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Visuo-haptic Illusions for Linear Translation and Stretching using Physical Proxies in Virtual Reality

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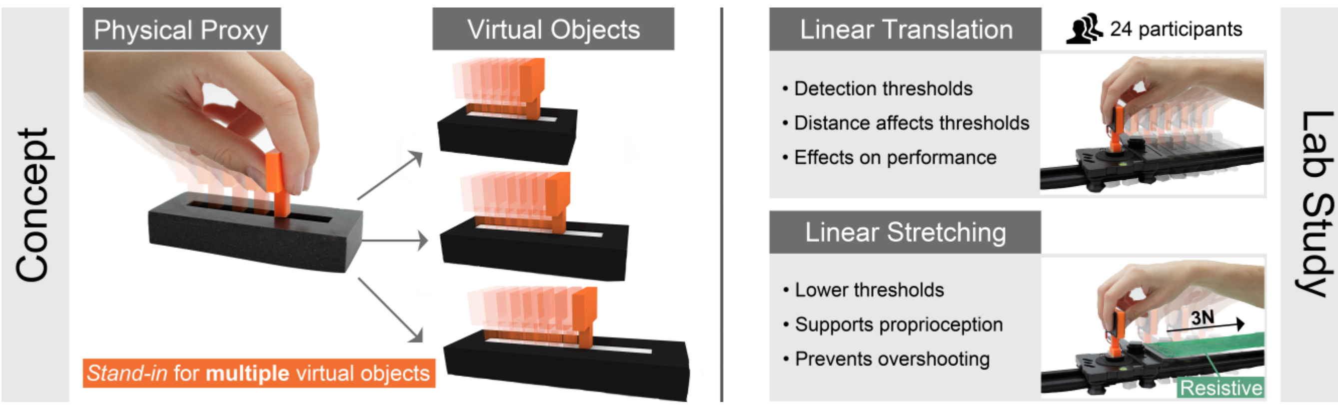

Figure 1: We create visuo-haptic illusions by using physical proxies with moveable parts. These proxies can represent multiple virtual objects. Highlights from our lab study reveal how much real-to-virtual discrepancy can be introduced for linear translation and stretching while remaining unnoticed.

ABSTRACT

Providing haptic feedback when manipulating virtual objects is an essential part of immersive virtual reality experiences; however, it is challenging to replicate all of an object's properties and characteristics. We propose the use of visuo-haptic illusions alongside physical proxies to enhance the scope of proxy-based interactions with virtual objects. In this work, we focus on two manipulation techniques, linear translation and stretching across different distances, and investigate how much discrepancy between the physical proxy and the virtual object may be introduced without participants noticing. In a study with 24 participants, we found that manipulation technique and travel distance significantly affect the detection thresholds, and that visuo-haptic illusions impact performance and accuracy. We show that this technique can be used to enable functional proxy objects that act as stand-ins for multiple virtual objects, illustrating the technique through a showcase VR-DJ application.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction paradigms; Virtual reality.

KEYWORDS

Virtual Reality; Tangible Interfaces; Haptics; Proxy Objects; Visuo-haptic Illusions.

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1 INTRODUCTION

Virtual Reality (VR) is a promising technology allowing users to enter a virtual environment. Here, users can interact with virtual objects which may result in an immersive experience for them. However, objects and their mechanics are purely virtual, meaning that humans cannot physically touch and interact with them; thus, they do not provide haptic feedback. A large body of work has focused on giving virtual objects tangible form by using proxy objects that approximate a virtual object's shape and size, or by providing realistic touch sensations, leading to more immersive VR experiences [5, 15, 21, 69, 70]. Researchers have now begun exploring the replication of richer object characteristics such as texture [9, 29, 64] and weight [53, 67], and started implementing more functional, manipulable aspects of objects, including rotatable, stretchable and bendable parts [5, 21, 46]. However, having a dedicated proxy for every object in the virtual word is expensive and would end up defeating the purpose of VR—i.e. one would be replicating the virtual world in the physical world using proxies.

A promising method to address this problem is to reuse a small set of physical proxies alongside visuo-haptic illusions. The method utilizes the visual dominance effect [26] by displacing the virtual object from its physical counterpart, allowing the same physical proxy to be used as stand-in for various virtual objects [8, 13, 41, 43]. Researchers have shown that we can introduce considerable discrepancy with respect to an object's shape and size, where the discrepancy goes unnoticed by a user [7, 60]. In the canonical example illustrated by Azmandian et al. [6], a single physical block acts as a proxy for multiple virtual objects through such a visuo-haptic illusion. Yet, while this approach works for simple static objects, we have not yet explored whether this works to mimic objects that have manipulable parts.

In this work, we address this shortcoming by designing visuo-haptic illusions combined with physical proxies, and study how much disparity we can introduce between the physical object and virtual model. We focus here on the fundamental object manipulation of linear translation (i.e. a 1D slider), which can be found in many domains including traditional 2D UI elements such as scrollbars as well as physical interfaces (e.g. sliders and switches to control machines, vehicles, devices and tools). We are interested in understanding how much linear translation capability a physical proxy needs in order to function as a realistic stand-in for a broad spectrum of virtual objects with translatable parts—that is, does the physical slider need to be as long as the virtual slider? If not, how much can this vary? Further, we explore linear stretching, where the object itself supplies force in the opposing direction of movement, to understand how this this might affect users' perception of movement.

Based on the findings from a controlled lab study involving 24 participants, our work identifies conservative detection thresholds for both linear translation and linear stretching. These thresholds help VR designers to incorporate haptic feedback into their designs with proxies. For instance, a VR designer interested in supporting novice DJs might build a virtual DJ desk without the need of expensive equipment; however, suppose the designer only has a single physical slider available. Because the designer cannot have a proxy for every virtual slider (and their lengths), she would employ visuo-haptic illusions alongside a single physical slider. Our findings would inform her the limits of what she can simulate without users noticing, which give her confidence to design an engaging and natural experience.

Our findings also help to outline the effects of the use of visuo-haptic illusions in the scope of linear translation (and stretching) may have on the interaction. Our eventual goal is to enable richer proxy objects that ultimately account for several virtual objects.

Our work makes five contributions:

1) We provide our estimates for the conservative detection thresholds for linear translation and linear stretching across two travel distances, 7 and 14cm, enabling VR designers to easily incorporate visuo-haptic illusions into their designs.
2) A deeper understanding of the contributing factors leading to a visual-proprioceptive conflict, and thus a semantic violation.
3) An investigation of the effects that linear proxy-based visuo-haptic illusions elicit on task performance and accuracy.
4) We contribute the design of a tool for evaluating visuo-haptic illusions for linear translation and linear stretching.
5) The development of an application illustrating the use of visuo-haptic illusions combined with a single physical proxy representing multiple virtual objects.

2 RELATED WORK

Our work is situated in the field of haptics in VR and tangible (embodied) interaction. We investigate visuo-haptic illusions using Control-Display (C/D)-ratio manipulations for linear translation and linear stretching. Thus, we outline current challenges in the haptics field, and we discuss recent work that addresses these challenges using visuo-haptic illusions and physical proxy objects.

2.1 Using Physical Proxy Objects in VR

Tangible interaction comes with well-known advantages over purely virtual interaction such as improving task performance [21], spatial memory [18], and it leads to faster and more intuitive interactions [11, 32, 33, 54]. Therefore, a large body of work in the VR field has focused on conveying as much tangible information as possible from the real to the virtual world leading to more immersive experiences – for instance, rendering objects properties such as size [3, 17, 21, 42], shape [9, 21, 42, 53, 64, 66], texture [9, 29, 64], and weight [16, 44, 51, 53, 67].

To do so, researcher have proposed to use physical proxy objects as "stand-ins" for virtual objects. A physical proxy aims to replicate various properties and characteristics of the virtual object enabling kinesthetic and tactile exploration and interaction. Generally, such proxies have been found to improve the realism, presence, and fluidity of interactions in the virtual world over purely virtual experiences [21, 32, 47, 63]. Hettiarachchi et al. [31] proposed annexing reality, an AR system which surveys the local environment for the suitable physical proxies given a virtual model. While this development is exciting, in the general case, it is unlikely to always have a representative set of physical proxies which match underlying requirements. Therefore, Cheng et al. [15] use a sparse haptic proxy and demonstrate that it can be used as an effective way to provide touch feedback in VR. Here, the idea is to use a set of geometric primitives in combination with hand retargeting providing realistic touch feedback for various elements in the virtual environment. Going beyond touch interactions, we have seen approaches utilizing actuated assembly blocks [52] or robotic assemblies [69] to approximate kinesthetic properties such as shape and size. Zhu et al. [70] developed HapTwist, a twistable artefact which can be manipulated in various ways to create different haptic proxies. Similarly, Arora et al. [5] and Feick et al. [21] presented modular toolkits moving away from the idea of a stiff proxy by introducing moveable object parts which can be e.g., rotated, stretched, and bent. However, it is impractical to build a dedicated proxy for each virtual object in the environment. To overcome this limitation, researchers have proposed the use of visuo-haptic illusions which leverage the visual-dominance phenomenon.

2.2 Visual-Dominance Phenomenon

Visual cues override proprioceptive cues when there is a visual-proprioceptive conflict (i.e. between the visually rendered position and the perceived limb position): this is known as the visual-dominance phenomenon [12, 13, 39, 45]. Several research projects have utilized this effect in VR across different scales. For instance, we have used this approach to redirect walking [56], to scale jumping [37], and even to manipulate the height of a visual step [40]. A common method is the manipulation of the Control-Display (C/D)-ratio—introducing a constant gain factor translating a smaller physical movement to a larger virtual, and vice versa. Traditionally, this approach has been successfully used to improve the performance of 2D mouse-pointing [14], and more recently has been adapted for virtual environments as well [24]. For instance, the Go-Go interaction technique let a user's arm grow to reach and manipulate distant virtual objects by manipulating the C/D ratio [49]. Similarly, this effect has also been utilized to redirect a user's hand when reaching out to grasp or touch an object. Here, the redirecting technique introduces a slight visual offset to the user's hand position which they then try to compensate for [6]. Hence, the user visually touches a different object, but in fact they have been redirected to the same physical proxies [15].

These prototypes that take advantage of the visual-dominance phenomenon raise the question: how much discrepancy can be introduced without resulting in a semantic violation (i.e. the discrepancy is too large, and is noticed by the user) [48]? To address these kinds of questions, Zenner and Krüger [68] investigated the detection thresholds for hand-redirection in a desktop-scale setup. They found that it is possible to apply gain factors between g = 0.88 and g = 1.07 without users noticing. Our work builds on this hand redirection work; however, we focus on instances where users interact with physical proxies and their manipulatable parts. This is a departure from hand redirection work, where there is typically no "counter force" from the object. Bergström et al. [10] resized the virtual hand to simulating different sized virtual objects. They redirect users' fingers by applying a gain factor resulting in an illusion of a wider grasp than the user's actual physical grasp. Their findings show that smaller physical objects can act as proxies for up to 50% larger virtual objects, and 10% smaller virtual objects, respectively. Using this visual-dominance effect in combination with haptic feedback can result in a visuo-haptic illusion.

2.3 Visuo-Haptic Illusions

Visuo-haptic illusions leverage the visual-dominance phenomenon and have also been successfully used alongside physical proxies. For instance, Ban et al. [7] introduced a perception-based shape display utilizing a simple cylinder primitive that can render various shapes by only visually displacing the user's hand. Kohli et al. [41] used a redirection technique in a passive haptics context allowing for continuous exploration of different virtual geometries, where movement is mapped to a single physical proxy by warping the virtual space. Strandholt et al. [57] proposed redirected touch combined with physical proxies to enhance tool-based interactions in VR. They applied an offset to a virtual hammer so that the physical impact on a proxy corresponds to the visually displayed impact. Similarly, VR Grabbers is a tool-based system allowing to grab different sized virtual object using the same physical tool through dynamic visual adjustments [65]. Dominjon et al. [19] found a strong influence of C/D-ratio on the perception of virtual object mass. Samad et al. [51] followed up on their findings by introducing a predictive model of weight perception for interaction designers, based on a series of experiments supporting the correlation between C/D-ratio and perceived object mass. Abtahi and Follmer [1] demonstrated that C/D-ratio manipulations may also be used to increase the perceived resolution of shape displays which can physically render virtual content.

To better understand how different a physical and virtual object can be, Kwon et al. [42] conducted a usability study investigating the effect of size and shape difference between virtual and physical object. They found that shape features seem to be a more critical factor for proxy design than size. In the light of this work, Tinguy et al. [60] ran an experiment to quantify this effect by investigating the JND (just notable difference) for proxy width, local orientation, and curvature. Their results show that for object width 5.75 %, local orientation 43.8 % and curvature 66.66% discrepancy can be introduced without being noticed by participants. Thus, using visuo-haptic illusions appear to be a promising direction allowing proxies to be reused for various virtual objects. In line with recent research showing that the C/D-ratio can be manipulated without affecting immersion and the sense of presence [2], we utilize this promising method to create visuo-haptic illusions for proxy-based interactions.

Our work marks a substantial contribution to the field of haptics in VR. Recent research has investigated the possible discrepancy between the virtual and physical object with respect kinesthetic properties. We undertake the next logical step by identifying how much discrepancy between the functional parts of a proxy object can be introduced while remaining unnoticed. In this paper, we look at a subset of possible object interactions, specifically: linear translation and linear stretching.

3 LINEAR TRANSLATION AND STRETCHING

Linear translation is a common object manipulation and plays an important role in our everyday life. For instance, humans can translate an entire object to a desired location, and many physical objects and interfaces offer translatable parts. Software GUIs also frequently make use of linear translation: scrollbars and sliders are used for input in video-, and photo-editing, design, office, programming, gaming and countless other softwares; physical sliders are often found to control machines, vehicles, devices and various other

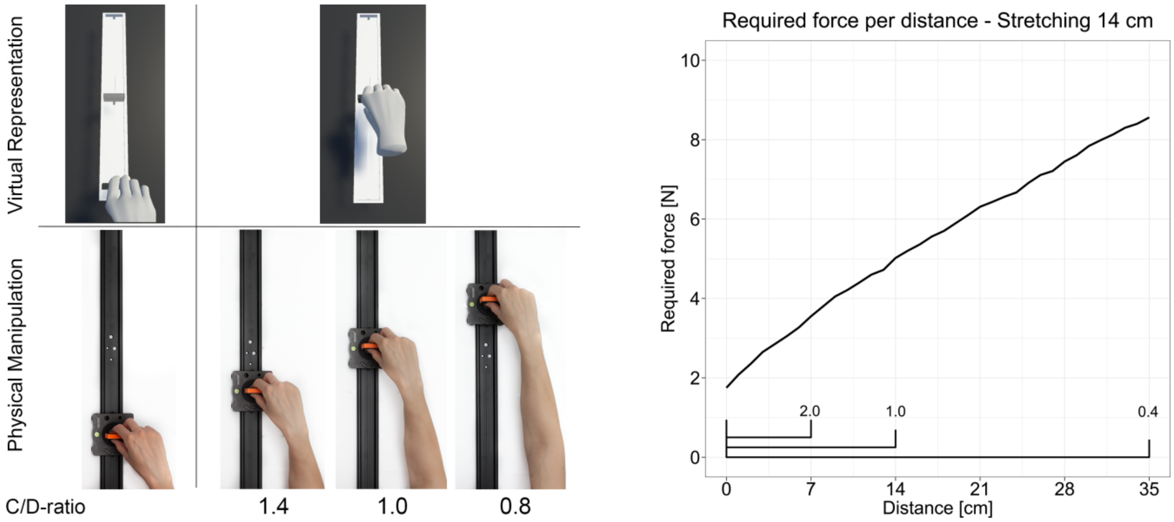

Figure 2: Effect of using C/D-ratio manipulation (left). Force needed (Newton) to stretch the object across different distances and C/D-ratios (2.0, 1.0 and 0.4) in our user study, measured with a PCE-DFG Series force gauge (right).

equipment. Additionally, many tools make use of translational mechanical parts such as, when measuring distances using calipers, opening and closing a containment or clothing through zippers, workshop tools such as screw clamps and mechanism to extent a device e.g., cutters, rulers or fishing rods to shrink their form factor.

Linear stretching shares a lot of similarities with linear translation but adds relative force feedback to the translation. This force feedback can give users an understanding of the extent to which they manipulated the device, allowing them to better predict the resulting state or action. For instance, when using a slingshot, a user can estimate distance, trajectory, and velocity with which the object is going to fly based on the stretched distance and the perceived resistance force. Thus, resistive force actively contributes to the understanding of travelled distance (see Figure 1 and 4).

3.1 C/D-Ratio

We take advantage of the visual-dominance effect by manipulating the C/D-ratio, with the goal of enabling functional proxy objects with translational parts to act as stand-ins for multiple virtual objects. Manipulating C/D ratios is well-known in the context of traditional 2D mouse interfaces [14] and can be easily adapted to VR [2, 19, 51]. By increasing the C/D-ratio, the method scales up the performed physical interactions resulting in a larger virtual movement than the actual physical movement (see Figure 2 (C/D: 1.4). Reducing the C/D-ratio leads to the opposite effect: the real travel distance is further than the displayed virtual distance (see Figure 2 (C/D: 0.8)). Our goal was to study to what extent we can use this technique for linear translation and linear stretching without being detected by humans.

3.2 Form Factor & Interaction Technique

The various examples above illustrate the importance of linear translation as a widely used interaction method. Yet, the size of the object being manipulated, how it is handled during manipulation, and so on varies widely. To control for these variables in our work, we decided to focus on single-handed manipulations and a simple physical slider proxy that users can comfortably grasp and hold. The from factor was determined using pilot studies experimenting with different slider sizes and widths (see Figure 4).

There are various ways to grasp and manipulate this simple slider [23]. The most common approach for this object size and width appears to be a pinching-type gesture using middle, index, and thumb fingers. We choose this interaction method based on pilot testing and previous work in this domain [10, 51]. Participants were asked to grasp the object using this pinching-type gesture, and this posture was replicated by a virtual hand (see Figure 4 and 5). The experimenter monitored participants through the experiment to ensure that they maintained this grip.

4 EXPERIMENT

In this experiment, we study how much discrepancy between the physical and the virtual representation can be introduced for linear translation and linear stretching without resulting in a semantic violation. We also investigate the effects that C/D-ratio manipulations have on the interaction.

We conducted a psychophysical threshold experiment to investigate the Conservative Detection Threshold (CDT) [1] of C/D-ratio manipulations for both manipulation techniques, linear translation and linear stretching, and for two different travel distances, 7 and 14 centimeters. We chose 7cm based on the travel distance offered by standard off-the-shelf slider potentiometers which are part of many UIs, and 14cm to test twice the length. In the experiment participants were seated on a chair while viewing a simple virtual environment (through an HMD) with their dominant hand being tracked. The virtual scene contained a table and the slider setup corresponding to the physical world. Participants used a thumb, index-middle finger pinch to grasp a virtual slider embodied by a functional physical proxy slider. They were told to translate the

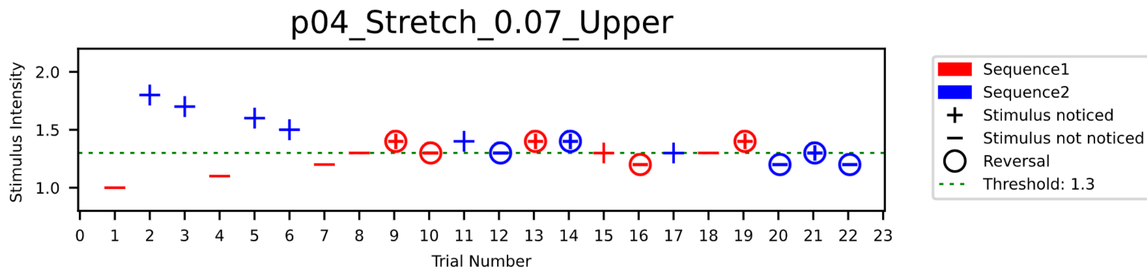

Figure 3: P#4's interleaved-staircase in the upper stretching 7cm condition converging at CDT = 1.3.

slider to a displayed position, while being exposed to different C/D-ratios repeatedly. Once they reached the target position, they were asked a forced-choice question about whether they noticed a manipulation [56]. Specifically, after each manipulation, they were to respond either 'yes' or 'no' to the following statements: "*The virtual slider moved faster*" or "*The virtual slider moved slower"* depending on the condition, following Steinicke et al.'s methodology [55]. Participants were informed about the procedure and had to report a manipulation as soon as they noticed it. The findings help to improve the understanding of how we can utilize the visual dominance effect for linear translation and stretching across different distances aiming to support the design of rich physical proxies.

4.1 Design

We used an adaptive psychophysical 1-up-1-down interleaved-staircase procedure with a 2x2 within-subjects study design. We had two independent variables: (1) manipulation techniques and (2) travel distances with two levels each. In total, we investigated four conditions. We measured three dependent variables: (1) participants' responses to the forced-choice question regarding the manipulation, (2) time needed to reach the target, and (3) movement profile for each trial.

An interleaved-staircase is an established method in psychophysics which exposes participants to different stimuli (C/D-ratios) repeatedly. We chose a fixed step size 1-up-1-down design targeting the CDT or point of subjective equality. Here, either of the two possible responses is equally likely to occur (50% due to chance) [38]. Since the procedure can target different probabilities, we can compute the required step-size (ψ_{target}) for the step Up(Δ^+)/Down(Δ^-) method and $CDT = 0.5$ as follows [35]:

$$\psi_{\text{target}} = \frac{\Delta^+}{\Delta^+ + \Delta^-} \Rightarrow \frac{\Delta^-}{\Delta^+} = \frac{1-\psi_{\text{target}}}{\psi_{\text{target}}} = \frac{1-0.5}{0.5} = \frac{1}{1}$$

The interleaved-staircase procedure makes use of two independent sequences: an ascending sequence (Figure 3 red) as well as a descending sequence (Figure 3 blue). The procedure randomly assigns each trial to one of the sequences and once a participant detects a stimulus, decreases by the step size for the next trial. At the same time, it increases the next stimulus within a sequence when a participant fails to detect the stimuli. A directional change within one sequence is marked as a reversal point.

We used the number of reversal points (r=5) in each sequence as a convergence criterion for the staircase procedure [25]. For each condition we utilized two separate staircase procedures to determine the upper (between 1.0 to 2.0) and lower (between 1.0 and 0.4) CDTs. Thus, the highest C/D-ratio subjects could be exposed to was 2.0, and 0.4, respectively. These values were chosen based on previous findings in hand/finger-redirection [1, 20, 27, 68], however after pilot testing, we set the start values in the staircase procedure to upper (1.0 - 1.8) and lower (1.0 - 0.5) using a 0.1 fixed step size as this leads to quicker convergence [38]. We counterbalanced the ordering of the four conditions using Latin square and randomized the order for the upper and lower threshold procedures for each condition.

4.2 Participants

We recruited 24 right-handed participants (eight females; sixteen males), aged 22-34 (mean: 27.04; SD: 3.42) from the general public and the local university. This excludes one participant who was omitted from the analysis due to not reaching convergence in the study. This could have been due to system error or the participant not understanding the study which we could not determine in hindsight. Participants had a range of different educational and professional backgrounds including media informatics, computer science, education, chemistry, pharmacy, biology, anglistics, economics and law. Five participants had never used VR before, twelve had used it a few times (one to five times a year), three people used it often (6 - 10 times a year), and four other people on a regular basis (more than 10 times a year). Nine participants reported that they have not played VR games before, fourteen people responded sometimes or infrequently (1 - 5 times a year), and one person on a regular basis (more than 10 times a year). Participants not associated with our institution received 10€ as renumeration for taking part in the experiment. The study was approved by the Saarland University's Ethical Review and DFKI's Hygiene Board.

4.3 Apparatus

In our study, we used the apparatus shown in Figure 4, consisting of an HTC VIVE [72] tracking system (2PR8100); HMD, base stations, a VIVE controller and a VIVE tracker with SteamVR [73] (v. 1.13.10) and the OpenVR SDK [71] (v. 1.12.5). The virtual scene was developed with Unity3D [59] (v. 2019.2.17f) representing a small virtual world including the slider setup on a table running on a MSI P65 Creator 8RE with an Intel Core i7-8750H CPU, 16GB RAM and a NVIDIA GeForce GTX 1060. For hand tracking, we used a Leap Motion controller [74] (SDK v. 3.2) attached to the HMD to

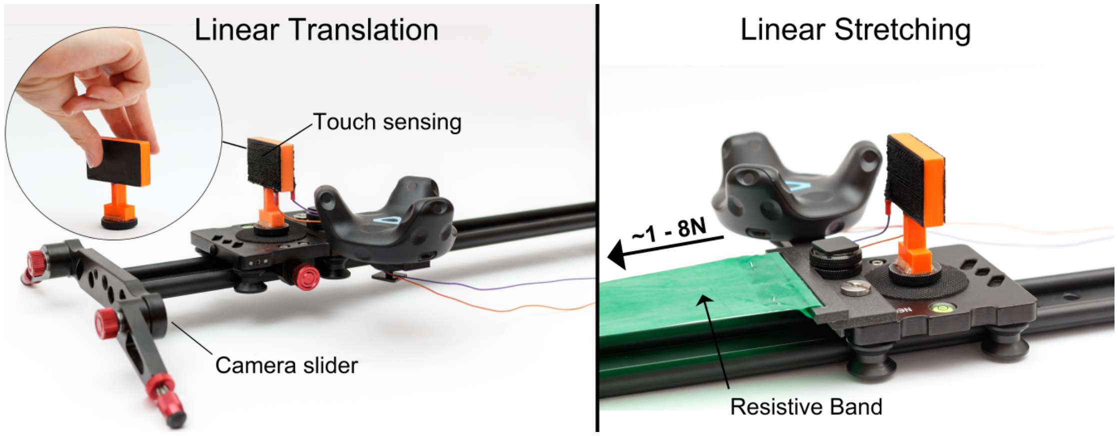

Figure 4: Study setup showing the camera slider hosting the 3D printed slider with a conductive coating on both sides of the slider. Resistive band and custom 3D printed quick-release mount are shown on the right.

avoid augmenting the user's hand. We used a simple hand representation in the VR world to avoid distractions caused by e.g., textures. The custom slider rig was built using an 80cm camera slider enabling a smooth translation movement across its length and forced participants to translate the object in this direction. We 3D printed a physical proxy slider and a custom mount for the VIVE tracker to ensure a fixed position while interacting with the device. Following initial testing we choose a slider width of 1cm which users could comfortably grasp and hold throughout the experiment. To avoid hand tracking issues, we snapped the virtual hand to the slider as soon as the participant grasped and hold-on to the physical proxy slider. To support this, we included capacitive touch sensing capability to the physical proxy slider using conductive 3D printing filament (composite PLA – Electrically Conductive Graphite Ø1.75mm) on either side of the slider connected via wires to an Arduino Nano 3.x [4] running capacitive touch sensing firmware. Once the participant grasped the proxy slider, the microcontroller sends a touch-event to the VR machine using serial port communication.

For the linear stretching conditions, we used a resistive rehabilitation band providing 3.05 Newton (7cm) and 5.02 Newton (14cm) resistance (see Figure 2 right – C/D-ratio: 1.0). We measured the resistance before and after the study and could not find any difference potentially caused by material fatigue. The components were secured on the standard camera mount, which also had a plug mechanism to quickly de-/attach the resistance band in-between conditions. We carefully calibrated the setup for each participant.

4.4 Procedure

The study was conducted in a quiet room to avoid distraction and ensuring the same testing conditions. After a study introduction, informed consent and explaining the hygiene measurements in place, participants filled in a demographic's questionnaire. Then, they were introduced to the virtual environment and the task. They were informed about the procedure and the goal of the study. Following this, they performed an open-ended practice round until they were familiar with the system and the task.

Participants were instructed to hold onto the slider throughout one staircase round followed by a break. They were not permitted to grasp the slider differently or repeat a trial. Once they reached the goal position, the forced-choice question ('yes' or 'no') about whether they noticed a manipulation appeared. Participants were instructed to answer as quickly as possible. The slider had to stay at the goal position within a 5mm threshold for the question to remain visible. Participants responded using the VIVE controller in their non-dominant hand through pointing with a laser, before bringing the slider back to the start position and repeating the procedure. In our pilot studies, we observed that movement speed may be another crucial variable when determining detection thresholds (aligned with Hall et al. [28]); therefore, we controlled for movement speed to isolate the effects of force and distance (position and movement). In our protocol, we instructed participants to translate the object with a consistent "normal" speed in the warm-up task. Later, participants were informed when they moved the object too slow/fast – outside of the initially established time frame. After completing the four conditions we asked them to fill in a Simulator Sickness Questionnaire (SSQ) in VR [36]. The total experiment took ∼1hour.

4.5 Data Collection

We collected data from five sources: a pre-study questionnaire for demographic information; the subjective responses to the forced-choice staircase question; system logs (including trial times, travelled distance, velocity and acceleration at a sample rate of 5ms, ∼100.000 data points), field notes and observations, and a poststudy SSQ [36] in VR using the VRQuestionnaireToolkit [22].

4.6 Hypothesis

Alongside determining the conservative detection thresholds, we had the following two hypotheses for this experiment:

1) Manipulation distance has a significant effect on the detection thresholds. Previous work investigating detection thresholds indicated a potential effect of the scale of movement [1, 68]. We hypothesize that this effect should be evoked

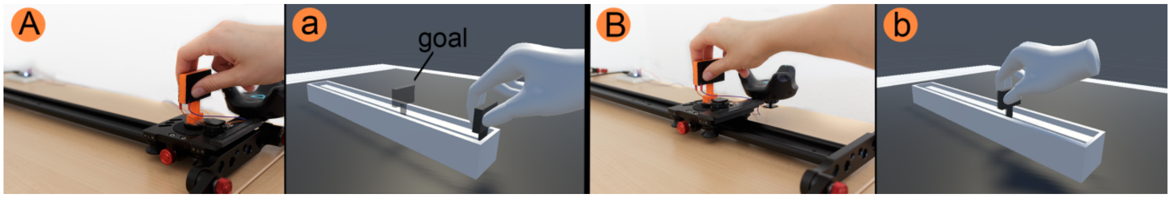

Figure 5: Study task: Participant waits at the start position (A-a) and stops at the goal position (B-b) followed-up by the forced-choice question asking participants whether they noticed a manipulation.

in our experiment - increased manipulation distance leads to smaller detection thresholds.

2) We hypothesis that linear stretching has lower detection thresholds since the added relative resistance force provides an additional kinesthetic cue which may support proprioception. Due to the proportional relationship between travel distance and resistive force, we give users an additional proprioceptive channel which may result in an earlier semantic violation, potentially leading to a quicker detection of a manipulation.

4.7 Results

We report our estimates for the CDT for linear translation and linear stretching at the two travel distances 7cm and 14cm. We then analyze the CDT with respect to our hypothesis. Finally, we take a deeper look at the effects that different C/D-ratios have on the overall performance and naturalism of the interaction. This helps to better understand the potential effects that visuo-haptic illusions for linear manipulations might have.

4.7.1 Detection Thresholds for Linear Translation and Linear Stretching. Overall, we collected 4080 responses as a result of our interleaved staircase procedure. On average participants completed 170 trials (SD: 8.20). Each participant contributed one conservative detection threshold per condition which was computed as the average of the last four reversals points out of each staircase sequences [38]. To determine the overall detection thresholds, we computed the means across the 24 detection thresholds for all eight conditions separately. The result can be found in Table 1 and Figure 6. For further analysis we plotted participants' responses to see how they converged (for example, see Figure 3). All 192 staircase plots are available in the supplementary materials.

Results from the SSQ questionnaire suggest that the haptic illusion did no trigger significant motion sickness. The Total Severity (TS) score was Mean = 18.23, SD = 10.54.

4.7.2 Hypothesis Testing - Effect of Manipulation Techniques and Travel Distance. To further analyze our collected data, we performed a Two-Way ANOVA on the two independent variables, manipulation techniques and travel distance with two levels each. The data was split into two groups, upper or lower threshold for analysis. We used Levene's test to check the homogeneity of variance and Shapiro-Wilk test to verify a normal distribution. Both threshold data sets, meet the ANOVA assumptions at $\alpha = .05$.

The Two-Way ANOVA revealed a significant difference for travel distance, 7cm and 14 cm for the lower ($F_{1,92} = 6.245$, $p = .014$) and upper ($F_{1,92} = 10.845$, $p = .001$) thresholds. This supports our hypothesis that travel distance ultimately determines how much discrepancy can be introduce while remaining unnoticed. This was also supported by various post-study comments, for instance: "*I just had much more time to see if it moved faster*" (P8). This provides evidence for our first hypothesis that translation distance significantly affects the detection thresholds.

Next, we found the manipulation technique to also have a significant effect on both, lower ($F_{1,92} = 4.753$, $p = .031$) and upper ($F_{1,92} = 4.548$, $p = .035$) thresholds. This supports our second hypothesis that adding relative resistance force feedback to the manipulation provides additional proprioceptive cues and therefore makes it easier to detect resulting in lower thresholds. However, there was no interaction effect between manipulation techniques

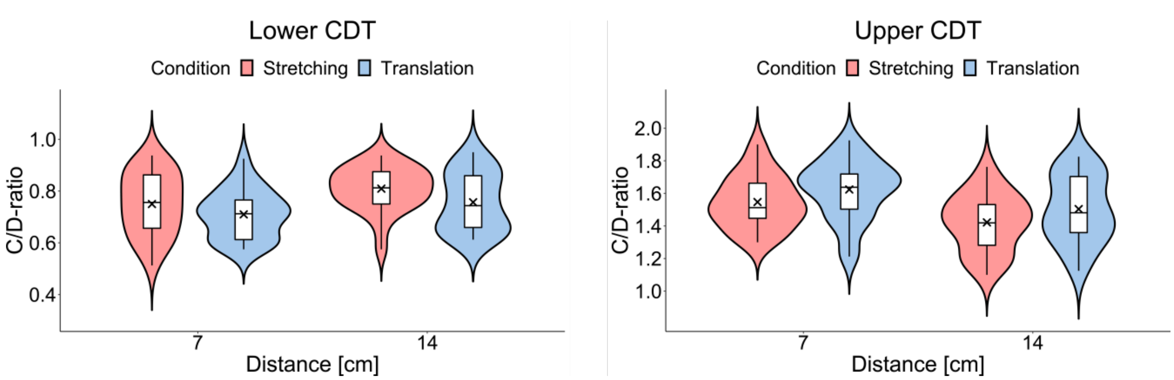

Figure 6: Violin plots visualizing the probability density of the collected CDT for each condition.

Table 1: Conservative Detection Thresholds indicate the C/D-ratio disparity that can be used without being detected by a user. SD here indicates the variation across participants.

Condition	Upper CDT	SD	Lower CDT	SD
Translation_7cm	1.62	0.18	0.70	0.09
Translation_14cm	1.50	0.20	0.76	0.11
Stretching_7cm	1.54	0.16	0.75	0.12
Stretching_14cm	1.42	0.12	0.80	0.08

and travel distance for lower ($F_{1,92} = .086$, $p = .076$) and upper ($F_{1,92} = .004$, $p = .949$) threshold.

Result: Manipulation technique and travel distance significantly affect detection thresholds

Our analysis showed that linear stretching has significantly lower thresholds than linear translation. Further, we determined that smaller travel distances allow for higher C/D-ratios regardless of the manipulation technique.

4.7.3 Proprioceptive Sensitivity. Even though the violin plots in Figure 6 support the assumption of a normal distributed data set (verified through Shapiro-Wilk test), it is inevitable that the individual thresholds can differ quite drastically. Most participants fluctuated around the threshold; however, we were also interested in the extremes, and we wanted to understand whether some participants' proprioceptive senses are more sensitive than others for these kinds of tasks [34]. Therefore, we used an extreme groups approach [50], allowing us to conceptually compare our population as if we had sampled "high" and "low" sensitivity groups. To do so, we computed participants' proprioceptive acuity as an overall performance score by adding-up all upper thresholds and the multiplicative inverse for all lower thresholds across the eight conditions for each individual participant. We then assigned participants to quartiles (groups of six) based on their overall performance score. Thus, we ended up with a high and low performance group as well as two average groups. We were mostly interested in whether participants in the high-performance group performed consistently better than the main group or underly a random spread, and vice versa.

Figure 7 shows the low- (red) and the high- (blue) performance group. Connected data points in the high- and low-performance groups represent an individual participant. Here, we see a strong tendency towards individuals in the high-performance group consistently performing better and constantly staying below the overall CDT (marked with 'x'), and vice versa. Following this, we investigate if there is a significant difference between the two performance groups by comparing them to the average group. Levene's test revealed a violation of the homogeneity of variance assumption at $\alpha = .05$. Therefore, we ran a Kruskal-Wallis-Test for unequal variances which did not indicate a significant effect ($H(2) = 1.343$, $p = .510$). Participants in both groups reported mixed experiences with VR and had various backgrounds countering our initial assumption that with more VR experience thresholds might become lower. Hence, we conclude that low- and high-performance groups belong to a single homogenous group.

Results: Individuals did not significantly differ in their proprioceptive sensitivity in our study

In this section we found a trend indicating individual differences in proprioceptive sensitivity (similar to [34]) leading to an earlier semantic violation regardless of participants prior VR experience and their professional background. However, this effect was not statistically significant in our experiment.

4.7.4 Trial Times and Movement. The question we address here is whether C/D-ratios within the CDT have acceptable performance and accuracy. We contrast this with performance and accuracy on C/D-ratios outside of the CDT. These results help us to understand which factors contribute to sematic violations, and therefore how different C/D ratios affect proxy-based interactions across the different conditions. First, we look at the trial completion times for all conditions at different C/D-ratios by choosing the two initial staircase C/D-ratios (0.5 and 1.8) as extremes, two C/D-ratios within the threshold in each individual condition and the baseline C/D-ratio = 1.0. We analyzed the trial time data at five C/D-ratios depending on the conditions. Shapiro-Wilk indicated a violation of the normality assumption at $\alpha = .05$.

Following this, we ran non-parametric Kruskal-Wallis-Test which revealed a significant effect in all four conditions, Translation 7 ($H(4) = 97.24$, $p < .001$), Stretching 7 ($H(4) = 88.45$, $p < .001$), Translation 14 ($H(4) = 40.00$, $p < .001$) and Stretching 14 ($H(4) = 65.17$, $p < .001$). We performed Wilcoxon post-hoc comparisons with Bonferroni corrections for each condition comparing baseline 1.0 to the four other C/D-ratios. As shown in Figure 8 it took participants significantly longer to move the slider to the goal position using a 0.5 C/D-ratio. In contrast, for each condition's lower threshold there was no significant difference between the threshold

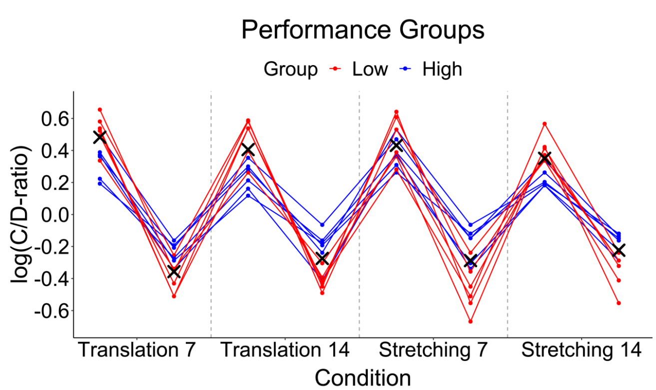

Figure 7: Visualizing the correlation between high- (blue) and low-(red) performance groups. 'x' indicates overall CDT.

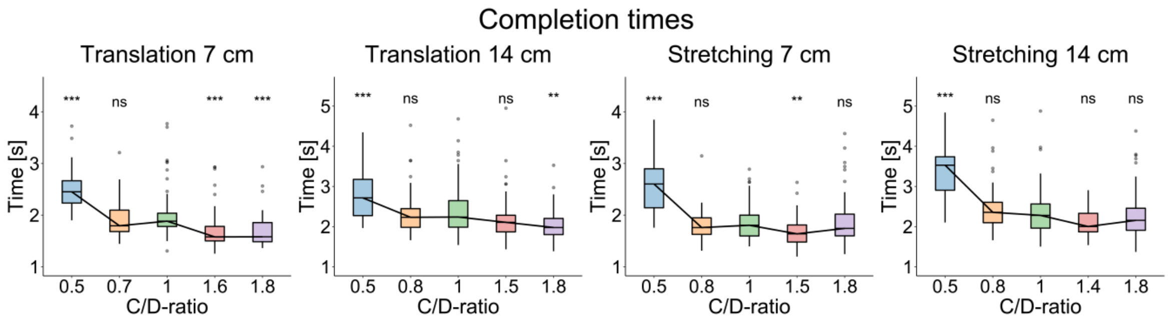

Figure 8: Trial completion times. Comparing two C/D-ratios within the individual CDTs and the two extremes (0.5 and 1.8) against the baseline (C/D-ratio = 1.0). * = *p* < .001, ** = *p* < .01, * = *p* < .05, ns = not significant.**

and the baseline in terms of trial completion time. However, in the upper conditions we did not see such consistent results. In the 7cm conditions participants were significantly faster within their CDT. Contrary, there was no significant difference in the 14cm condition. At the extremes (C/D-ratio: 1.8) participants reached significantly faster completion times in the translation condition, however there was no effect in the stretching condition.

Throughout the study, we frequently observed that participants overshot the goal as a consequence of exposing them to higher C/D-ratios. Moreover, some participants reported that they used this effect as an indicator to detect a manipulation. We followed-up on this observation by investigating the movement data. To do so, we plotted the virtual distance - time relationship graph for again five different C/D-ratios consisting of the two extremes (0.5 and 1.8), upper and lower CDT for each condition as well as the baseline (1.0). The graph is based on the logged timestamps and the corresponding median distance value across all participants. In Figure 9, we can observe that the different C/D-ratios show a substantial effect on the movement data. First, the CDT curves (red and yellow) are closest to the baseline and result in a consistent stable movement i.e. accelerating at the beginning and slowing down when approaching the goal position.

Aligned with our observations the median curve for C/D-ratio = 1.8 (purple) shows that participants frequently overshot and had to correct for it: especially, in the translation condition. However, stretching seem to prevent overshooting, even with higher C/D-ratios leading to high accuracy. In contrast, the curve in lower extrema condition (blue) slowly approaches the goal and in the stretching 14 cm condition almost ends-up in a linear motion (see Figure 9 – bottom right).

Results: Performance and accuracy remain stable within the CDTs

Our analysis showed that higher C/D-ratios generally result in quicker completion times but create problems with accuracy. However, staying within the CDT seem to prevent these effects from occurring.

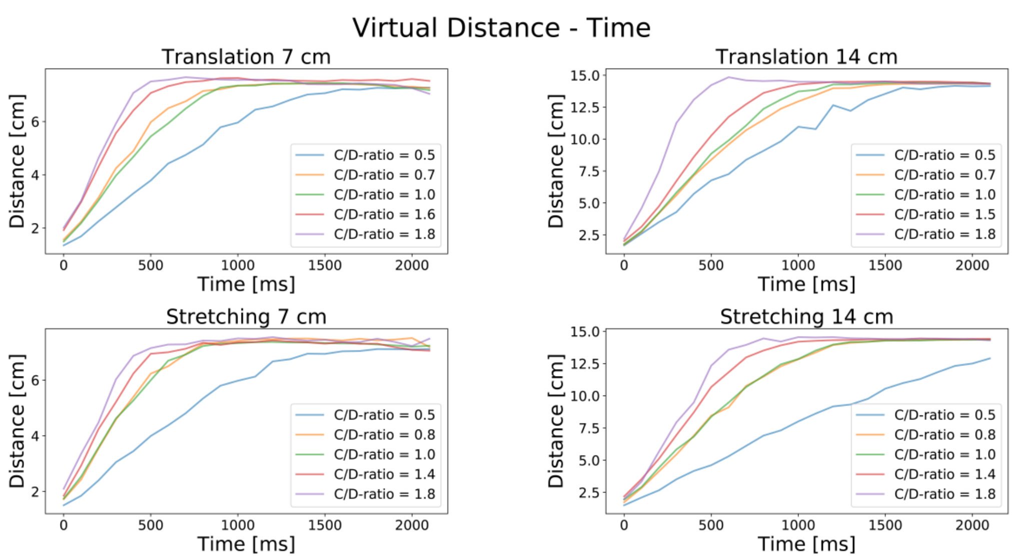

Figure 9: Virtual distance travelled – time relationship graph for all conditions. Comparing two C/D-ratios within the individual CDT and the two extremes (0.5 and 1.8) against the baseline (C/D-ratio = 1.0).

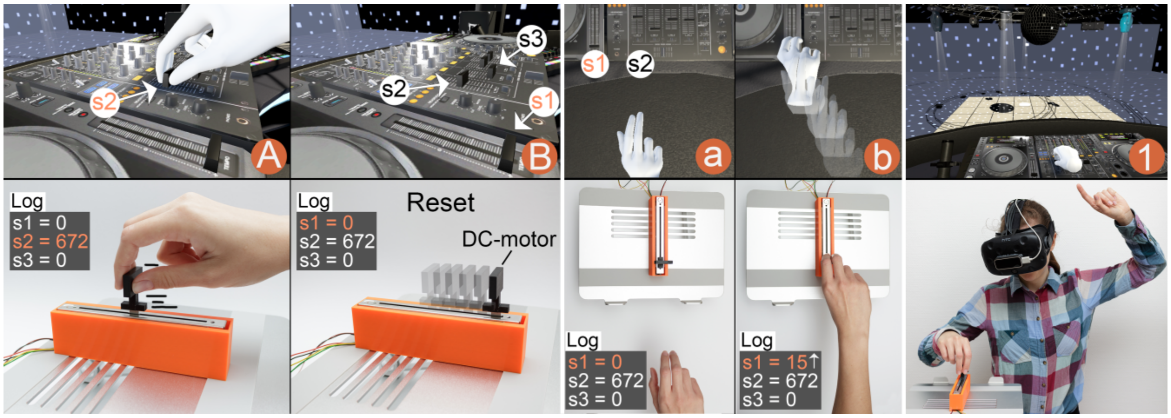

Figure 10: A user translates the "high-pass filter" slider (A – s2) through the physical proxy, and then wants to operate the "track-speed" slider (B – s1). The proxy slider resets itself to the previously stored position of s1 (see B - bottom Log). For the proxy to work as a stand-in for multiple virtual objects an *on-the-fly* hand redirection technique is used (a and b). Finally, (1) shows a user interacting with the VR-DJ environment.

4.7.5 Summary. In this section we reported our estimates for the conservative detection thresholds for all four conditions. Further, we demonstrated the significant effect of travel distance on the thresholds: smaller distances allow for higher C/D-ratios. Moreover, we found that added relative resistance force feedback in the linear stretching condition provides an additional proprioceptive cue which supports people in detecting manipulations consequently leading to significantly lower thresholds. Then, we ran an investigation regarding the possible differences in human's proprioceptive capabilities identifying a trend towards some people being more sensitive to visual-proprioceptive conflicts than others; however, this effect was not statistically significant in our experiment. Finally, we show that keeping C/D-ratios within the CDT generally preserves performance and accuracy.

5 POTENTIAL APPLICATIONS & USE CASES

5.1 Linear Translation: VR-DJ Experience

To illustrate how visuo-haptic illusions in the scope of linear translation can be used, we developed a VR-DJ experience. The main goal of this application was to demonstrate the possibilities that visuo-haptic illusions offer by replicating several virtual sliders (Figure 10B – s1, s2 and s3) of different lengths, on a DJ-desk through a single functional proxy slider. Here, users can enter a virtual discotheque in order to practice their performances without the need of expensive mixer equipment [75]. Various effects can be triggered e.g., a fog machine by using a switch.

The single physical slider stands in for every slider in the virtual DJ mixer. Here, we use a 10cm linear potentiometer (RSA0N11M9-LIN10k) offering 10kΩ resolution which can be moved by using a 10V DC-motor. The DC-motor was controlled using an Arduino Uno Rev3 (AVR ATmega328) [4] and a L298N Dual H Bridge motor driver powered by a 12V (1.0A) DC power supply. When interacting with the device, the motor needs to be turned off. Therefore, we included capacitive touch sensing capability to the proxy by 3D printing a conductive slider mount (~600Ω resistance) using composite PLA – Electrically Conductive Graphite Ø1.75mm. The sensor states and touch events were transmitted via serial communication to the VR machine and adequately mapped to the different slider lengths of 12cm (s1 = C/D-ratio: 1.2), 10cm (s2 = C/D-ratio: 1.0) and 8cm (s3 = C/D-ratio: 0.8) remaining within the CDT. On the VR side, we use a similar implementation as in our user study utilizing an HTC VIVE [72] for VR and Leap motion [74] for hand-tracking. Figure 10 illustrates how the system works.

A user manipulates the "high-pass filter" slider (Figure 10A – s2) to a position and releases the slider. The system stores the slider state (analog potentiometer signal) for s2 in a position log. Then, the user wants to manipulate the "track-speed" slider (Figure 10B – s1) which is still at the default position. The system fetches the current state of s1 from the position log and resets the physical proxy slider accordantly (Figure 10B - bottom). For the proxy slider to function as a stand-in for multiple virtual sliders we implemented an *on-the-fly* haptic retargeting technique using Cheng et al.'s algorithm [15]. Hence, a user touches a different virtual slider, but in fact has been redirected to the same physical proxy (Figure 10a and b). Finally, she starts to manipulate s1 which updates the position log simultaneously (Figure 10b - bottom).

5.2 Linear Stretching

There is huge potential in applying our findings in context of linear stretching. For instance, toolkits such as TanGi [21] and VirtualBricks [5] allow the creation of proxy objects including stretchable parts. Our findings help to expand their interaction space enabling multipurpose manipulable proxies. Moreover, several haptic VR controllers utilize resistive forces for example, ElasticVR [61], Haptic Links [58] and ElastiLinks [62]. They support a rich set of interactions which can further be enhanced by using visuo-haptic illusions.

6 DISCUSSION & FUTURE WORK

Based on our study, we discuss visuo-haptic illusions for linear translation and stretching in VR. Finally, we identify potential future directions enabling the design of more generic proxy objects.

6.1 Proprioceptive Limits

Through our study we determined the CDTs for linear translation and stretching at the travel distances 7 and 14cm. We found that in some cases relatively high C/D-ratios remained undetected; thus, it appears that individuals' proprioceptive capabilities vary. We assume these differences are grounded in more fundamental human experiences. For instance, some people participate in sports [34], arts and crafts, or playing musical instruments—perhaps these activities select for, or enhance people's proprioception skills, since these activities demand moving limbs out of binocular vision—which is not necessarily connected to people's prior experience with VR. Investigating these differences appear to be an interesting and valuable direction for future VR research.

The difference between translation and stretching shows that not only the absolute limb position and potential differences to the virtual position can lead to a semantic violation. Instead, the entire arm chain, muscle contractions and moreover, the required force to manipulate an object may contribute to a semantic violation. This appears to be an unconscious process since none of our participants reported that it was easier to detect a manipulation in the stretching conditions. When designing generic proxy objects, these findings need to be carefully considered to create a compelling VR experience. Addressing the question to what extent these individual differences might impact the practical feasibility of using visuo-haptic illusion is discussed in the section below.

6.2 Role of Movement Speed

In our study, we controlled for movement speed, which appears to be another important variable contributing to a semantic violation. Our work provides supporting evidence for the role of position and force feedback as relevant proprioceptive factors; however, at this point we cannot disentangle the effects of movement, speed, and force as well as possible correlations between them. Therefore, we propose this as an important direction for future work allowing us to better understand how closely physical proxy and virtual objects need to match to enable the design of truly multipurpose proxies.

6.3 Practical Feasibility

Our reported estimates are the result of investigating the most CDTs by informing participants about the procedure, reducing distractions to a minimum level, and converging at 0.5 probably (CDT) for a correct answer in the staircase procedure. In a more realistic VR experience, users are exposed to other distracting factors such as ambient sounds, incident light, multiple objects and so on. Thus, being immersed in the virtual environment most likely allows for higher manipulation factors while remaining unnoticed or at least are not experienced as disruptive [15, 20]. This is also supported by the SSQ results which did not indicate any significant motion sickness because of the illusion, even though we exposed participants to C/D-ratios above their detection threshold.

There is also an interesting trade-off regarding the interaction speed and accuracy. For instance, lower C/D-ratios result in longer and constantly more stable interactions. In contrast, a designer likely wants to expand the virtual interaction space (e.g., let a virtual slider appear longer than its real counterpart is) by applying a higher C/D-ratio. Here, a manipulation factor within the CDT could prevent overshooting, which impacts accuracy. Designers should be aware that using visuo-haptic illusions may affect accuracy and overall performance.

6.4 Generalizability for Proxies Design

In this first iteration, we abstracted from different grasping types and form factors. However, this raises the question: to what extent can these thresholds be applied to a larger set of translatable objects and interactions? As already discussed, in this work we look at the most conservative case. Therefore, we believe that these thresholds might also work for different grasping types and form factors. We recommend these ideas to be further explored as researchers begin continuing to expand the scope of such proxies in future VR systems.

Moreover, visuo-haptic illusions offer great potential to enhance proxy-based design by incorporating richer object characteristics such as bendable, twistable, and deformable object parts [21, 30, 46]. By doing so, we allow for re-usable, multipurpose, and realistic proxy objects pushing towards tangible VR. Finally, going beyond proxy design, this research also poses an interesting question to the hand redirection approach, as it shows that force feedback is a proprioceptive factor; to what extent does lifting and holding an object affect hand redirection thresholds?

7 CONCLUSION

In this paper we investigated the use visuo-haptic illusions for linear translation and stretching to enhance proxy-based interactions in VR. Our results show that this is a promising method enabling generic proxy designs addressing one of the main challenges on the way to tangible VR. Moreover, we found that travel distance significantly affects how much discrepancy can be introduced not resulting in a semantic violation and further, we provide a deeper understanding of the contributing proprioceptive factors. Then, we ran an investigation regarding the possible effects that this method may have on the interaction. Our findings show that higher C/D-ratios lead to quicker completion times, but decreased accuracy, and vice versa. Finally, we presented the VR-DJ application showing that visuo-haptic illusions can be used alongside physical proxy objects with moveable parts. Our work contributes to the use of haptics in VR by revealing the extent we can use the visual dominance phenomena without resulting in a semantic violation, pushing the boundaries of physical proxy design.

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