportion to the velocity of hand movements along y-axis. According to previous results, Ownershift technique significantly reduces physical strain for overhead interactions, at a slight sacrifice of task performance and body ownership illusion of the virtual hand. In this study, we repeated Ownershift's experimental procedure with a replacement of the Instantshift condition with Non-linear shift. Results showed that Non-linear shift did not significantly improve the tracking task performance, whereas it provides more robust body ownership illusion than Ownershift.

Author Keywords

Virtual reality; Virtual hand shift; Physical strain; Body ownership illusion; Change blindness.

ACM Classification Keywords

Information interfaces and presentation (e.g., HCI): Miscellaneous

MSc Contribution Type

Empirical; Interaction Techniques.

MSC HCI-E FINAL PROJECT REPORT

Project report submitted in part fulfilment of the requirements for the degree of Master of Science (Human-Computer Interaction with Ergonomics) in the Faculty of Brain Sciences, University College London, 2020.

1. INTRODUCTION

The development of tracking technologies, 3D graphics and commercial VR devices have flourished VR system, not only in demonstrating vivid scenes but also allowing users to naturally interact with the virtual environment (VE) as they would do in reality [35] and feeling of presence [33]. However, manipulating objects that are not positioned optimally could bring users a strenuous and uncomfortable experience when users reach them in VE; in particular if the interaction is overhead and takes a period of time. Nevertheless, remaining virtual hands at mid-air while shifting real hands to a more comfortable position is applicable in VR. This kind of technique that shift or translate the virtual hand space (VHS) has been applied on reaching targets at distance. For example, the Go-Go interaction technique [29] nonlinearly extends user's virtual arm and allows the user to reach a distance object. Erg-O [23] makes virtual target more easily accessible through dividing the interaction space into tetrahedrons where virtual hands' position is adjusted dynamically.

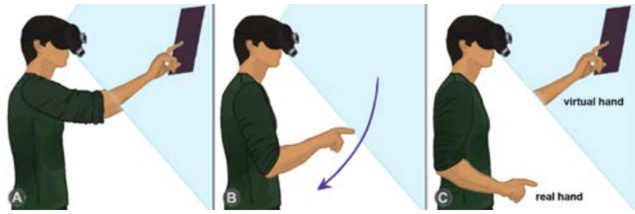

Figure 1. The interaction in Ownershift starts with 1:1 mapping (A), which allows initial reaching towards virtual targets. The VHS is gradually shifted if the target requires an extend amount of time (B), guiding the user's real hand into a comfortable position. Then it retains similar task performance and body ownership of the virtual hand (C) [12].

More recently, Ownershift [12] provides a technique that significantly reduces physical strain of overhead interactions. It applies more hand-space transformations (avg. 65 cm) at waist level in terms of alleviating physical strain of overhead interactions compared to maximum 10 cm offset in Erg-O. Meanwhile, the Ownershift technique only slightly decreases the sense of body ownership of the virtual hand by providing visual and haptic feedback. In addition, with the help of the collocated virtual and real hand at beginning, swiftly reaching targets during short interactions become easier; and the VHS only starts shifting after a while due to increasing physically demanding. Ownershift is designed based on the Go-Go interaction technique and Erg-

O technique as well as refines them in order to facilitate less strenuous overhead interactions particularly. However, there are three aspects which could be improved based on previous approach.

Firstly, although user has to continuously adjust his real hand to keep the virtual hand tracking the moving target, the actively and linearly applied hand shift probably influences tasks that involve smaller hand movements or intermittent pauses. One of the participants from the Ownershift experiment explicitly indicated that "[…] when it was gradually offset, you had to adjust all the time and that was a bit difficult" [12]. To ameliorate this potential defect, an alternative hand shift technique was devised which is only applied during hand movements, meanwhile, its shift speed is proportional to the speed of hand movements along y-axis. It is believed that in this way the shift of the VHS could be further masked by user's hand movement and the task performance can be improved at least during the hand shift period.

Secondly, nowadays most commercial VR headsets are sold with hand-held controllers with functionalities of locating the position of hands and tracking hand gestures, which are similar to Leap Motion sensors used by Ownershift experiment. In addition, controllers can also provide haptic feedback. Although its way of providing haptic feedback is vibrating the whole palm rather than concentrating on the fingertip by taping a small vibration motor to the index finger in Ownershift, the discrepancy would be nuance in terms of making interactions more convincing and reflecting the movement speed through vibration [34]. In this way, extra materials such as Leap Motion sensors and small vibration motors could be replaced with more accessible accessories while achieving similar body ownership of the virtual hand and task performance as Ownershift.

Thirdly, Ownershift currently resets the shift by instantly switching them back to 1:1 mapping when the virtual hand leaves the user's field of view. During the experiment, researcher found that users would notice about the hand shift before the virtual hand leaving away from the field of view. Users normally need to fully lay down their arm to make sure the shifted virtual hand is disappeared from the view due to a large vertical shift. And this could influence the body ownership rating between the condition with VHS shift and the condition with collocated hand. Therefore, designing a continuous resetting technique conducted in a short period of time after task completed is required, which is potentially beneficial for the result of body ownership ratings.

In this study, we repeated Ownershift's general procedure that is to conduct a pursuit tracking varied in type of VHS shift and position, with the following hypotheses: Compared to a linearly and actively applied hand shift (Ownershift), shifting the VHS proportionally to the movement of the real hand promotes better task performance while maintaining a same effect of physical strain reduction (H1). In addition, proportionally shifting the VHS according to real hand's movement will provide the user better body ownership and feeling of agency over the virtual hand compared to Ownershift technique (H2). Therefore, this study aims to find whether users could perform better with non-linear hand shift technique compared to Ownershift technique in pursuit tracking task (RQ1). Another research question is whether body ownership and agency ratings between Ownershift and Non-linear shift condition are significant different (RQ2).

2. LITERATURE REVIEW

2.1 Change Blindness

Change blindness denotes that people fail to notice significant changes to visual scenes [26]. Many previous researches observe this phenomenon through disrupting or hiding the localisable features accompanied with an immediate change [31]. For example, observers fail to notice changes in two pictures presented alternately which are separated by a brief flicker [32], eye blinks [26], "mud splashes" [27], or saccades [15], or if one is simply attending to something else [21]. In addition, gradually changing information over a period of time so that the changed feature is not sufficiently strong to draw attention also makes observers fail to notice changes [34]. According to this method, shifting objects unnoticeably without disrupting or blocking the user's view becomes achievable.

2.2 Reduce Fatigue during Mid-Air Interaction

Interacting with vertical screen displays and other mid-air interactions at around eye level bring arms fatigue [3, 4], commonly known as the "Gorilla Arm". To design low-fatigue interfaces, the optimal regions for interaction need to be identified in advance. According to RULA (rapid upper limb assessment) [22] model, the least strenuous working posture is positioning the hands in front of body at waist level while slightly bending the elbows. Hincapi´e-Ramos et al. [16] had a similar conclusion that positioning hands between shoulder and waist level with elbows bent is least strenuous.

2.3 Hand Space Transformations

Go-Go interaction technique [29], the early example of hand space transformations, enables users to get access to remote virtual object by shifting virtual hand further than their real hand reach. Later, shifting virtual space approaches such as virtually extending VE through redirected walking [19, 30]; as well as haptic retargeting [2, 10] which provides passive haptics for various virtual objects with a single physical prop. Those techniques utilise the vision dominance over proprioception [14] and people's reliance on eye-hand coordination while reaching towards an object. However, this is not user-friendly when the user tends to reach towards a target during initial ballistic hand movements. Ownershift [12] addresses this problem by starting with collocated hands and only gradually shifting the virtual hand for extended interaction.

With the aim of providing perceptually plausible experience in the VE, Zachmann and Retting [37] proposed two methods for determining the position of the virtual hand after being shifted from the user's real hand for preventing visual avatar interpenetration. For the rubber band method, the virtual hand will be blocked and retain on the virtual object's surface while the user is drawing his hand out of the object (Figure 2 A). It minimises the offset between the visual and real hand at the cost of generating different velocity of the visual and real hand. The other method is called incremental motion method, which maintains the relative displacement of the virtual and real hand (Figure 2 B). This method minimises the discrepancy between the velocity of the visual and real hand at the cost of maintaining the offset between the visual and real hand.

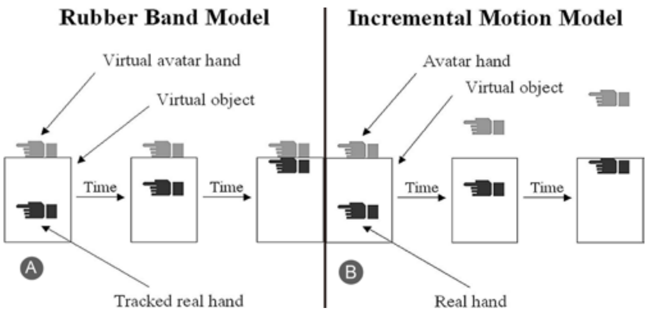

Figure 2. The discrepancy of distance between virtual and real hand in rubber band model (A) and incremental motion model (B) [8].

Although the rubber band model and the incremental motion model endeavour to make compensation to side effects caused by shifted hands, neither technique is ideal. Both of the techniques achieve minimum discrepancy in one variable only. Burns et al. [8] propose Credible Avatar Limb Motion (CALM) technique that combines these two extremes to abate sensory discrepancy. In this technique, the virtual hand will move towards the user's real hand only if the user's real hand moves towards the virtual hand's current position. Otherwise, it will maintain the offset between virtual and real hand. According to CALM technique, we applied a new method that the speed of virtual hand moving towards real hand is proportional to the real hand's velocity along the direction of virtual and real hand.

2.4 Body Ownership Illusions

The illusion of body ownership is a result of psychological and physical interactions between people's body and sensory feedback perception [36]. Take the rubber hand illusion (RHI) [6] as an example; participants sat with eyes fixed on the rubber hand while the rubber hand and the participant's hidden real hand are stroked synchronously by two paintbrushes. Because the participant is only observing the rubber hand being touched, this becomes a referral of touch and interpretation that the rubber hand must be part of the own body. Comparted to body ownership, the feeling of agency more refers to a feeling of control and causing a change in the world [7, 9]. For example, you reckon the cursor acting as an agency while clicking something on screen, instead of feeling body ownership of it.

Researches find that the body ownership is weaken by either horizontal or vertical displacement between the artificial and real hand, and even no body ownership beyond a vertical displacement of 27.5 cm [17, 20, 24]. However, latter examples prove that users are more tolerant of the distance between the virtual and real hand in immersive VR [13, 18]. Ownershift [12] hypothesised that the reason why body ownership illusions become robust in immersive VR is due to the lack of visual cues from the real world. Although the results from Ownershift show that radical vertical position offsets (avg. 65 cm) still contribute to decreased body ownership illusion as previous researches found [19, 20, 24], the additional haptic feedback can mitigate this negative effect and lead to more robust virtual hand illusion (VHI) [1].

3. METHOD

3.1Participants

Eleven participants (2 left-handed, 7 male) were recruited in this experiment, among which four were supervised by the researcher in the same environment when the experiment was conducting. The rest seven received experimental materials from the researcher and finished the experiment remotely without supervision. Most participants were 22 to 27 years old (mean = 24.67, std = 2.06) and yet two exceeding this age range. All participants' version was normal or corrected-to-normal. As for the physical impairment for right arm, there was only one participant reported that his right forearm got injured about 5 months ago and he still felt a little painful while grabbing items. Most participants' previous VR experiences were high (median = 5, std = 1.01), which translates to "10 or more times" on a scale from 1 ("never") to 5 ("10 or more times"). They were offered a £10 Amazon voucher for participating in the experiment after completing the task.

3.2 Design

A within-subjects design was conducted to evaluate interaction technique regarding to the following dependent variables: task performance, the illusion of ownership and physical strain. There are five conditions deigned according to the independent variables: panel position and type of shift (Table 1). The order of five conditions is randomised since there will be a potential confounding variable that participants would feel fatigue as experiment continue.

	linear	**non-linear**	**none**	**quasi-random**
top	O	N	T	-
bottom	-	-	B	C

Table 1. The experiment consisted of five conditions varied in panel position (first column) and type of shift (first row): Ownershift (O), Non-linear shift (N), Top (T), Bottom (Bottom), and Control (C).

3.2.1 Task Performance

Task performance indicates the participant's ability to track the moving target. In order to compare the results with previous work, this study continue to use relative errors [11] which is an error ratio comparing the root-mean-squared error (*rmse*) with the error that would occur if the user put his index finger at the centre of the tracking task panel during the whole trail (*refE*).

$$task\ performance = \frac{rmse}{refE}$$

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

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

$P_{F(t)}$ and $P_{T(t)}$ were logged each frame. $P_{F(t)}$ is the position of the projected user's index fingertip on the tracking task panel at time t. $P_{T(t)}$ is the position of moving target at time t. C is the centre of the tracking task panel.

3.2.2 Physical Strain

After each trial, participants were asked to evaluate how much physical strain they felt at the end of the tracking task with respect to right shoulder, upper arm, forearm, hand and neck. The intensity of physical strain was rated on the Borg-CR 10 scale [5], which was also used as a rating-scale for self-evaluating physical strain in Ownershift experiment. Questions (17-21) for asking the participant's physical strain are listed in appendix 1.

3.2.3 Illusion of Ownership

Apart from rating physical strain, participants also need to evaluate the feeling of agency over their virtual hands after each trial and feeling of body ownership. Those questions (see appendix 1 13-16) and rating-scale (7-point Likert scale) are same as Ownershift's in order to compare the results.

3.2.4 Panel Position

In top position, the height of the tracking task panel is dynamically adjusted to the user's eye level. Unlike top condition where VR headset can automatically estimate the user's eye level, the panel in bottom position is located at the height of 112 cm for each user, which is an average height of bottom position in Ownershift experiment.

3.2.5 Type of Shift

Linear and Non-linear vary in VHS shift speed; the former applies shift speed linearly and stop at maximum offset results, there is no significant difference between the task performance of Ownershift (Linear type of shift) and Instantshift while qualitative findings reveal that Ownershift if preferable to an instant shift due to less conspicuous [12].

3.3 Materials

In the study participants have to finish 5 pursuit tracking tasks in the VE implemented by Unity3D. They wear Oculus Quest as an HMD, which has 1440×1600 display resolution for each eye (288×1600 combined pixels) and a refresh rate of 72 Hz. The controllers used are the original Oculus Quest controllers with hand tracking function and haptic feedback.

3.3.1 VHS Shift Techniques

VHS shift is translated through rotating the virtual hand around the user's shoulder on the sagittal plane. To locate the position of the user's shoulder, the VRArmIK [28] was implemented in the scene, which uses hand and head positions to estimate shoulders' and arms' realistic movements in VR. In addition, we implemented hand avatar that map the real hand gesture from Oculus Integration package [25] in order to compensate for the lack of visual feedback of the real hand gesture simulated by Leap Motion sensors.

For the Ownershift technique, the hand shift was applied actively and linearly over a duration of 45 seconds where shift speed was barely noticeable and yet shifted the virtual hand to maximum offset within 1 minute based on results of Ownershift pilot studies. Rather than applying the shift actively, the shift speed of Non-linear technique would be proportional to the velocity of the real hand along y-axis. The proportion rate was set to 5.43×10^{-3} (angular velocity : real hand velocity along y-axis = 5.43×10^{-3}) in order to restrict the shift duration time close to Ownershift's (45 seconds). The real and virtual hands are also collocated at the very beginning. However, the shift duration time varied in each participant (avg. 44.72 seconds) due to the slight discrepancy of the real hand's velocity while tracking the target, although movements of the tracked target are always same across each trial. To disrupt the sense of body ownership and control, the quasi-random shift was carried on as Ownershift experiment did. The virtual hand position is calculated as sum of 4 sinusoids (Table 2). Furthermore, any movements of the right hand along y-axis after the pursuit tracking task stops, will trigger the shifted virtual hand move towards the real hand's position (virtual hand velocity : real hand velocity along y-axis = $1{,}74 \times 10^{-2}$).

axis	**sin1**	**sin2**	**sin3**	**sin4**
x	2.51t	2.4t	0.28t	0.44t
y	2.51t	0.12t+0.25π	2t	2.51t+0.5π
z	1.31t	1.16t+0.5π	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)

3.3.2 Pursuit Tracking Task

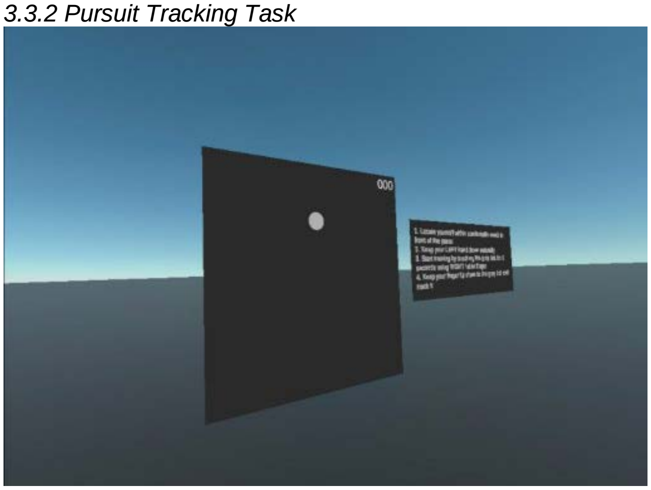

Figure 3. Pursuit tracking task panel at top position. The grey circle is the moving target that participants need to track. Remaining time is demonstrated on the upper right corner of the panel.

2D pursuit tracking task continues to be used in this study, with quasi-random target motion. Each tracking task will take 121 seconds, though the data log for the first 1 second will not be calculated as task performance since the moving target will suddenly accelerate when task starts. Similar to aforementioned quasi-random hand shift, quasi-random motion is also generated by a sum of 4 sinusoids (Table 3). In the task, a grey dot of 1 cm radius moved on 30×30 cm panel (Figure 3). The participant needs to track the moving dot with his right index fingertip centred on the target. Since the task is conducted in VR where the virtual either slightly hover over the panel or penetrate into it, a blue ball casted from the right index fingertip will provide a visual feedback for the participant as well as represent the position of the index fingertip projected on the panel (Finger 4).

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

Table 3. Angular frequencies and phase shifts of the quasi-random target motion in pursuit tracking task. (the amplitude is 0.036 and t is time in seconds)

Compared to the way that Ownershift provided haptic feedback when the user is tracking the target, we decide to use VR controllers as vibration providers in this study. Moreover, the intensity and frequency of the vibration will mimic the sensation of moving an index finger over an uneven surface as previous research did. The user will feel more intense and frequent vibration when moving the finger faster. In addition, they will only feel the vibration when the blue beam (3 cm) casting from fingertip hit the grey dot (Figure 5). It will remind the participant not to raise the index finger too high.

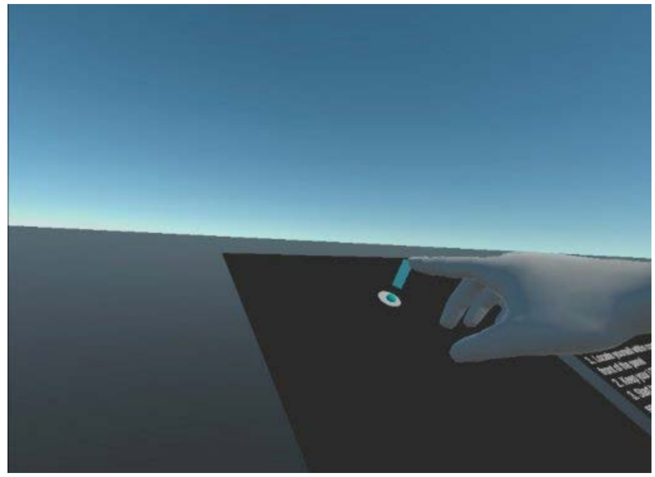

Figure 4. The blue ball casted on the tracking task panel represents the position of the right index fingertip. The task panel is at bottom position.

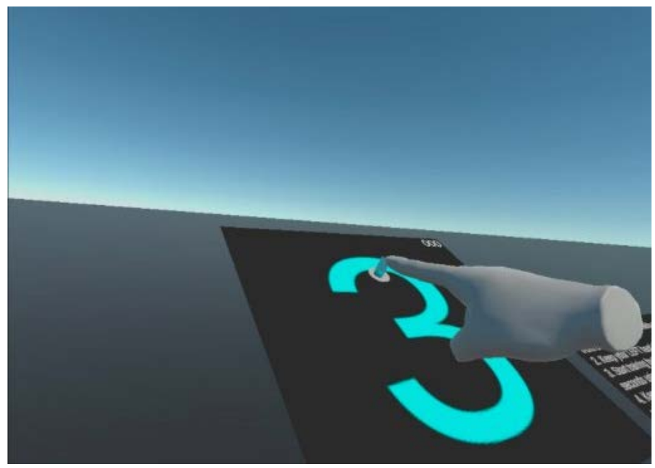

Figure 5. Participants have to keep the index fingertip closer to the task panel and make sure the blue beam can hit the moving target. The background number is counting down before the tracking task starts.

3.4 Procedure

For those participants who took part in this study remotely, they had to email researchers to get experimental materials first, including participant information, online consent form and questionnaire, and an APK file for running the experiment. Before it started, every participant was required to be in a quit environment where they would not be interrupted or interfered by any other people or notifications during the experiment.

In the VE where the experiment would be conducted, there was an introduction in front of the participant and the training area under the introduction. The participants were asked to read the instruction and familiarise the process of the whole experiment. There was a training area for the pursuit tracking task under the introduction panel where participants were guided before starting a formal trial. The training section took the Bottom condition as an example. Firstly, they were asked to stand and locate themselves with comfortable reach in front of the tracking panel using the left thumb stick. Next, participants would extend their right index finger and point the grey dot for 5 seconds to start the tracking task whenever they were ready. During the task, they had to keep their left hand down naturally since raising the left hand or bending left arm would cause an unwanted rotation of the simulated shoulder avatar. Participants were encouraged to practice the tracking task until they felt confident about it. Before they entered the first trial through clicking the "Next" button on the instruction menu, they were asked to type the randomly generated participant ID into the online questionnaire for demographics section, as well as fill in the other questions in the demographics section.

Every participant would go through 5 trials, one for each condition, in the experiment. The sequence of the 5 trials were randomised in order to mitigate the influence of feeling fatigue as experiment continue. In each trial, participants followed the same process as they did in training section to complete the pursuit tracking task. After each trial, there would be notification in the VE reminding participants to remove the HMD and answer the questionnaire for a current condition. They would respond to the first four questions concerning agency of the virtual hand and feeling of body ownership, followed with five questions regarding how much strain they felt at the end of the tracking task. Then, they would again wear the HMD and continue the next trial. After they finished the questionnaire for the last trial, they were reminded to go back to the VE and upload the data to UCL servers. At the end of the questionnaire, participants were encouraged to share any impressive experiences about this experiment in a free-text question. Each tracking task and following questionnaire took around 4 minutes to complete; and the experiment took approximately 30-40 minutes.

4. RESULTS

All the participants have submitted their online questionnaires successfully, whereas three of them were unable to upload data set from their Oculus Quest to the UCL server. During the data filtering process, there was a group of data set whose data of the distance between index fingertip and moving target were predominately larger (about 80%) than 0.42 cm (the length of the task panel's diagonal), which meant most of the time the participant's virtual fingertip penetrated into the task panel and the blue cursor hit the ground rather than the panel. However, we still keep his questionnaire answers since he was purely not sure whether he was supposed to hold the virtual finger up to the moving target exactly or to see the blue cursor based on the message he left at the end the questionnaire. In summary, there are 11 data sets from questionnaires and 7 data sets for task performance to be analysed.

Through statistical analysis, it is found that Non-linear shift technique does not significantly improve the task performance compared to Ownershift, which is contrary to H1. However, questionnaire responses reveal that Non-linear shift maintains relatively more robust feeling of agency and body ownership than Ownershift (H2).

4.1 Physical Strain

Questions Q17-Q21 (see appendix 1) of the trial questionnaire asked about the amount of participants' physical strain after finishing each tracking task. The results were responses on the Borg-CR10 scale, which were analysed through repeated-measure ANOVA, followed by post-hoc pairwise t-test with Bonferroni correction.

As shown in Figure 6, the Top condition contributes to the highest degree of strain compared with all other conditions. Repeated-measure ANOVA manifests that there are significant effects on shoulder, upper arm and lower arm (Q17-shoulder: $F(4, 40) = 4.1$, $p < 0.01$; Q18-upper arm: $F(4, 40) = 3.57$, $p < 0.05$; Q19-lower arm: $F(4, 40) = 2.82$, $p < 0.05$).

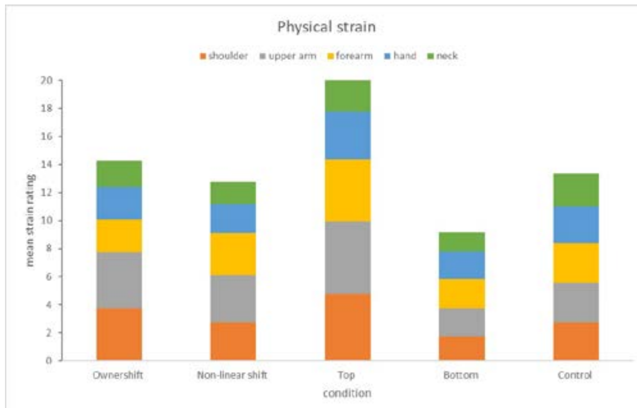

Figure 6. The sum of mean strain ratings for each body part per condition.

Post -hoc pairwise t-tests indicate that the shoulder strain is marginally significantly lower in the Bottom condition (mean = 1.77, std = 2.05) than in Top condition (B vs. T: $p = 0.062$). However, there is no significant main effect of condition where the tracking task panel is at eye-level (Ownershift, Non-linear shift and Top condition), the average ratings are 3.73, 2.73 and 4.77 for the shoulder strain, which correspond to the Borg-CR10 scale somewhere between "moderate" and "somewhat strong", "light" and "moderate", "somewhat strong" and "strong" respectively. The upper arm strain is also marginally significantly lower in the Bottom condition in Top condition (B vs. T: $p = 0.06$), which averaged between "strong" and "very strong". The lower arm, hand and neck are not significantly influenced by five conditions. Analysis results for physical strain are provided in appendix 2.

4.2 Body Ownership Illusion

Responses to questions Q13, Q14 and Q16 (see appendix 1) were evaluated on the Likert scale which is non-parametric. Therefore, the Friedman's repeated measures ANOVA was performed to find significant effects of condition on body ownership illusion, followed by Conover's post-hoc test. The result shows that Non-linear shift condition maintains a

0.033; C vs. N: p = 0.006; C vs. T: p < 0.001; C vs. B: p < 0.001).

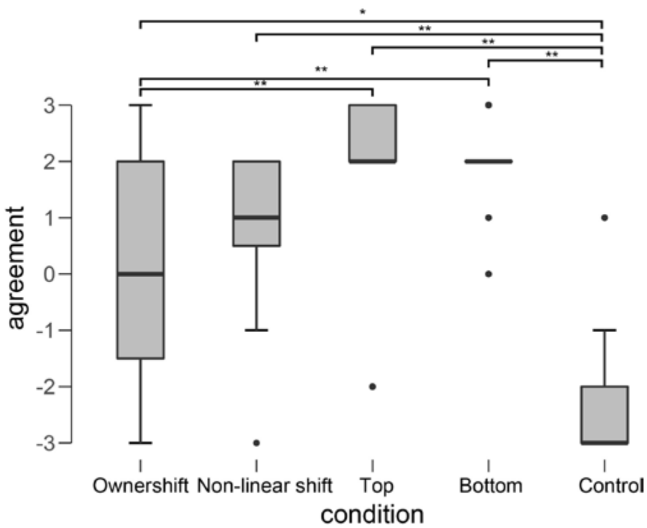

Figure 10. Responses to agency: control virtual hand like own (Q15). Significant effects are indicated by * (p < 0.05) and ** (p < 0.01).

4.4 Task Performance

Distances between the centre of moving target and the right index fingertip, as well as the centre of moving target and the tracking task panel were logged every frame during the experiment. Participants would sometimes penetrate index fingertip into the task panel unintentionally, which caused the position of the index fingertip was projected on the ground rather than the panel. Therefore, data were firstly filtrated out only if the value of distance was larger than the length of the task panel's diagonal (0.42 cm). Furthermore, the data log for the first one second after tracking task started were also deleted due to a sudden acceleration of the moving target. Repeated-measure ANOVA reveals a significant effect of condition on task performance (F (4, 24) = 35.05, p < 0.01).

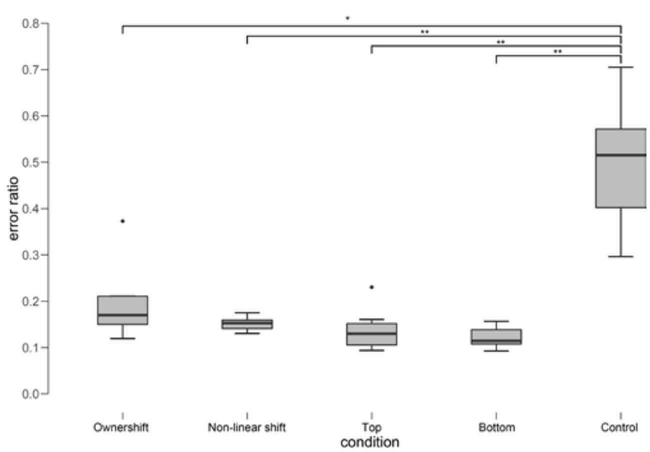

Figure 11. Task performance, presented as the error ratio. Significant effects are indicated by * (p < 0.05) and ** (p < 0.01).

Post-hoc test with Bonferroni correction shows the error ratio of Control condition is significantly higher than the other four conditions' (C vs. O: p = 0.022; C vs. N: p = 0.004; C vs. T: p = 0.002; C vs. B: p = 0.002). However, VHS shift in Ownershift and Non-linear shift condition do not significantly reduce the task performance and there is no significant difference between Non-linear shift and Ownershift. Participants achieved the lowest average error ratio in Bottom condition (avg.error = 0.122) and yet made relatively higher average error ratio in Ownershift condition (avg.error = 0.198). Compared to Ownershift and Top condition, the error ratio of Non-linear shift and Top condition are more similar (N: avg.error = 0.151; T: avg.error = 0.138).

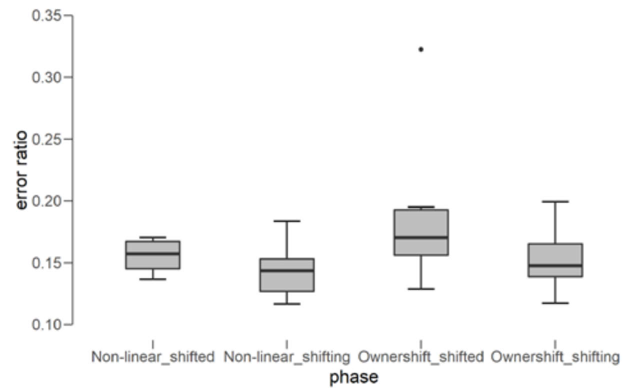

Figure 12. Error ratio for shifting and shifted phase in Non-linear shift and Ownershift condition.

In order to further explore the difference between Ownershift and Non-linear shift regarding their influence on task performance during the hand shifting process, a pursuit tracking task is divided into two phases, shifting virtual hand and virtual hand shifted phase (shifting and shifted). Repeated-measure ANOVA shows that there is no significant difference among those four discrepant phases on task performance (F (3, 18) = 2.695, p = 0.077; avg.error (N_shifted) = 0.156; avg.error (N_shifting) = 0.143; avg.error (O_shifted) = 0.188; avg.error (O_shifting) = 0.153).

5. DISCUSSION

The research aims are to examine whether the Non-linear shift would significantly improve the user's tracking task performance, as well as maintain more robust body ownership and feeling of agency over right virtual hand compared to Ownershift technique. As a previous research, Ownershift experiment [12] has provided insights into mitigating physical strain of overhead interaction in VR by applying radical vertical offset. In this study, we conducted the experiment using similar procedures together with a further developed VHS shift technique, Non-linear shift. The results from this study will be further interpreted combined with previous research.

5.1 Comparison with Previous Research

For the statistical data analysis of physical strain, we did not get similar results as Ownershift, which found that shoulder and upper arm strain are significantly higher in Top condition than in all other conditions. However, we only got marginally significant difference on shoulder and upper strain between Top and Bottom condition. The discrepancy could be mainly due to the lack of large-scale simple size though the difference of total mean strain across conditions was quite obvious. Moreover, since the experiment had to be conducted basically by participants themselves; and it was not convenient and accurate to let them measure their waist level with consistent standard. Unlike the other three conditions where the height of the task panel was adjusted to the user's eye level dynamically, the height of the tracking task panel for Bottom and Control condition was fixed to 112 cm, which was the average height of bottom position in Ownershift experiment. Nevertheless, according to logged data of headset's position, the average height of task panel at top position is around 165cm (the average height for top position in Ownershift experiment is 178 cm), indicating that a part of participants was doing tracking task slightly above their waist level in Bottom and Control condition. This could be a reason why there is no significant difference between Top and Bottom condition in addition to small sample size.

Non-linear shift performs better than Ownershift regarding maintaining body ownership and feeling of agency over right virtual hand, as the rating for Ownershift condition is significantly lower than Non-linear and Top condition in Q13 ("There were times when I felt that the virtual hand was part of my body"). Similarly, it is also significantly lower than Top and Bottom condition in Q15 ("There were times when I felt I could control the virtual hand as if it was my own"). There is no significant difference on agreement between Non-linear shift two collocated conditions across 4 questions in spite of relatively small simple size. However, this result is inconsistent with previous finding that the user has lower body ownership when the offset increase [12, 24]. There are three potential factors. Firstly, it could be influenced by the experiment procedure. Participants were only supposed to practice the tracking task in Bottom condition during the training section, whereas Ownershift experiment encouraged participants to try all conditions before formal task started, indicating they knew there were different types of VHS shift mingled with collocated hands in advance. Therefore, participants would probably observe their virtual hands occasionally to check whether the hand shift happened, rather than concentrate on tracking the target. Since they were not informed about any VHS shift that they would experience in this study, unusual experiences could be trivialised which contributed to less significant difference on body ownership and feeling of agency between VHS shift and collocated hand. Furthermore, Non-linear shift's own feature could also make a difference. Since the shift speed is in proportion to the participant's own hand movement, shift process could be masked to some extent, like redirected walking [17, 30]. Therefore, we did not find any significant difference between Non-linear shift and conditions with collocated hand across 4 questions, despite no significant difference between Ownershift either. Thirdly, we have further developed an approach to reset the shift in a less unnoticeable way, which was even potentially beneficial for maintaining body ownership of conditions with VHS shift when the task was finished. Future studies could further explore the influence of those two resetting techniques on body owning illusion.

The results of task performance do not demonstrate any significant differences among Ownershift, Non-linear shift, Top and Bottom condition, whereas task performance for each condition is significantly different from the others, excluding the difference between Ownershift and Instantshift condition. This result could be due to participants' abundant previous VR experiences, as manipulating virtual hands to complete tasks was a common thing for them even if the virtual hand is shifted from its original place. As for Ownershift experiment, the recruited participants had less VR experiences and perhaps tended to feel more difficult to finished the task with a shifted hand.

5.2 Limitations

The study has a few limitations with the first one that the number of recruited participants is less than original planned. It is reflected in results that the mean error ratios are similar to Ownershift experiment's but they are not significant. There could be more significant results if more people were willing to participate and all the tests had been conducted in a laboratory environment. Secondly, aforementioned fixed bottom position of the tracking task panel is also a limitation which could influence the rating of physical strain for Bottom and Control condition. Since most of the participants have conducted the experiment without supervision, any doubts regarding the experiment procedure or questions from the questionnaire could not be answered by researchers timely. They had to stop the experiment, email researchers questions and wait for reply, which is really time-consuming for them. Therefore, they may give up asking questions and continue the experiment based on their personal understanding or simply select "neutral" as an answer.

6. Conclusion

This project presents Non-linear shift interaction technique that is further developed based on the previous Ownershift technique. Rather than actively shifting the user's virtual hand with a constant speed, Non-linear shift applies the hand shift speed in proportion to the velocity of hand movements along y-axis. Although statistical analysis reveals that Non-linear shift do not significantly improve the tracking task performance, whereas it provides more robust body ownership illusion than Ownershift.

Some main changes were implemented compared to the previous research, including replacing Leap Motion sensors and vibration motors with a VR controller, providing no clue for VHS shift before the formal task. Furthermore, replacing the VRArmIK asset with attachable tracking devices is beneficial for locating shoulder position more accurately in future study, which will be advantageous for investigating how VHS shift performs on overhead interaction involving radical motion on both hands.

ACKNOWLEDGMENTS

I would like to thank my supervisor, David Swapp, for his guidance and support throughout the project. I would also like to thank Felix Thiel, for his constructive feedback and generous help. I also want to show gratitude to UCL VR lab for supporting this project with experimental apparatus. Last, I feel thankful to all the participants for their contribution to this project.

REFERENCES

1. Ferran Argelaguet, Ludovic Hoyet, Michael Trico, and Anatole Lecuyer. 2016. The role of interaction in virtual embodiment: Effects of the virtual hand representation. *2016 IEEE Virtual Reality (VR)* (2016). DOI: http://dx.doi.org/10.1109/vr.2016.7504682 [33]
2. 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 (CHI '16). Association for Computing Machinery, New York, NY, USA, 1968–1979. DOI: https://doi.org/10.1145/2858036.2858226 [19]
3. Myroslav Bachynskyi, Gregorio Palmas, Antti Oulasvirta, Jürgen Steimle, and Tino Weinkauf. 2015. 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 (CHI '15). Association for Computing Machinery, New York, NY, USA, 1817–1826. DOI: https://doi.org/10.1145/2702123.2702607 [13]
4. Myroslav Bachynskyi, Gregorio Palmas, Antti Oulasvirta, and Tino Weinkauf. 2015. Informing the Design of Novel Input Methods with Muscle Coactivation Clustering. *ACM Transactions on Computer-Human Interaction* 21, 6 (2015), 1–25. DOI: http://dx.doi.org/10.1145/2687921 [14]
5. Gunnar Borg. 1998. *Borg's Perceived exertion and pain scales*, Champaign, IL: Human Kinetics. [35]
6. Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (1998), 756–756. DOI: http://dx.doi.org/10.1038/35784 [25]
7. 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). DOI: http://dx.doi.org/10.1371/journal.pone.0111967 [26]
8. E. Burns, M.c. Whitton, S. Razzaque, M.r. Mccallus, A.t. Panter, and F.p. Brooks. The hand is slower than the eye: a quantitative exploration of visual dominance over proprioception. *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* DOI: http://dx.doi.org/10.1109/vr.2005.1492747 [23]
9. Emilie A. Caspar, Axel Cleeremans, and Patrick Haggard. 2015. The relationship between human agency and embodiment. *Consciousness and Cognition* 33 (2015), 226–236. DOI: http://dx.doi.org/10.1016/j.concog.2015.01.007 [27]
10. 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 (CHI '17). Association for Computing Machinery, New York, NY, USA, 3718–3728. DOI: https://doi.org/10.1145/3025453.3025753 [20]
11. Eustace Christopher. Poulton. 1974. *Tracking skill and manual control*, New York: Academic Press. [34]
12. Tiare Feuchtner and Jörg Müller. 2018. Ownershift: Facilitating Overhead Interaction in Virtual Reality with an Ownership-Preserving Hand Space Shift. *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18* (2018). DOI: http://dx.doi.org/10.1145/3242587.3242594 [5]
13. 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 (CHI '17). Association for Computing Machinery, New York, NY, USA, 5145–5157. DOI: https://doi.org/10.1145/3025453.3025689 [31]
14. J.J. Gibson. 1933. Adaptation, after-effect and contrast in the perception of curved lines. Journal of Experimental Psychology 16, 1 (1933), 1–31. DOI: http://dx.doi.org/10.1037/h0074626 [21]
15. John Grimes. 1996. On the failure to detect changes in scenes across saccades. In K. A. Akins (Ed.), Vancouver studies in cognitive science, Vol. 5. Perception (p. 89–110). Oxford University Press. DOI: https://psycnet.apa.org/record/1996-97608-003 [10]
16. 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 SIGCHI Conference on Human Factors in Computing Systems (CHI '14). Association for Computing Machinery, New York, NY, USA, 1063–1072. DOI:[16]

Post Hoc Comparisons - Conditions

		Mean Difference	SE	t	p_{bonf}
Linear_Top	None_Bottom	0.075	0.030	2.512	0.403
	None_Top	0.059	0.030	1.994	0.863
	Proportional_Top	0.046	0.028	1.675	1.000
	Quasi_random_Bottom	-0.297	0.051	-5.881	0.006
None_Bottom	None_Top	-0.016	0.014	-1.153	1.000
	Proportional_Top	-0.029	0.006	-4.801	0.020
	Quasi_random_Bottom	-0.373	0.042	-8.910	< .001
None_Top	Proportional_Top	-0.013	0.014	-0.909	1.000
	Quasi_random_Bottom	-0.356	0.037	-9.731	< .001
Proportional_Top	Quasi_random_Bottom	-0.344	0.042	-8.230	< .001

Note. Bonferroni adjusted confidence intervals.

Data divided into shifting and shifted:

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p
phase	0.008 [a]	3 [a]	0.003 [a]	2.695 [a]	0.077 [a]
Residual	0.018	18	9.978e -4		

Note. Type III Sum of Squares

[a] Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < .05$).

Post Hoc Comparisons - phase

		Mean Difference	SE	t	p_{bonf}
Non-linear_shifted	Non-linear_shifting	0.012	0.006	2.146	0.453
	Ownershift_shifted	-0.033	0.023	-1.446	1.000
	Ownershift_shifting	0.002	0.008	0.295	1.000
Non-linear_shifting	Ownershift_shifted	-0.045	0.027	-1.687	0.855
	Ownershift_shifting	-0.010	0.011	-0.892	1.000
Ownershift_shifted	Ownershift_shifting	0.035	0.016	2.187	0.428

Note. Bonferroni adjusted confidence intervals.

APPENDIX 5. CONSENT FORM