

Pseudo-Haptics for Weight Perception in VR: Controller vs. Bare Hand Interactions with Tracking Delay and Vertical Offset

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Abstract—Training in virtual reality (VR) offers advantages such as a safe learning environment, good scalability, and cost saving. However, state-of-the-art simulations are limited in faithfully conveying real-world physical object properties such as weight without complex technologies and instrumentation of the user or environment, which may negatively impact learning. A potential solution is the application of pseudo-haptics: illusory haptic sensations induced by a mismatch between real and virtual hand positions. Researchers have proposed various pseudo-haptic techniques to alter the perception of weight in virtual environments, but their effectiveness with hand tracking compared to VR controllers is underexplored. Hence, we investigate impacts of the interaction method for two different types of pseudo-haptic feedback based on Tracking Delay and Vertical Offset. Our results indicate that pseudo-haptics can effectively facilitate the sensation of weight both with controllers and bare hands, whereby each has benefits: hand tracking can enhance body ownership, while controllers may improve perceived responsiveness of virtual environments. Also, pseudo-haptics with Tracking Delay may be preferable for repetitive lifting tasks, as Vertical Offset can be prone to higher physical demand. The current study provides insights into the design of pseudo-haptic feedback and interaction technologies for weight perception in VR.

Index Terms—Pseudo-Haptics, Weight Perception, Virtual Reality, Human-Computer Interaction.

I. INTRODUCTION

Virtual reality (VR) offers a safe and attractive learning environment for industrial trainees to practice manual skills with virtual tools and objects, while being independent of particular location and saving expenses in comparison to face-to-face training [1], [2]. However, training in virtual environments may not always lead to successful outcomes, due to insufficient fidelity of the achievable simulations. For instance, learning

manual skills often requires trainees to manipulate various objects with different masses and perceiving their weights may play an important role in learning. Unfortunately, it remains challenging to simulate such physical properties of virtual objects in VR. As a result, learners may have incomplete knowledge after training in VR and the discrepancy between the virtual and real environments can lead to mistakes or accidents at work.

Haptic technologies that complement visual contents with actuators on the human body may provide a solution to the problem. Researchers have studied different hardware-based approaches to simulate physical properties through cutaneous or kinesthetic haptic feedback [3]–[6]. Others propose software-based solutions that elicit illusory haptic perception by manipulating visual information, which is called pseudo-haptics [7]–[9]. The latter have the advantage that they do not require additional hardware. As a result, they can be applied to various objects flexibly without causing discomfort to users or restricting their movements during VR experiences.

Pseudo-haptics has been shown to support weight perception in VR by modifying the movement speed of the virtual hand or applying offsets between the real and virtual hand positions [10]–[12]. However, this typically involves the use of VR controllers or other physical objects (i.e., physical props), and the impact of bare hand interaction is unexplored. Hand tracking may be beneficial for VR training in which users learn how to correctly grasp and manipulate objects of various shapes and sizes. Hence, the current study investigates the effectiveness of hand interaction in comparison to controllers, while applying two different techniques to deliver pseudo-haptic feedback for weight perception: Tracking Delay and Vertical Offset. In addition, this study examines potential impacts of the interaction method on body ownership, quality of weight perception, user satisfaction, sense of presence, and perceived workload.

The results show that hand and controller interactions can be similarly effective to perceive weights in VR through pseudo-

haptic feedback from both Tracking Delay and Vertical Offset. In Experiment 1 with Tracking Delay, participants tended to prefer bare hand interaction slightly more than controller interaction without having significant differences. On the other hand, participants in Experiment 2 with Vertical Offset were able to distinguish differences in weight significantly better with a controller when virtual objects became heavier, but this difference was not observed when the weight of target virtual object was altered to feel lighter. In addition, each interaction method provided different benefits for user experience. Employing hand gestures with one’s own hand may improve body ownership whereas holding a controller can contribute to a better sense of presence.

Our work contributes to the advancement of pseudo-haptics and Human-Computer Interaction (HCI) research by a) demonstrating the effectiveness of two different types of pseudo-haptic feedback for perception of weight with bare hand in comparison to controller, and b) presenting potential effects of the two interaction methods on user experience.

II. RELATED WORK

A. Weight Perception

Weight is perceived not only by haptic senses when touching objects and exerting forces on them, but also through visual stimuli [13]–[15]. For example, the weight of an object may be estimated based on its visual features, such as size, brightness, or material. As a result, large and dark objects that are made of hard materials like metal may be perceived as heavier than small and bright objects of lighter materials (e.g., plastic). Also, motion of objects may influence their perceived weights and distinguishing weights is more successful when lifting an object instead of holding it passively [13], [16]. In our work, we take advantage of the visual effects to simulate weight through pseudo-haptic feedback when lifting virtual objects, instead of applying hardware-based approaches as demonstrated by previous research [5], [17].

B. Pseudo-Haptics

According to Lécuyer, pseudo-haptics exploits visual stimuli to facilitate sensations of haptic properties such as weight in VR through illusive haptic perception [7]. For instance, Taima et al. demonstrated that pseudo-haptic feedback can alter perception of weight when lifting small boxes by adjusting the movements of virtual hand displayed to users [18]. Similarly, Samad et al. manipulated the perceived weights of physical cubes in hand by changing the control-display ratio (CD ratio) so that the users’ virtual hands and handheld objects in VR move differently than their physical hands and objects in reality [10]. The authors in these studies [10], [18] utilized hand tracking for pseudo-haptics and weight perception, but the participants held physical props in their hands. As the applicability of such an approach is limited by the availability of props, we attempted to take a step further by exploring pseudo-haptic feedback with a bare hand without grabbing any physical object.

Other researchers have investigated pseudo-haptics with controller interaction. For example, Hirao et al. compared two different types of controller-based interactions in VR showing that both methods support weight perception with pseudo-haptics [19]. Kim et al. induced the perception of weight when lifting an object vertically in VR adjusting the CD ratio and measured perceptual thresholds [12]. In a related study, Rietzler et al. demonstrated that applying vertical offsets between real and virtual hands can elicit pseudo-haptic weight perception in VR during lifting movements [11]. Inspired by these studies, we designed and implemented two different types of pseudo-haptic feedback with Tracking Delay and Vertical Offset to facilitate the perception of weight in VR through bare hand and controller interactions.

C. Interaction Method: Controller vs Hand tracking

Comparing hand tracking and controllers for interaction in VR, Masurovsky et al. reported improved performance (e.g., accuracy or completion time) and higher satisfaction with controllers when handling a cube [20]. Similarly, Hameed et al. observed better performance and reduced mental workload with controllers compared to hand tracking when interacting in VR although they mentioned that familiarity with controllers may have affected the results [21]. On the other hand, Voigt-Antons et al. stated that hand tracking may lead to more pleasant and less demanding interaction in VR [22]. Luong et al. showed that participants had better performance with less physical effort when using controllers for raycast interactions, but preferred bare hand interaction through hand tracking when directly touching virtual objects [23]. Still, the impact of bare hand interaction compared to controller interaction when applying pseudo-haptics for weight perception has been underexplored and our work aims to shed light on that.

III. PSEUDO-HAPTICS FOR WEIGHT PERCEPTION IN VR

We implemented two techniques to induce pseudo-haptic feedback, by either delaying the virtual hand motion or applying a fixed offset to its position. A detailed description is provided below.

A. Approach 1: Tracking Delay

Application of a tracking delay results in a decoupling of the virtual and real hands, when users lift an object in VR: Instead of displaying the virtual hand at the same position as real hand (i.e., co-location), the virtual hand follows the real hand with a delay (Figure 1). Consequently, this may give an impression of heaviness by slowing down the movement of the virtual hand, compared to that of real hand.

This method has can be described through the following mathematical expression [12], [19]:

$$V_f = V_{f-1} + (R_f - V_{f-1}) \cdot D \quad (1)$$

The position of the virtual hand in the current frame (V_f) is calculated based on the difference of virtual hand position in the previous frame (V_{f-1}) and the real hand position in the current frame (R_f), multiplied by the delay parameter (D).

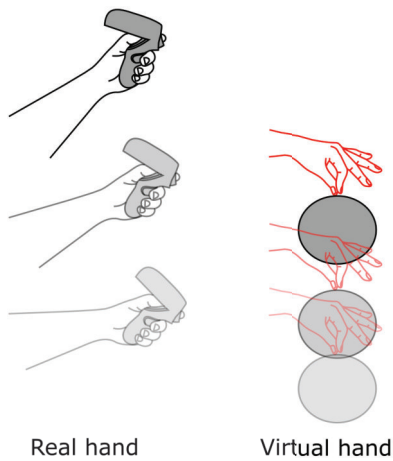


Fig. 1: With *Tracking Delay*, we manipulate the movement speed of the virtual hand by applying a delay parameter. The virtual hand moves slower than the real hand and takes longer to reach the top when lifting a sphere in VR.

If the delay parameter D is 1, the virtual hand is co-located with the real hand, and when D is 0, it does not move at all. When D is between 0 and 1 the movement speed of virtual hand is slowed down accordingly. In addition, once the user stops moving their hand, the real and virtual hand positions gradually match up again.

B. Approach 2: Vertical Offset

Introducing a fixed vertical offset between the virtual and real hands when lifting an object in VR has been found to modulate perceived weight [11]. In contrast to the tracking delay that only allows to increase perceived weight, we can apply vertical offsets in two directions for both heavier and lighter weight perceptions, as illustrated in Figure 2.

Here, the virtual hand position is determined by subtracting an offset from the y -coordinate (vertical location) of real hand position. To simulate a heavier weight, the virtual hand is positioned below the real hand with a positive offset. Thereby users must raise their arms higher when lifting objects in VR and the greater physical effort may result in the perception of heaviness. Conversely, if the virtual hand is positioned above the real hand by subtracting a negative offset, the lifting task becomes less physically demanding and users may perceive a lighter weight.

In the early phase of the lifting movement, the vertical offset is applied gradually according to the elevation of the virtual hand, so that it is not noticed by users. The full offset is reached when the virtual hand arrives at a specified elevation (threshold) and does not increase further thereafter. Given the maximum offset (O_m), the position of real hand (R), and the threshold (T), the current offset (O_c) is calculated as:

$$O_c = \begin{cases} O_m \cdot \frac{R}{T}, & \text{if } R \leq T \\ O_m, & \text{otherwise} \end{cases} \quad (2)$$

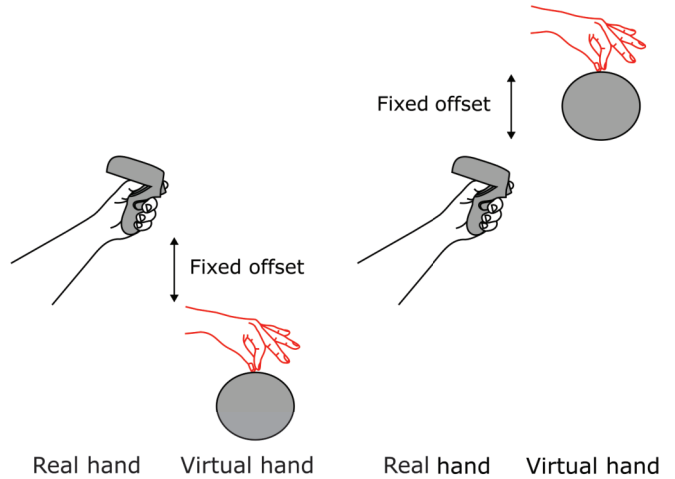


Fig. 2: With *Vertical Offset*, we apply a fixed offset between the virtual and real hand positions. For heavier weight perception, the virtual hand is below the real hand so that users raise their arm higher when lifting the virtual sphere to a target position. In contrast, lighter weight is simulated by putting the virtual hand above the real hand so that users raise their arm less to reach the same height in VR.

Before the virtual hand reaches T , O_c changes depending on R relative to T . Thereafter O_m is maintained until the end of the lifting trajectory. Note that here the fixed vertical offset (O_m) between the real and virtual hand remains at the top, whereas with the previous Tracking Delay technique the gap between the real and virtual hand positions gradually shrinks once the hand stops moving.

IV. EVALUATION

We conducted two separate user studies to investigate hand and controller interactions when lifting virtual objects with pseudo-haptic feedback using the previously described approaches of Tracking Delay and Vertical Offset. In each of the experiments, we explored the following research questions.

- RQ1: How does pseudo-haptic feedback from Tracking Delay and Vertical Offset affect the perception of weight?
- RQ2: Does the interaction method (hand vs. controller) influence pseudo-haptic weight perception?
- RQ3: How does the interaction method (hand vs. controller) impact body ownership, quality of weight perception, user satisfaction, sense of presence, and perceived workload?

A. Weight Estimation Task in VR

The VR application programmed in Unity¹ places users in a virtual space with minimal visual features to control potential confounding effects from the environment (Figure 3). To assess pseudo-haptic feedback for weight perception, two spheres were presented on the black base platforms at the bottom, which should be lifted straight up. Once a sphere

¹Unity Engine: <https://unity.com/>

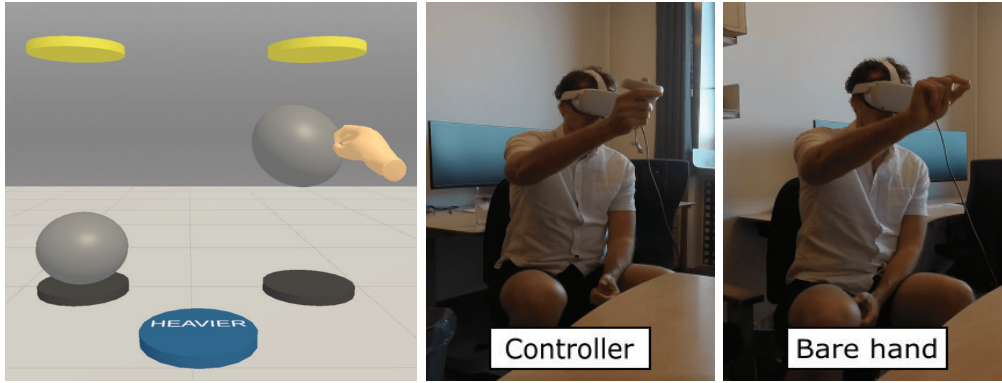


Fig. 3: In our weight estimation task, users grasp virtual spheres and lift them vertically from the bottom to the top positions. We thereby compared interactions with a controller and a bare hand.

touches the top yellow platform, this turns black and the bottom platform turns yellow instead, to indicate that the sphere should be put down again. After lifting each of the two spheres to compare their weights, the heavier is to be placed on the blue answer platform. This platform then turns green to show that the answer is recorded and the next trial starts.

When using hand tracking, we support grabbing with a pinch gesture as illustrated in Figure 3, which is mimicked by the virtual hand. When interacting with controllers, the sphere is grasped by holding down the grip button. Here the user equally sees a virtual hand performing a pinch gesture as hand interaction, to ensure comparable visual feedback and avoid any potential influence of apparent grip type on perceived weight. In our experimental setup, the Meta Quest 2² head-mounted display (HMD) allowed participants to view the virtual scene and interact through controllers and hand tracking.

B. Experiment 1: Tracking Delay

1) *Participants:* In total, 12 participants (9 male) were recruited at Aarhus University in Denmark. Majority of them were students at the Department of Computer Science and right-handed (9/12). There were 2 ambidextrous participants and one of them used right hand and the other used left hand in the experiment. Mean participant age was 26 years (SD = 5.1), and all had normal or corrected-to-normal vision.

2) *Procedure:* In the beginning, participants were asked to sign a consent form confirming their agreement to participation and data collection. The experimenter explained the lifting task in VR and participants had a practice session to get familiar with the VR headset and interaction techniques. The participants' view in VR was mirrored to the experimenter's PC screen so that the experimenter could monitor the participants interacting in the virtual space and respond to any problems.

In the VR scene, two identical virtual objects (spheres) appeared in front of the participants as shown in Figure 3. One of the spheres (delay object) had pseudo-haptics applied: the

virtual hand movement was modified according to the delay parameter shown in Equation 1. The other sphere (reference object) had unmodified lifting behavior (virtual and real hand were co-located). Participants were asked to lift the two spheres, one after the other, with their dominant hand and compare their weights. They performed the lifting motion at least twice for each sphere moving it to the top and bottom platforms. They could repeat this lifting motion as many times as desired to identify the heavier object (two-alternative forced choice). The positions of the reference and delay objects (i.e., left vs. right) were counterbalanced across trials. Based on pilot tests and related studies [10], [12], we applied five delay parameter values (0.1, 0.3, 0.5, 0.7, 0.9) to the delay object, and participants completed 10 comparison trials for each value.

The procedure above was repeated for controller and hand conditions, resulting in 100 trials in total (5 delay parameter values \times 10 trials \times 2 interaction methods). The order of interaction methods was counterbalanced across participants, and delay parameter values were presented in random order. Participants were allowed to take a rest whenever they wanted. Further, after finishing all trials with an interaction method, they were asked to take off the HMD for an extended break, during which they answered the questionnaire in Table I. Questionnaire items were rated on a 7-point scale ranging from "strongly disagree" to "strongly agree", except for questions from the NASA-TLX [24], which used a 7-point scale from "very low" to "very high" or "perfect" to "failure" (NQ4). Questions regarding weight perception and body ownership were inspired by Samad et al. [10], while items about satisfaction and sense of presence were adapted from Brooke's System Usability Scale (SUS) [25] and Witmer and Singer [26]. At the end of the questionnaire, participants were encouraged to provide general written comments about their experience.

3) *Results:* For each trial, we calculated probabilities to select the delay object as heavier and computed the average per delay parameter. As the parameter values for delay decreased, participants more frequently identified the delay object as heavier (Figure 4). To compare the effectiveness of both interaction methods, we fitted a psychometric function

²Meta Quest 2: <https://www.meta.com/quest/products/quest-2/>

TABLE I: This questionnaire was presented to participants after experiencing each of the two interaction methods. Responses were given as scores on a 7-point Likert scale.

Category	No.	Question
Body ownership	BQ1	The virtual hand felt like my real hand.
	BQ2	The virtual hand moved at the same speed as my real hand.
	BQ3	The virtual hand seemed to be at the same position as my real hand.
Weight	WQ1	I could imagine how heavy the virtual objects (spheres) were when I saw them for the first time.
	WQ2	It was easy to choose a sphere that felt heavier than the other in each trial.
	WQ3	I could perceive different levels of heaviness across trials (e.g., in one trial, an object felt very much heavier, but in another trial, an object felt only slightly heavier than the other).
Satisfaction	SQ1	I think this technique would support weight perception in virtual reality.
	SQ2	I want to use this technique again in virtual reality.
Presence	PQ1	My interactions in the virtual space were natural.
	PQ2	The virtual environment was responsive to my actions.
	PQ3	I felt confident in my interactions in the virtual space at the end of the study.
Perceived workload (NASA TLX)	NQ1	How mentally demanding was the task?
	NQ2	How physically demanding was the task?
	NQ3	How hurried or rushed was the pace of the task?
	NQ4	How successful were you in accomplishing what you were asked to do?
	NQ5	How hard did you have to work to accomplish your level of performance?
	NQ6	How insecure, discouraged, irritated, stressed, and annoyed were you?

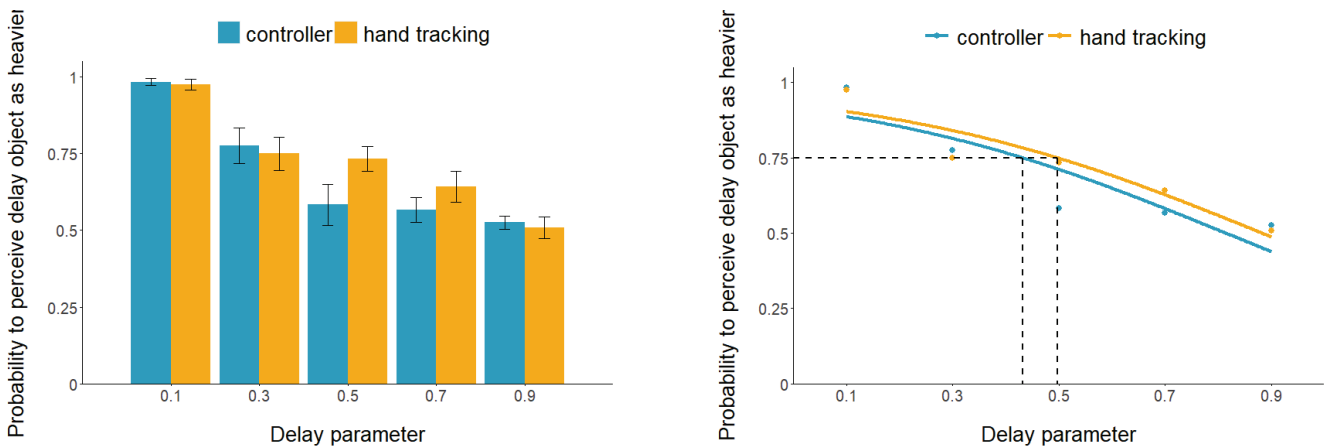


Fig. 4: Left: Average probabilities to choose the delay object as heavier for each interaction method in Experiment 1. Error bars indicate the standard error of the mean. Right: A psychometric function is fitted and dotted lines indicate thresholds to reach 75% probability.

(Equation 3) and examined the thresholds to reach 75% correct responses in the two conditions through bootstrap [27]–[29]:

$$\Psi(x) = \gamma + (1 - \gamma - \lambda) \cdot \text{fun}(x) \quad (3)$$

In the equation above, γ stands for the guess rate, λ is the lapse rate, and fun is a logistic sigmoid function. As depicted in Figure 4, the thresholds for 75% probability were 0.5 in hand condition and 0.43 in controller condition, which did not differ significantly. The results indicate that our implementation of pseudo-haptic feedback with Tracking Delay successfully induced perception of heaviness as intended. Moreover, lifting virtual objects with a bare hand was similarly effective as using a VR controller. It suggests that hand tracking technology combined with Tracking Delay can facilitate the sensation of

a heavier weight, without demanding users to grasp and hold physical objects like VR controllers or haptic props.

Participants' responses to the questions in Table I are illustrated in Figure 5 displaying medians (Mdn). Using Wilcoxon signed-rank tests to compare Likert scale ratings for the individual questions, we found no significant differences between controller and hand conditions. Yet, it seemed like participants tended to assess hand condition more favorably than controller condition with regards to body ownership, weight perception, satisfaction, and sense of presence. Particularly, BQ1 and PQ3 showed noticeable differences between the two conditions ($p = .06$ and $.07$ respectively). In addition, hand interaction was slightly favored when assessing perceived workload as well having lower scores on NQ1, NQ2, and NQ5 (not significant).

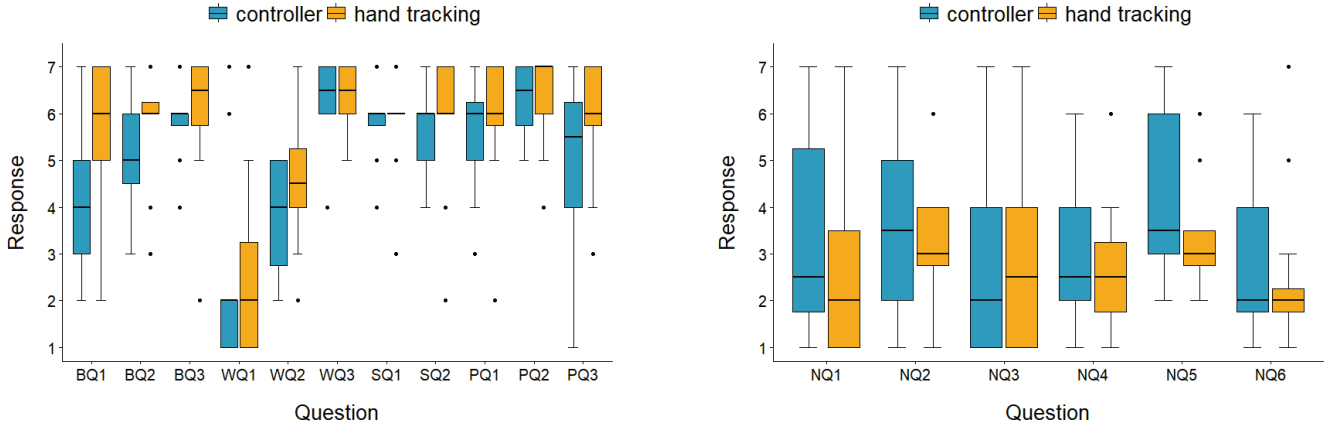


Fig. 5: Left: Subjective ratings for body ownership (BQ), weight perception (WQ), satisfaction (SQ), and sense of presence (PQ) in Experiment 1 (see Table I). Right: Responses to NASA-TLX (NQ). Scores were given on a 7-point Likert scale.

In concluding free-text responses, five participants stated that they liked hand interaction better than controller interaction, because it felt more natural and was easier to feel the weight in VR. In contrast, three participants preferred controller, as it felt more comfortable and provided physical contact with their hands.

C. Experiment 2: Vertical Offset

1) *Participants*: 12 new participants (9 male) were recruited at both Aarhus University in Denmark (9/12) and Ulsan National Institute of Science and Technology in South Korea (3/12). Their mean age was 27.6 (SD = 5.4) and 8 participants were right-handed. In addition, 2 ambidextrous people used their right hand in the experiment.

2) *Procedure*: The overall procedure was almost identical to Experiment 1 and participants were asked to make two-alternative forced choices by determining the heavier object (reference object or offset object) in each trial. We applied six vertical offsets (-6cm, -4cm, -2cm, 2cm, 4cm, 6cm) to the offset object based on results from pilot tests and related research [11]. Hereby, negative offsets were used to simulate lighter weights by positioning the virtual hand above the real hand resulting in shorter vertical hand motions to touch the top platform with the sphere. In contrast, positive offsets were applied to induce the perception of heavier weights, as lowering the position of the virtual hand increased the lifting distance.

Participants again completed 10 trials for each vertical offset and repeated it with both interaction methods (controller and hand tracking) having 120 trials in total (6 offsets \times 10 trials \times 2 interaction methods). It was expected that participants would choose the offset object when a positive offset was applied, but pick the reference object for negative offsets. Participants completed the same questionnaires as Experiment 1 (Table I) after finishing 60 trials with each interaction method. They also provided general comments about the experiment at the end.

3) *Results*: Probabilities to select the offset object as heavier were calculated in each trial and we analyzed the average across participants per offset value. As expected, participants were less likely to choose the offset object as heavier when negative offsets were applied, and this tendency was reversed with positive offsets in both controller and hand conditions (Figure 6). We again fitted the psychometric function described in Experiment 1 (Equation 3), to investigate the difference between controller and hand conditions. Here we examined thresholds at 75% probability for positive offsets and 25% probability for negative offsets.

As illustrated in Figure 6, the thresholds to reach 75% probability were significantly different between conditions ($p < .05$), with 2.5cm in controller condition and 3.4cm in hand condition. This suggests that participants were more sensitive to changes in positive offsets when using a controller than when interacting with their bare hand. In contrast, the thresholds to reach 25% were not significantly different, with -3.6cm in controller condition and -3.7cm in the hand condition. Overall, these results indicate that we can effectively alter the perception of weight in two different directions using pseudo-haptic feedback based on Vertical Offset making it feel lighter or heavier. Further, when the virtual hand is positioned below the real hand with a positive offset, the controller appears to be more effective than hand tracking.

Analysis of questionnaire responses with Wilcoxon signed-rank tests revealed significant differences for BQ1 and PQ2 depending on the interaction method, as shown in Figure 7. Participants experienced significantly stronger body ownership (BQ1) for hand interaction (Mdn = 6) compared to controller (Mdn = 3.5, $p < .05$). In contrast, responsiveness in VR (PQ2), which contributes to the sense of presence, was rated significantly higher with controller (Mdn = 6.5) than with hand (Mdn = 6, $p < .05$). With respect to perceived workload, participants showed a tendency to prefer controller over hand interaction. While there was no significant difference for responses to the NASA TLX, all items except NQ3 (temporal

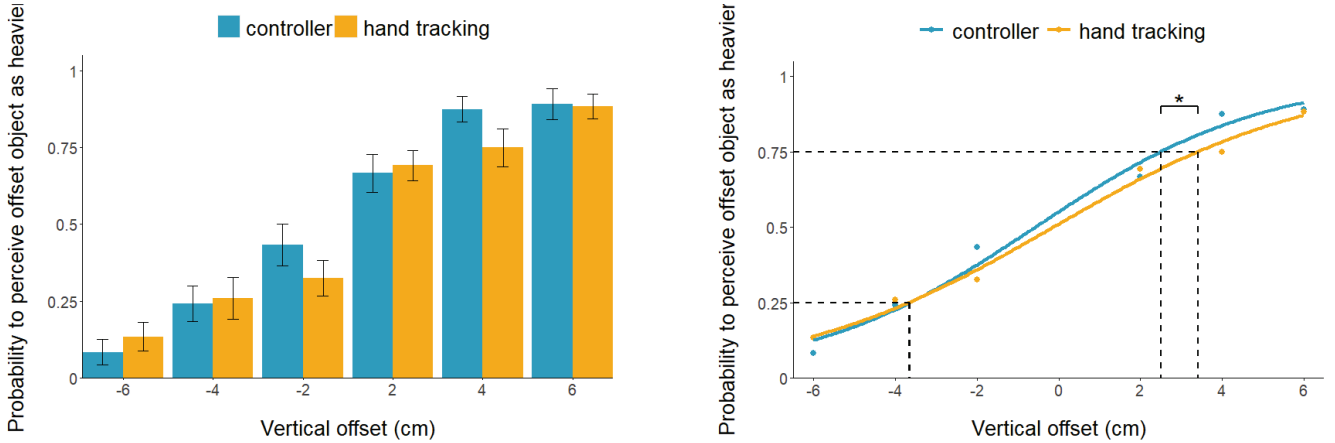


Fig. 6: Left: Average probabilities to choose the offset object as heavier with both interaction methods in Experiment 2. Error bars indicate the standard error of the mean. Right: A psychometric function is fitted with dotted lines that represent thresholds to reach 75% and 25% probabilities. Asterisk represents a significant difference between controller and hand tracking conditions ($p < .05$).

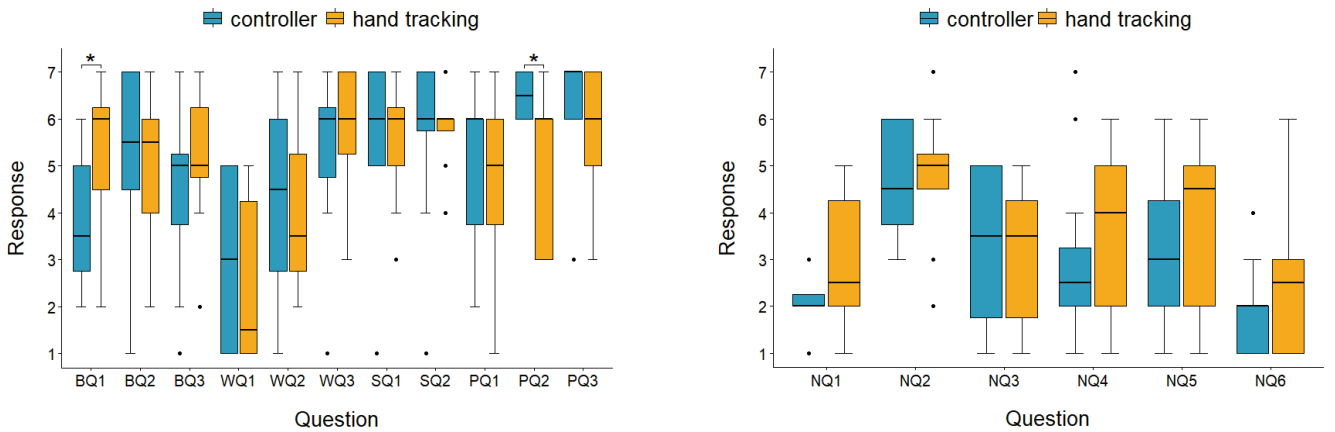


Fig. 7: Left: Subjective ratings for body ownership (BQ), weight perception (WQ), satisfaction (SQ), and sense of presence (PQ) in Experiment 2 (see Table I). Significant differences between controller and hand tracking conditions were found for BQ1 and PQ2, which are indicated by asterisks ($p < .05$). Right: Responses from NASA TLX (NQ). Scores were given on a 7-point Likert scale.

demand) had higher ratings in hand condition compared to controller condition. For instance, NQ1 ($p = .06$) implies that performing the lifting task with Vertical Offset technique may be perceived as more challenging when applying hand tracking.

In the general comments, three participants wrote that they preferred controller to hand, since it was easier to perceive weight and more stable without tracking issues. Conversely, two people were more satisfied with hand, because it felt more natural and differences in weight were clearer. However, two other participants mentioned that lifting the spheres with a pinch gesture did not feel realistic.

V. DISCUSSION

Answering RQ1, Experiment 1 and 2 showed that pseudo-haptic feedback from both Tracking Delay and Vertical Offset

can change the perceived weight of virtual objects, which is consistent with prior findings [10]–[12]. However, we speculate that the Vertical Offset method (Experiment 2) may be more subject to physical fatigue than the Tracking Delay approach (Experiment 1), since large positive offsets force users to lift their hand substantially higher. In particular, the scores for physical demand (NQ2) appeared higher in the second experiment. Unfortunately, our study design does not permit a direct statistical comparison, so this remains to be confirmed in future work. Nevertheless, we suggest that Vertical Offset may be less useful in situations where users lift objects frequently, especially with heavy weights.

We aimed to answer RQ2 and RQ3 by investigating the impact of interaction method on weight perception and user experience. To this end we compared bare hand interaction with traditional handheld VR controller for both types of

pseudo-haptic feedback. A noteworthy finding from Experiment 2 (Vertical Offset approach) is that weight perception was significantly more effective with controllers compared to hand interaction for positive offsets (see Figure 6). Interestingly, this effect was not apparent with negative offsets, nor with the Tracking Delay approach in Experiment 1. Although hand tracking may boost the sense of body ownership, maintaining certain hand gestures (e.g., pinch) to lift objects high repeatedly may increase perceived workload. In this case, simply pressing buttons on a controller may reduce physical and mental fatigue improving performance.

Beyond these differences, the results suggest that our pseudo-haptic weight illusions can be equally effective with both interaction techniques. Still, it may be worth highlighting additional benefits and disadvantages for each interaction method. For instance, hand interaction may be more susceptible to tracking issues than controllers and can therefore feel less responsive, as we discovered in the second experiment with Vertical Offset. Additionally, controllers offer the opportunity to provide tactile feedback (e.g., through physical buttons and vibration). On the other hand, holding controllers may hinder users from performing proper grabbing gestures to hold virtual objects of various shapes. Therefore, hand interaction may be preferable in some application scenarios (e.g., when users need to practice complex manual skills grasping unfamiliar objects).

A limitation on our interaction design for hand tracking technology is that participants grasped the virtual sphere with a pinching gesture, instead of wrapping their fingers and palm around it. As commented by two participants in Experiment 2, this may feel unnatural. The pinch gesture was adopted as it was the most reliable gesture for hand tracking to grasp and release the spheres minimizing errors in gesture recognition with Meta Quest 2 hand tracking system [30]. It would be worthwhile to investigate the impact of distinct grip types on users' susceptibility for pseudo-haptic weight perception in future work. In addition, the current study only measured absolute thresholds for both Tracking Delay and Vertical Offset, without assessing just-noticeable differences of weights, as done in prior works [11], [12]. Subsequent experiments would help us better understand the impact of hand and controller interactions on the sensitivity of users toward weight differences when delivering pseudo-haptic feedback. Finally, experiments of the current study were conducted with a simplified setting in VR and confirming the findings in more complex and realistic environments involving multiple virtual objects of various shapes, sizes and weights would be valuable.

VI. CONCLUSION

In this paper, we explored the use of pseudo-haptics for altering weight perception in VR, which may be beneficial in scenarios where realistic weight perception of objects matters, such as VR training simulations for the manufacturing industry. We implemented two techniques to deliver pseudo-haptic feedback, Tracking Delay or Vertical Offset, and investigated

the effectiveness of two interaction methods, bare hand and controller. The current study demonstrates that users can successfully perceive weights through pseudo-haptic feedback in VR without holding anything in their hands, as well as with controllers. Although hand interaction involves some limitations, such as tracking issues, it holds the potential to enhance user experience through stronger embodiment and the use of natural hand gestures. Moreover, the impact of interaction methods on perception and experience may change, depending on the type of pseudo-haptic feedback, and it may be worth considering physical demand when designing pseudo-haptics. With our findings, we hope to inform the design of future VR interaction techniques and inspire further research on pseudo-haptics for non-instrumented, low-cost, and multimodal user interaction to facilitate effective learning in virtual environments.

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