Delusionized? Potential Harms of Proprioceptive Manipulations through Hand Redirection in Virtual Reality

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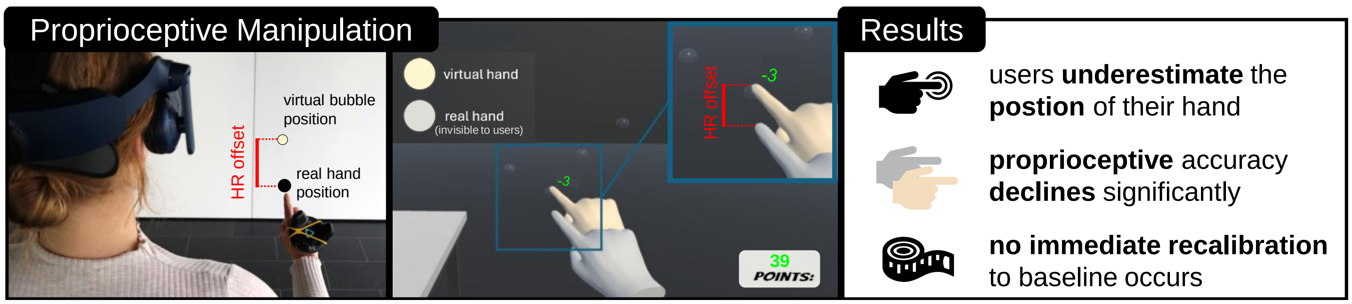

Figure 1: A participant performs an aimed-reaching interaction to hit a virtual bubble under the influence of gain-based hand redirection (HR). The technique virtually scales up her real-world movement, and as a result, she needs to cover less physical distance to reach the virtual target. Our study found that such visual-proprioceptive offsets induced by HR can lead to a significant decline in proprioceptive accuracy, which users cannot easily recover from.

Abstract

To enhance interactions in VR, hand redirection (HR)-based illusion techniques apply offsets between the virtual and real-world position of users' hands. While adaptation to such HR offsets is recognized, their impact on proprioception accuracy remains unexplored. However, deploying HR without understanding its potential effects on proprioception accuracy may pose risks to users in real-life situations. To investigate this, we conducted an experiment with 22 participants, studying the influence of prolonged exposure to unnoticeable HR offsets on proprioceptive accuracy during hand-reaching in VR. Our results show that proprioceptive accuracy declines significantly after prolonged exposure to redirected hand interactions. However, short-time exposure to unaltered hand interactions can – yet only partially – restore normal levels. Thus, we advocate being aware of potential risks arising from prolonged exposure to visual-proprioceptive offsets to ensure users' safety.

CCS Concepts

• **Human-centered computing → Virtual reality**.

Keywords

Virtual reality, hand redirection, detection thresholds, illusions

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1 Introduction

Virtual Reality (VR) has experienced a rise in popularity throughout the last decade, both in scientific research and in the consumer market. However, many envisioned VR applications are still far from becoming viable for several reasons. One major problem is missing haptic feedback for interactions with virtual objects. Here, haptic proxies, i.e., physical "stand-ins" for virtual objects, can help to overcome this problem but are often severely limited in their flexibility [43]. To address this issue, researchers developed hand-based illusion techniques to improve the haptic resolution of proxies by tricking users' perception—decoupling what users see from what they feel through visually manipulating the interaction [17, 30]. Typically, such illusions exploit the visual-dominance phenomenon, where in the case of two conflicting senses, vision usually dominates over other senses such as proprioception [11, 26].

As these techniques are very effective, they have resulted in a continuously growing research stream with various kinds of hand-based illusion techniques that can enhance interactions with haptic proxies [8, 13, 23, 51, 53], expand the resolution of active haptic devices [1, 3, 27], controller-based interactions [39, 50, 60, 65], or allow users to interact with their surroundings more ergonomically through novel ways of interaction [40], e.g., manipulate virtual objects that are out of reach [25, 46]. A large body of work specifically focuses on HR-based techniques in VR. HR offsets the virtual hand's position from the real hand's position during reaching, as illustrated in Figure 1. It is the underlying method for many techniques, such as Haptic Retargeting [4], Redirected Touching [33], or for creating Pseudo-haptic forces [23, 36, 51, 58, 65]—which can remain completely unnoticed by users. While many papers openly acknowledge that users quickly adapted to the induced offsets, we ask the question of whether prolonged interaction time under the influence of HR leads to a significant decline in proprioceptive accuracy and, if so, whether users can recover from this, leading to:

RQ1: *Does the presence of unnoticeable HR influence proprioceptive accuracy?*

RQ2: *Does the absence of HR restore proprioceptive accuracy?*

There is good reason to study the impact of HR, as proprioception plays a significant role in our daily lives. For example, we can manipulate objects without directly looking at our hands, e.g., using a steering wheel in a car while paying attention to the road or using a handrail while watching obstacles or steps—and making errors in these situations could be fatal. However, the existing work on hand-based illusions for VR has been studied with the goal of manipulating perception with little consideration for after-effects when exiting the VR environment. With increasing time in simulated environments, potentially under prolonged exposure to sensory manipulations, we want to highlight the question if we can design perceptual illusions in a safe and responsible manner to mitigate potential harms.

To do so, we conducted a within-subjects lab experiment with 22 participants, asking participants to play a simple VR game requiring continuous hand reaching while being exposed either to unmodified virtual reaching motions or to motions manipulated by HR. We assessed participants' proprioceptive accuracy through the physiological joint position reproduction (JPR) method [31]. Our results show that participants' proprioceptive accuracy of their dominant hand significantly deteriorates with prolonged exposure to visual-proprioceptive offsets caused by HR. This effect was still present after 5 reach interactions without HR. Considering that our task was only about 10 minutes and already significantly affected users' ability to perform basic reaching movements, we highlight the importance of future research in this domain as illusions slowly become an effective tool in VR interaction design.

2 Related Work

2.1 Threats Through Sensory Manipulations

The field of illusion techniques for VR is very broad, ranging from redirected walking (RW) [12] and creating impossible spaces [54] to body illusions [10]. These perceptual phenomena are truly fascinating; nevertheless, these techniques play with the users' perception, exploiting how our brain processes sensory inputs. While short experiments or occasional use might be unproblematic, VR has the potential to become an intrinsic part of our everyday lives. For example, people might work, train, collaborate, meet, and play in virtual environments [32]–the opportunities seem endless. However, with more time in VR and with sensory manipulations becoming an effective tool for VR designers, it is crucial to understand the potential harm they may cause. Tseng et al. [55] conceptually explored the risks posed by maliciously exploiting perceptual manipulations through an attacker. They focus on the resulting action, such as a loss of agency, which could result in hitting some unintentionally. Our work differs substantially from theirs because we focus on ***potential harm*** to ***users' own sensory processing***. However, if HR techniques could also be exploited to recalibrate proprioception unconsciously, threats in everyday situations could be as fatal as those discussed by Tseng et al. [55].

2.2 Hand-based Illusions in Virtual Reality

Hand-based illusions manipulate the mapping between the real and the virtual hand, which, e.g., can be achieved by changing the Control/Display (C/D) gain, introducing a gain factor g, that, e.g., amplifies ($g > 1.0$) users' real-world movements. For instance, the *Go-Go* interaction technique [46] allows users to grasp and interact with distant virtual objects beyond their arm's reach ergonomically. On the other hand, hand-based illusions have become a widely used technique to improve proxy-based interactions. For example, *Haptic Retargeting* [4] in combination with a sparse haptic proxy to provide haptic feedback for interactions such as button presses [13], manipulating sliders [19], knobs [23], buttons [3], switches and toggles [38]. In summary, hand-based illusion techniques are commonly applied to enrich interactions, resulting in a large body of related literature [1, 5, 8, 15, 27, 51, 53, 58, 65]. Many of these studies examined how much hand offset can be used while remaining unnoticeable, reporting so-called detection thresholds (DTs) [16, 19, 20, 23, 28, 64]. However, unnoticeable illusions may be even more problematic because users do not notice that their perception is manipulated. Thus, we ask whether even ***unnoticeable HR*** can already lead to a ***decline*** in the ***proprioceptive accuracy*** of the user's hand.

2.3 Proprioceptive Accuracy & Recalibration

Proprioception allows us to sense the position of our body parts without directly looking at them [48]. It can be influenced by a variety of factors, such as age [49], physical activity [42], and diseases [35], with research suggesting that the deterioration of proprioception is one of the leading causes of accidents, because of falls, collisions, or misjudgments of spatial relationships [24].

Exposing users to offsets leads to sensorimotor adaptation in order to maintain a high level of control (agency) over their movements [2]. Proprioceptive recalibration can result from sensorimotor adaptation, describing that the effect is still measurable in the absence of (visual) feedback [14]. For example, Cressman and Henriques [14] studied a mouse cursor pointing task, where the real hand was hidden from participants, and prolonged exposure to movement offsets causes hand proprioception to recalibrate, with the effect even being measurable the day after [44].

In VR, adaptation to sensory mismatches has been studied by Bölling et al. [12] in the context of RW, which gradually offsets users' viewports. This results in them walking in circles, even though they think they walk in a straight line. Bölling et al. [12] found that adaptation to such curvature gains during RW occurs after about 20 minutes and 150 repetitions in VR. Adaptation to hand offsets in VR has been anecdotally noted by Kohli et al. [34], who examined the performance difference between redirected vs. normal movements in VR. Here, visual-proprioceptive movement offsets that were initially perceived as extreme became acceptable towards the end of the experiment. Feick et al. [21] found that DTs of redirected hand movements shift due to adaptation effects after 4–8 repeated reach interactions. However, it remains unclear if these sensorimotor adaptations are only coping mechanisms or truly lead to ***proprioceptive recalibration***, especially for visuo-proprioceptive ***offsets below*** the ***noticeability level***.

3 Experiment

We conducted an experiment to investigate how prolonged exposure to gain-based HR affects proprioceptive accuracy in VR. Participants repeatedly performed aimed hand movements in an immersive game environment while being exposed to either unnoticeable gain-based HR or no HR. However, participants remained uninformed about the presence of HR over the course of the experiment. We assessed participants' change in proprioceptive hand accuracy caused by HR using the physiological JPR method. It involves having a participant actively move a joint (e.g., hand or leg) to a specific target position and then attempting to replicate that position without seeing the respective body part [31]. The accuracy of the reproduced position is measured to assess proprioceptive accuracy. JPR is widely used in rehabilitation, sports science, and clinical settings to assess joint stability, neuromuscular control, and the effects of injuries or interventions on proprioceptive accuracy [31]. In our experiment, each JPR measurement consists of 5 hand position reproductions, where participants position their real hand (invisible to them) at a virtual target (30 cm in front of them) and then confirm the position verbally to avoid, e.g., jittering, which could occur by using a secondary input device. The experimenter pressed a button to record the position, automatically calculating the offset vector between the position of the virtual target and the fingertip of the real hand. Despite the target's location, no visual feedback of the hand position is provided during this procedure.

3.1 Design

We used a within-subjects design with one independent variable, REDIRECTION (no HR vs. HR). We counterbalanced the order of no HR vs. HR between participants to minimize potential carry-over effects. We measured the dependent variables: proprioceptive accuracy of the hand through the JPR method and assessed self-reported presence using the SUS questionnaire [56]. In total, participants performed 6 rounds of the game, and we took 8 JPR measurements (each consisting of 5 hand position reproductions) to capture changes in proprioceptive accuracy over the course of the experiment (see Figure 2).

3.2 Method

3.2.1 Does the presence of unnoticeable HR influence proprioceptive accuracy? To answer **RQ1**, we exposed participants to unnoticeable gain-based HR through a game that required continuous and precise reaching movements for about 10 minutes. We measured participants' proprioceptive accuracy in VR using the JPR method before and after completing the game with and without HR (see Figure 2). The change (Δ) between the proprioceptive accuracy observed from JPR2 to JPR3 (after the "no HR" condition) and the change observed from JPR2 to JPR3 (after the "gain-based HR" condition) represents the impact that gain-based HR has on proprioception. Note that a decline or increase in proprioceptive performance observed within a condition, i.e., when directly comparing JPR2 to JPR3 for either the "no HR" or the "HR" condition, could be an effect of fatigue, training, or other task-related factors.

3.2.2 Does the absence of HR restore proprioceptive accuracy? If the presence of unnoticeable HR affects proprioceptive accuracy, we wanted to understand if it can be quickly restored. To address this research question (**RQ2**), we let participants perform 5 consecutive aimed hand movements with unmodified visual feedback, i.e., with a one-to-one mapping between the position of the virtual and real hands, to investigate if the deactivation of HR can restore their proprioceptive accuracy. After these 5 reach motions, we took a JPR4 measurement. By comparing the change (Δ) in proprioceptive accuracy from JPR3 to JPR4 (in the "no HR" condition) with the change from JPR3 to JPR4 (in the "gain-based HR" condition), we assessed the impact of 5 visible hand reaches on the process of proprioceptive recalibration. Additionally, we look at the change (Δ) in proprioceptive accuracy from JRP2 to JPR4 to assess if users fully return to the expected, original proprioceptive accuracy.

3.2.3 Task: Bubble Game. We designed a game that requires continuous hand-reaching movements while allowing us to apply unnoticeable gain-based HR (see Figure 1: left). The goal of the game was to collect as many points as possible by touching bubbles in the user's environment using the index finger. 3–5 bubbles randomly appeared in the environment at a fixed distance of 30 cm away from the user's body to ensure that they were reachable for the seated participant. We varied the position and number of bubbles to keep participants engaged, mixing up the kinds of interactions to mimic a variety of touch interactions. Then, the bubbles were highlighted in a randomized order, and participants had to touch them in this order to receive the maximum number of points. They were not required to retract their hand after touching a bubble, but after completing one round, in order to start the next round. The bubbles measured 2.5 cm in diameter, requiring some precision but without being too challenging to hit, following our pilot tests. Hitting the correct bubble resulted in +1 points, whereas hitting the wrong bubble resulted in the deduction of −3 points. Initially, the game setup was calibrated to the seated head position of the participant, with the game origin placed 30 cm below and 30 cm in front of the participant, as depicted in Figure 3. This way, we ensured that the game and JPR bubbles could be reached comfortably without requiring users to fully extend their arm.

3.3 Participants

We recruited 22 right-handed participants (10 female, 12 male) from our campus through flyers and e-mail lists. This includes one participant who was omitted from the analysis due to technical issues with the system. The average age of the participants was 27.62, ranging from 24 to 33 (SD: 2.10). Participants had a range of backgrounds, including computer science, law, cybersecurity, media informatics, environmental biology, computer linguistics, office work, facility

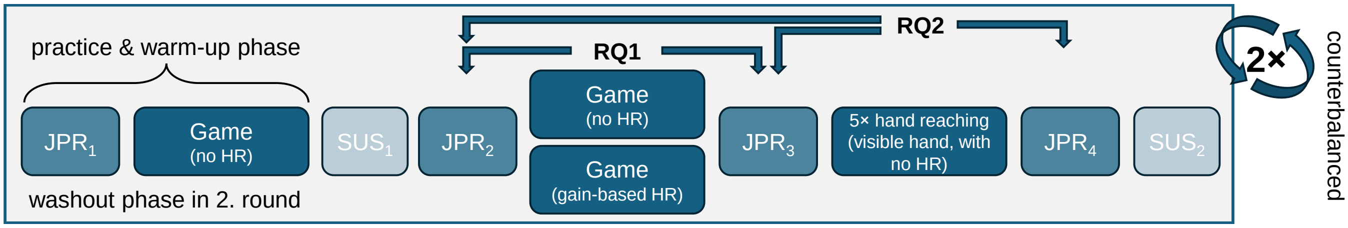

Figure 2: Study design, showing how the order of our joint position reproduction (JPR) measurements, the SUS presence questionnaires, and the tasks relate to our two core research questions. We counterbalanced "no HR" and "gain-based HR".

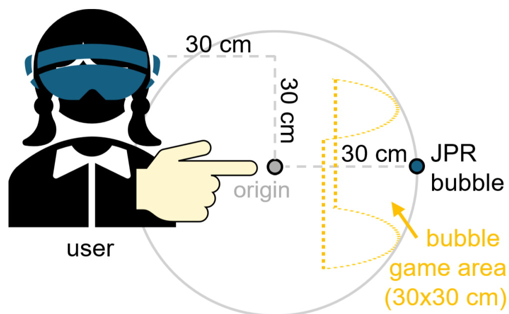

Figure 3: Study setup showing the game's origin in relation to the user, the JPR measurement, as well as the game area in which the bubbles appeared that users were required to hit.

management, pharmacy, and teaching. All remaining 21 participants had normal (N=11) or corrected-to-normal vision (N=10). No one stated any known diseases or health issues that may influence their proprioception and vision, except for one person. The study was approved by the Ethical Review Board of the University.

3.4 Apparatus

We used a simple virtual scene, which was implemented in Unity3D (v.2021.3.3f1), consisting of a virtual replica of the real world (e.g., a table) to provide visual depth cues, the game UI and an instruction screen. We used the HTC Vive Pro Eye HMD and HTC Vive tracker (v3), which we attached to the back of the user's hand using a rubber band. To fixate the position of the index fingertip in relation to the tracker, we attached a finger splint alongside the palm of the participant's hand. For HR and fingertip calibration, we used the procedure provided by the open-source Virtual Reality Hand Redirection Toolkit by Zenner et al. [63]. We included an androgynous hand model[1] with a generic skin color RGB (250, 227, 195), as suggested by Schwind et al. [52] to prevent unwanted effects such as increased sensitivity to visuo-proprioceptive offsets [45].

Gain-based Hand Redirection. Redirecting users' hand movements is most often done by gradually offsetting the virtual hand from its physical counterpart as users reach a virtual target (in our case, the virtual bubbles). For example, Cheng et al. [13], Azmandian et al. [4], Kohli [33], Matthews et al. [37], and Zenner et al. [62] presented algorithms to achieve this, where the virtual hand can be offset horizontally, vertically, and in the depth axis. We only opted for gradual depth displacement by applying a gradual gain factor in this experiment because it is a well-studied direction [7, 16, 21, 64]. As a result, the user's virtual hand moves faster than the real hand. Thus, the user's real hand needs to cover less distance to reach the virtual target (see Figure 1 left).

Conservative DTs for HR are typically established by directly comparing two hand reaches while participants are aware of the technique, with the objective of detecting offsets and no factors that distract from this task [22, 61, 64]. As a result, they provide a lower bound that often does not allow for manipulations that have practical relevance. This neither applies to our task nor typical VR applications, where users are unaware of HR and distracted, e.g., by a game [6]. Benda et al. [7] recently reported DTs for unaware HR ($gain = 3.37$) that promised to be more suitable for our task. However, our pilot studies suggested that this gain-value was too high to remain unnoticed in our setup, which is why we decided to use a gain-value just below the 75% DT ($gain = 1.7$) [21]. This seemed to be a reasonable trade-off in terms of a likely unnoticeable gain-value that designers can use in practical settings. As noticeable HR can disrupt the immersive experience, we used a presence questionnaire before and after the intervention to assess if our HR magnitude affected the experience.

3.5 Experimental Protocol

Participants arrived at the location and first received a general introduction to the study without being informed about HR or the true purpose of the study. Next, we gathered participants' consent and asked them to fill in a demographic questionnaire. We then started with the procedure of attaching the Vive tracker and the finger splint, followed by the calibration routine in VR. Subsequently, participants were placed in the game environment and guided through the practice and warm-up phase, where they learned the JPR procedure and the game (without HR applied). By doing so, we allowed them to familiarize themselves with the system and the task. They were told to sit comfortably and to move their hand at a comfortable speed. Once the participant's virtual index fingers hit the bubble, it popped and, as a result, disappeared with the achieved points displayed. The overall points score was always visible to participants.

One round of the game consisted of 42 hand-reaching movements (i.e., bubbles), which roughly took 10 minutes to complete due to memorization of the order and execution of movements. The first JPR measurement and the initial game were used to let participants practice the task. In the second round, they served as a

[1] https://assetstore.unity.com/packages/3d/characters/hands-for-vr-basic-54532

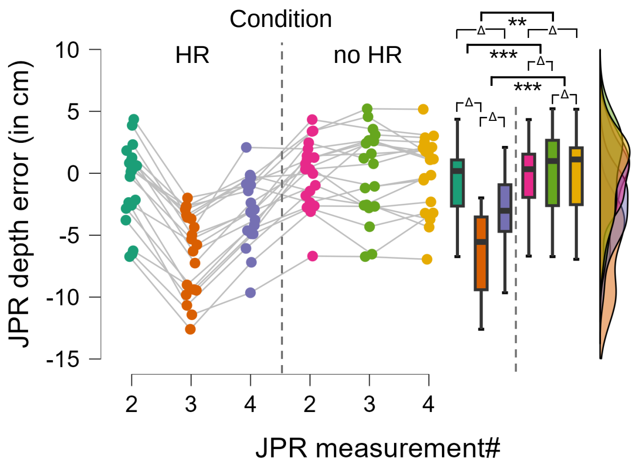

Figure 4: The results of our four JPR measurements that are relevant to our research questions show that with no HR, participants improved their proprioceptive accuracy after repeated interaction through repeated reaching. Proprioceptive accuracy significantly declined after exposure to HR, which could not immediately be restored to the normal level.

washout phase to reduce potential carry-over effects. Hence, JPR2 was the first measurement that was included in the analysis. After completing JPR2 and the game, the virtual hand was made invisible, and participants performed the third JPR measurement procedure. Following this third JPR measurement procedure, we enabled the virtual hand and continued with 5 hand reaching movements before performing the fourth JPR measurement procedure (without a visible virtual hand). In addition, participants filled in the presence questionnaire (in VR) as indicated in Figure 2. The study took about 70 minutes, and participants received candy for their participation.

3.6 Data Collection

We collected data from five sources: a pre-study questionnaire for demographic information, the offset vectors recorded for each JPR measurement, the responses in the SUS presence questionnaire [56] in VR using the VRQuestionnaireToolkit [18], field notes and observations, and a short post-study interview.

3.7 Analysis

First, we removed significant outliers in the recorded JPR offsets using the box plot method. Next, for each JPR, we averaged the 5 related JPR offsets to compute a single score. We statistically analyzed the changes in proprioceptive accuracy (Δ) after verifying the parametric test assumptions at α=.05. We performed RM ANOVAs and applied Greenhouse–Geisser corrections when the assumption of sphericity was violated. In the presence of a main effect, we performed post-hoc pairwise t-tests adjusted using the Bonferroni-Holm method. In addition, we conducted a Bayesian analysis using JASP[2] (v.0.19.3.0) following Wagenmakers et al. [57].

[2]https://jasp-stats.org/

Table 1: Mean results of JPR measurements

2.HR	3.HR	4.HR	2.noHR	3.noHR	4.noHR
-1.20 cm	-6.73 cm	-3.10 cm	-0.24 cm	-0.32 cm	0.00 cm

3.8 Results

First, we were interested in participants' proprioceptive performance in the "no HR" condition. Generally, we found a slight tendency of participants to underestimate their real hand position in VR (JPR2.noHR mean: -0.24 cm; SD: 3.23 cm) that improved with repeated reach interactions in VR (JPR4.noHR mean: 0.00 cm; SD: 3.54 cm) according to the descriptives and our analysis (p = .040, $d = -.258$, BF_{10} = 1.644) with Bayesian providing only anecdotal evidence for an effect. In the latter case, participants were extremely accurate with the positioning of their hands, and thus, they did not seem to suffer from fatigue over the course of the experiment.

Our analysis of the changes (Δ) in proprioceptive accuracy caused by unnoticeable HR suggested a main effect ($F(5.0)$ = 53.603, p < .001, η_p^2 = .728, BF_{incl} > 1000). Thus, we applied post-hoc tests to investigate our two research questions.

3.8.1 *Does the presence of unnoticeable HR influence proprioceptive accuracy?*

We found strong evidence for an effect of unnoticeable HR on proprioception accuracy (p < .001, d = 2.709, BF_{10} > 1000). Participants moved from very accurate estimates of their real hand position to significant underestimation after exposure to gain-based HR ($\Delta_{JPR3-JPR2}$ = -5.53 cm). The direction of the effect, i.e., undershooting the virtual target, is in line with the effect caused by gain-based HR, which provides further evidence that the presence of HR caused proprioceptive recalibration to occur.

3.8.2 *Does the absence of HR restore proprioceptive accuracy?*

Performing 5 restorative aimed hand movements to the virtual target without HR had a measurable positive effect ($\Delta_{JPR4-JPR3}$ = 3.42 cm) on proprioceptive accuracy (p < .001, d = 1.348, BF_{10} = 332) compared to the baseline case "no HR" ($\Delta_{JPR4-JPR3}$ = -0.10 cm). However, it was insufficient to restore proprioceptive function completely, as there still remained a significantly greater miscalibration (p < .005, d = 1.072, BF_{10} > 1000) in proprioceptive accuracy ($\Delta_{JPR4-JPR2}$ = -1.90 cm) compared to the "no HR" condition ($\Delta_{JPR4-JPR2}$ = 0.24 cm).

3.8.3 *Detecability of HR.*

Finally, our goal was to study if even unnoticeable HR already results in a decline in participants' proprioceptive accuracy of the hand. As previous work suggested that HR DTs are highly individual, we wanted to ensure that our gain factor of $gain$ = 1.7 remained largely unnoticeable and, if not, how it may have impacted participants' experiences.

We analyzed the self-reported responses in the presence questionnaire, comparing the change in presence through the intervention (see Figure 5). Our results suggest that HR was not strong enough to disrupt presence measurably in the experiment ($F(3.0)$ = 1.004, p = .397, η_p^2 = .048, BF_{excl} = 5.422). Especially the Bayesian analysis provided moderate evidence, suggesting that it is 5.4 times more likely there was no effect on the SUS score within our collected data.

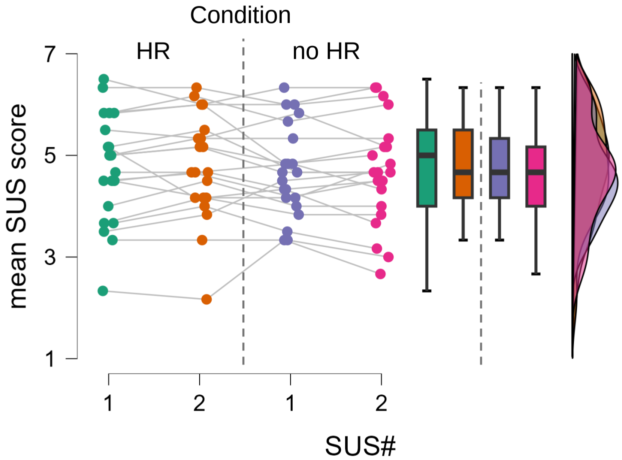

Figure 5: Average SUS presence scores remained consistent throughout the experience, suggesting that HR did not significantly disrupt the experience.

This is supported by the results of interviews, where we asked participants about their experience, and they did not mention anything that would suggest an overly strong presence of HR.

3.8.4 Summary of Results. Our study showed that even an unnoticeable HR could lead to a significant decline in the proprioceptive accuracy of the hand. Proprioceptive performance increased again but remained significantly worse than in the condition without HR, even after participants performed 5 restorative hand movements with an unmodified visual view of their real hand position.

4 Discussion & Future Work

Finally, we discuss our findings and limitations in light of existing work and provide recommendations for future work.

4.1 HR Influence on Proprioceptive Accuracy

4.1.1 Recalibration occurs regardless of Proprioceptive Accuracy. We found that participants initially underestimated the position of their hand, which is in line with previous work on distance estimation in VR [29]. This significantly improved with more time and repeated interactions in the virtual environment, leading to an impressive 0.00 cm mean error. When inspecting individual users' JPR measurements (see Figure 4), it becomes clear that there is quite a large range of errors. However, this remained consistent over the conditions and followed a normal distribution, suggesting that, like with DTs [21], participants differed in their proprioceptive accuracy [42]. Our data suggest that all our participants experienced proprioceptive recalibration. Thus, we believe that the initial level of proprioceptive accuracy of the hand does not seem to affect this.

4.1.2 Recalibration to Average Offset Induced by HR. Our results show that proprioceptive accuracy significantly declines after prolonged exposure to hand-reaching movements under the influence of HR vs. no HR. Proprioceptive accuracy decreased in the form of undershooting the goal position by an average of -6.36 cm. This is in line with previous findings suggesting proprioceptive recalibration following visual-proprioceptive sensory conflicts [14]. Interestingly, the magnitude of JPR undershooting was about 50% of HR offset in the target position (12.35 cm difference in the z-axis between the virtual and real hand position in the target location, 30 cm away from the start position). This suggests that proprioception did not recalibrate to the maximum offset in the final position but to the average offset between the real and virtual hand over the course of one reaching movement. However, whether this is just a coincidence remains to be explored. For example, it could be that with more interaction time under the influence of gain-based HR, users would eventually recalibrate to the maximum offset. Nevertheless, introducing a gradual offset, as typically done by HR, separates our work to the best of our knowledge from any other works in the psychology literature on proprioception, which typically use fixed offsets and report that users can fully adapt to them [9, 14].

4.1.3 Recalibration Limits Application Space of Illusions. As HR techniques are frequently used in the field of ergonomics [40, 41] and haptic feedback [4, 13] to enhance VR experiences, designers should be aware of the potential harm caused by unconscious recalibration. This is even more important for training and simulation applications, as this could lead to incorrect acquisition of motor behavior that potentially transfers to real-life scenarios. For example, skills acquired in flight or surgical simulators would be of limited utility and could even lead to dangerous situations. Recently, redirection techniques have also been proposed for rehabilitation purposes to enhance the motivation of patients with motor impairments [59]. While acknowledging the potential of motivating users, we want to sensibilize research in this domain. As proprioceptive training is an essential part of improving recovery from injuries and preventing them in the future [48], the application of HR-based techniques could, in fact, interfere with these therapy goals if effects on proprioception are not considered.

4.1.4 Effects May Be More Severe Than We Found. Finally, as concerns about the malicious use of perceptual manipulations have already been discussed by Tseng et al. [55], unnoticeable proprioceptive recalibration leaves users completely unaware when returning to the real world. Despite our efforts, we cannot guarantee that the HR offset was unnoticeable for every user because we applied an average conservative DT, but HR DTs are known to be highly individual [21]. Still, such conservative DTs are relatively low in comparison to offsets used by many techniques [4, 13], which may result in more severe effects on proprioception.

4.1.5 Generalizability of Applied HR Technique. In this paper, we only investigated proprioceptive recalibration of one type of hand-based illusion, i.e., HR, and only along one axis by introducing a gain factor > 1.0, speeding up virtual hand movements. However, it remains to be explored if, e.g., horizontal or vertical offsets show similar recalibration effects. We recommend that future work consider different types of hand-based illusions. Moreover, the external validity of our experiment needs to be verified. To this end, participants performed all reaching movements inside VR. Future studies should investigate study designs in which proprioceptive accuracy can also be assessed after users exit the virtual environment.

4.2 Restore Proprioceptive Accuracy after HR

4.2.1 Retention of Recalibration Remains to Be Explored. We chose 5 aimed hand reaches without HR to restore proprioceptive accuracy because of previous work on adaptation to visual-proprioceptive offsets [9, 21]. Following these hand reaches, proprioceptive accuracy was partially restored but was still significantly worse than in the baseline condition. On the one hand, this is good news because it shows that proprioceptive function can be restored, but it leaves us with the question of how many hand movements in the absence of HR are necessary to achieve this. Most likely, there is no absolute number of interactions that are needed to restore proprioception, but it may depend on how much time users were exposed to the illusion and the magnitude of the visual-proprioceptive offset. Thus, we are not yet able to draw conclusions about the retention of this HR-induced proprioceptive recalibration effect because this requires a different study setup.

4.2.2 Trade-offs between Proprioceptive Fatigue and Exposure Time. Due to the repetitive hand-reaching, we aimed to keep the total number of hand movements as low as possible so as not to induce too much fatigue, which could affect the JPR measurements. However, this limits the interaction time under the influence of HR, leading to the question of whether 42 hand movements (about 10 minutes) are sufficient to create very robust proprioceptive recalibration–especially in light of Bölling et al.'s [12] study on RW, in which participants were exposed to 150 trials (about 20 minutes) over the course of 3 days. While we saw a significant decline in proprioceptive accuracy immediately after exposure to HR, only 5 aimed hand movements without HR could partially restore normal proprioceptive performance levels. Thus, one may argue that the effect can be reversed relatively quickly; however, we believe that with more time under the influence of HR, proprioceptive recalibration may become more robust. In this study, we tried to find a balance between reducing fatigue and increasing interaction time to systematically measure the effects. Nevertheless, we recommend future work to investigate how long-time exposure to HR influences the robustness of proprioceptive recalibration.

4.2.3 Recalibration Method & Sensory Manipulations Beyond HR. Understanding how time under exposure and HR magnitude affect the robustness of recalibrated proprioception could help to inform the design of a method that facilitates the transition between real and simulated VR environments [17]. This could help to mitigate the immediate risks when re-entering the real world. However, the use of hand-based illusions for training and simulation applications may still be questionable based on our findings. Therefore, we see our findings as a *call for action*, encouraging the community to further look into this topic before illusions become ubiquitous tools in VR design. In this work, we only considered proprioceptive manipulation of the hand because it is widely used, but the design space for illusions in VR does not stop here. For example, researchers introduce mismatches between the vestibular (balance) and visual sense to create flying illusions [47]. Recalibration of the vestibular sense has not been investigated yet, but adaptation to mismatches could have even more serious consequences than proprioception.

5 Conclusion

In this work, we investigated how gain-based HR affects the proprioceptive accuracy of users' dominant hand. To do so, we conducted an experiment with 22 participants, exposing participants to an unnoticeable magnitude of HR and measuring if the induced virtual-to-real hand offsets resulted in a decline in proprioceptive accuracy. We applied the physiological JPR method to assess proprioceptive accuracy before and after prolonged exposure to gain-based HR. Our results showed that participants' ability to position their hands accurately in VR significantly deteriorated in the form of undershooting, which is in line with the expected direction caused by HR. Participants partially recovered from this recalibration of hand proprioception after 5 non-manipulated hand reaching movements, but proprioceptive performance was still significantly worse than users' normal performance, i.e., their performance when HR is not applied. Our results have implications for a large range of hand-based perceptual illusions in VR. Especially because people spend an increasing amount of time in virtual environments, and with illusion techniques becoming an effective tool for designers. Thus, we need to carefully consider their impact on people.

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