Turn-It-Up: Rendering Resistance for Knobs in Virtual Reality through Undetectable Pseudo-Haptics

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Figure 1: Pseudo-Haptic Resistance can be created by 'slowing down' a user's real-world rotations of a knob. As a result the red needle rotates slower than the white needle.

ABSTRACT

Rendering haptic feedback for interactions with virtual objects is an essential part of effective virtual reality experiences. In this work, we explore providing haptic feedback for rotational manipulations, e.g., through knobs. We propose the use of a Pseudo-Haptic technique alongside a physical proxy knob to simulate various physical resistances. In a psychophysical experiment with 20 participants, we found that designers can introduce unnoticeable offsets between real and virtual rotations of the knob, and we report the corresponding detection thresholds. Based on these, we present the *Pseudo-Haptic Resistance* technique to convey physical resistance while applying only unnoticeable pseudo-haptic manipulation. Additionally, we provide a first model of how C/D gains correspond to physical resistance perceived during object rotation, and outline how our results can be translated to other rotational manipulations. Finally, we present two example use cases that demonstrate the versatility and power of our approach.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**; **User studies**.

KEYWORDS

Virtual Reality, Pseudo-Haptic Resistance, Detection Thresholds

1 INTRODUCTION

Enhancing haptic feedback in Virtual Reality (VR) has been a long-time goal for researchers and developers. Providing appropriate haptic feedback for interactions with interface elements, such as buttons, sliders, and knobs, has been of central interest to the VR community; this feedback would, for example, support realistic simulations and training [8]. To achieve such haptic feedback, many VR applications utilize proxy objects, i.e., physical "stand-ins" for virtual objects [28, 29] that approximate properties such as shape and size [17, 18, 27], texture [13], weight [49] or function [17, 37]. Matthews et al. [38] presented a proxy interface with buttons, sliders and knobs, studying synchronization approaches between the physical and the virtual interface. The central idea is that users get redirected [3] to an interface element that represents the state of the selected virtual control, reducing the number of required proxies. Feick et al. [21] demonstrated a single proxy slider, providing haptic feedback for virtual sliders of varying lengths. To achieve this, the authors scaled up/down real-world manipulations of the proxy slider by applying Control-Display (C/D) gain manipulations without users noticing. Depending on the selected virtual slider, the proxy slider resets itself to represent the corresponding state.

Despite these recent advancements, there still exists a high demand for inexpensive techniques that can be used to improve the haptic resolution of proxies and devices that render 3DUIs. One such approach is *Pseudo-Haptics* [36], which provides haptic feedback based solely on visual stimuli; taking advantage of the vision perception over proprioception. This technique has been successfully used to simulate 3D button presses in mid-air [6]. Ariza Nunez et al. [2] presented the *Holitouch* technique, conveying the holistic sensation of stiffness, contact, and activation when pressing mid-air buttons. They used a wearable device combining tapping and vibrotactile sensations on the fingertip, kinesthetic extension of the pressing finger, and C/D ratio manipulation on a pseudo-haptic button. There exists a considerable amount of work on 3D sliders and buttons, but knobs, i.e., rotational elements that make part of many interfaces with clear affordances in the real world, have received little to no attention. This prevents VR designers from incorporating such elements in VR as it is unclear how appropriate haptic feedback can be achieved through proxy interfaces, and how many proxies would be required to render virtual knobs that differ, for example, in resistance.

To fill this gap, we present a novel type of pseudo-haptic effect, called *Pseudo-Haptic Resistance*, which combines rotational C/D gain manipulations with a physical proxy knob. In a psychophysical user study with 20 participants, we found that we can introduce unnoticeable offsets between real and virtual rotations of the knob. Further, we show that the technique effectively conveys different levels of physical resistance while staying within the unnoticeable range of C/D gains. Finally, we provide a first model of how C/D gains correspond to physical resistance and outline how our results can be applied to other rotational manipulations. In this work, we make five core contributions:

(1) We demonstrate that considerable offsets between virtual and real-world rotations of a knob remain unnoticed, and we report the detection thresholds.

(2) We present a novel pseudo-haptic technique, called *Pseudo-Haptic Resistance*, which is specifically tailored to rotational interactions.

(3) We report the just-noticeable difference in perceived resistances caused by changing the C/D gain.

(4) We study the relationship between C/D gains and physical resistance, developing a model for rotational, pseudo-haptic resistance.

(5) We outline how our technique can be applied by presenting two example use cases.

2 RELATED WORK

2.1 Haptic Feedback in VR

The VR community broadly distinguishes between two types of haptic feedback, active and passive. In the latter, real-world physical objects act as proxies for virtual objects [28, 29], approximating their physical properties such as shape and size [17, 27], weight [49], texture [19], stiffness [4] or function [17, 37]. The ultimate goal is to find a set of generic proxies that can be used to provide appropriate haptic feedback for various virtual objects [12, 47]. To this end, researchers have presented approaches for constructing proxies using toolkits [17, 18], re-configurable devices [52], and systems that seek a user's environment for a real-world object that closely matches the virtual object [27]. One disadvantage of such passive haptic approaches is their inflexibility: the haptic rendering capabilities of a single proxy are limited, and often many proxies are required to support rich VR experiences.

In contrast, active haptics uses computer-generated actuation, computing the appropriate haptic stimulus for the interaction. For example, Park et al. [41] simulate different buttons by coupling the interaction to the vibrotactile output. Other active devices actuate human limbs through electrical tendon stimulation (ETS) to provide kinesthetic haptic feedback, e.g., for finger displacement when pressing a mid-air button [2]. However, when larger counterforces are needed, systems quickly become bulky. Since there is often limited space available, e.g., in VR controllers, it is challenging for designers and developers to embed more powerful actuators due to space constraints.

2.2 Visuo-Haptic Illusions in VR

Here, VR illusions may help, because it has been demonstrated that small discrepancies between the virtual and real world can remain unnoticeable for users [1, 5, 7, 15, 21, 23, 26, 46, 48, 50]. This can be attributed to the visual-dominance phenomenon, where in the case of conflicting senses, vision usually dominates over other senses [11, 24]. In VR, researchers utilized this effect to offset the position of a user's virtual hand from its position in the real world [10, 35]. By doing so, Azmandian et al. [3] effectively redirected a user's hand to the same physical proxy while touching virtual models placed at different locations. Cheng et al. [12] used hand redirection to allow users to touch interface elements such as buttons in the virtual environment. Kohli [34] demonstrated redirected touching, changing the perceived shape of the virtual object by visually offsetting users' hands while re-mapping the proxy's haptic features. *Pseudo-haptics* 'suggests' haptic feedback only through visual information based on a user's interaction [36]. Ban et al. [4] changed the perceived stiffness of a proxy when pinching it using a pseudo-haptic effect that is coupled to the applied force. Samad et al. [42] introduced *Pseudo-Haptic Weight*, a technique that 'slows down' a user's virtual movements with a proxy and thereby creates the illusion of a heavier object. Pseudo-Haptic effects have also been used alongside active haptic devices. For example, Stellmacher et al. [45] use a combined approach for continuous weight illusions by adapting the resistance of the VR controller's trigger button when grasping a virtual object and by manipulating the control-display (C/D) ratio during lifting. Nevertheless, there exist limits of what is believable to a user.

Researchers report on "detection thresholds" with these techniques: how much discrepancy between the real and virtual world can be introduced without people noticing. For example, Zenner and Krüger [50] studied how much unnoticeable hand redirection can be applied for a single hand, whereas Gonzalez and Follmer [26] investigated bi-manual hand redirection thresholds. Furthermore, researchers looked at variables that potentially affect the possible discrepancy, such as movement direction [15] or trajectory [23], reporting so-called detection thresholds. Such thresholds have also been reported regarding shape [46], size [5] and stiffness [7, 48] variations of proxies.

2.3 3D Interfaces—Buttons, Sliders and Knobs

Many of the envisioned applications for VR cover areas such as training and simulation [8]. Here, a clear need exists for control types that resemble real-world user interfaces. The most basic interface elements are buttons, sliders, and knobs. Providing appropriate haptic feedback for interactions with them has been of central interest to the community. Virtual mid-air buttons have received considerable attention, from audio, visual and haptic techniques [6] to combined multimodal approaches [2, 41]. When using proxies, one key challenge is the re-mapping of interactions—allowing a single proxy to act as a "stand-in" for multiple virtual controls. Matthews et al. [39] introduced *interface warping*, a technique to remap interface elements, specifically for virtual buttons using redirection. Matthews et al. [38] presented a proxy interface with buttons, sliders, and knobs, studying synchronization approaches between the physical and the virtual interface. Here, users get redirected to an interface element that represents the state of the selected virtual control. Feick et al. [21] looked at virtual sliders, scaling up or down users' real-world manipulations of a proxy slider without their noticing. Yet, to the best of our knowledge, rotational manipulations of knobs or switches have not been investigated.

There exists a need for haptic illusions that enrich the rendering capabilities of proxies and haptic devices that afford rotational manipulations. In this work, we study how much offset between rotations of a real and a virtual knob can unnoticeably be introduced. Moreover, we introduce a novel type of pseudo-haptic effect, called *Pseudo-Haptic Resistance*, simulating physical resistance, that can be created by 'slowing down' users' rotational movements.

3 PSEUDO-HAPTIC KNOB

In this section, we introduce our pseudo-haptic resistance technique and outline the design and implementation of the prototype that provides physical resistance. Finally, we show the most relevant findings from our preliminary experiment.

3.1 Pseudo-Haptic Resistance

Figure 1 illustrates pseudo-haptic resistance as it is experienced by users. Here, the user has physically rotated the knob 60 degrees, but the virtual knob has only rotated 30 degrees. We create this effect by scaling the user's real-world movements (Control) with what is displayed in the virtual world (Display) with the C/D ratio. This is a common approach to create illusions in VR, for example, pseudo-haptic weight [42, 45]. Therefore, we opted for this method scaling down users' real-world movements, resulting in smaller virtual movements than physically performed, which can be achieved with a C/D gain factor ≤ 1.0. We hypothesize that by combining this technique with functional proxies that restrict users' movements [23] it may be possible to suggest physical resistance through a pseudo-haptic effect [36]. In this work, we are only interested in *increasing* the perceived resistance, since this would require embedding larger actuators into the hardware to achieve the same haptic sensations with alternative, active haptic approaches.

3.2 Proxy Knob

We built a proxy knob consisting of an ESP32, a brushless DC Motor2204 260KV, a ICTMC6300 motor driver and magnetic position sensor (MAQ473) that enables sensing and actuation (see Figure 2) inspired from Feick et al. [18]. The motor was controlled using FoC [43] through a proportional controller, which after an immediate

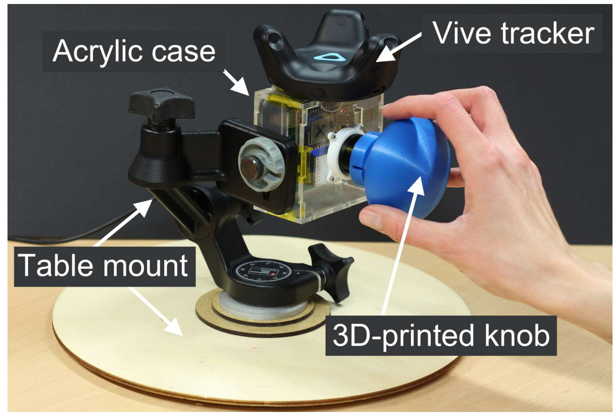

Figure 2: Proxy knob.

(unnoticeable) ramp, provides a constant level of resistance. We laser-cut an acrylic case for the hardware components, and designed and 3D-printed a proxy knob, measuring 7 cm in diameter, with a custom mount that a user can comfortably hold and rotate. In addition, we built a table mount using a Manfrotto 3D pan/tilt tripod head with individual axis control attached to a laser-cut wooden plate with adhesive tape on the bottom. The proxy knob can generate between 0.3–3.2 Nmm of resistance, measured with a PCE-FB 50N force gauge. A corresponding virtual replica of the knob and its functionality was implemented in Unity3D (v.2022.2.1f1). The proxy knob can be rotated to any desired position, which is directly streamed using serial port communication (baud rate 155200), ensuring direct coupling of the real and the virtual world.

3.3 Preliminary Experiment

We conducted a small preliminary experiment with 4 participants to understand how users perceive our proposed pseudo-haptic technique and inform the design of our main experiment. To do so, we asked novices to rotate two knobs and compare them. One knob used a 1-to-1 mapping between the real and the virtual rotations; on a second knob, we applied C/D gain manipulations of different magnitudes (0.1−1.0). The physical resistance provided by the device was set to the minimum (0.3 Nmm). Then, we specifically asked participants about the differences between the knobs with respect to their properties, their general impression of the visualization and the provided haptic feedback. We did not specifically ask them any questions that would point them towards our pseudo-haptic effect. Below, we summarize the most relevant feedback and suggestions of our participants:

Range of C/D gains. All participants reported that the virtual knob rotated noticeably slower than the real knob when applying a C/D gain below 0.6. Therefore, in the following main experiment, we set the minimum C/D gain to 0.5 to ensure that we would stay within a reasonable range of C/D gain manipulations.

Pseudo-Haptic Resistance. P1 and P3 felt the virtual knob sometimes had more 'friction', while P4 described this sensation as feeling 'resistance'. These sensations corresponded to when we applied a C/D gain below 1.0. This suggests that participants were able to feel the pseudo-haptic effect.

Visuo-Haptic Integration. To assist participants during the task, we visualized tick marks, creating a dial-like layout (see Figure 1). P2 commented that s/he expected to also haptically "feel" these tick marks. We found this to be very intriguing, and because our proxy knob and FoC [43] supported the haptic rendering of tick marks, we included this variation, with and without tick marks, in our main experiment. Following multisensory integration theory [14], higher visual-haptic congruence provided by tick marks on the knob could potentially allow for more offset between real and virtual rotations to go unnoticed, similar to what has been found for realism by Ogawa et al. [40].

Expected Physical Resistance. P2, P3 and P4 stated that the physical knob rotated too loosely, and suggested that it should have more physical resistance. As a result, we asked them to increase the physical resistance of the knob (C/D gain = 1.0) using the keyboard, until it matched their expectations. We took the average of the three values (1.1 Nmm) and used it as the default value in our main experiment.

4 EXPERIMENT

We designed an experiment to investigate: (1) the detection thresholds for manipulating the C/D gain when rotating knobs (i.e., how much manipulation goes unnoticed), (2) the just-noticeable difference in resistance caused by C/D gain manipulations (i.e., how much manipulation is required to change the user's perception of resistance), and (3) how C/D gain manipulations translate to perceived physical resistance. To do so, we conducted an experiment using different psychophysical methods [2, 33, 42]. We formulated the following five hypotheses:

H1: Considerable offsets between rotations of the real and virtual knob can be introduced without users noticing.

H2: By increasing visuo-haptic synchronization, the range of unnoticeable offset becomes larger.

H3: Users associate C/D gain manipulations with changes in physical resistance.

H4: Within the range of unnoticeable C/D gains, designers can effectively manipulate the perceived physical resistance.

H5: With unnoticeable C/D gain manipulation we can achieve multiple distinguishable levels of perceived resistance.

4.0.1 How much C/D gain manipulation goes unnoticed? To determine detection thresholds (**H1** and **H2**), we used an established adaptive psychophysical 1-up-1-down interleaved staircase procedure, exposing participants to different stimuli (C/D gains) repeatedly. Using a fixed step size, we target the Conservative Detection Threshold (CDT) or point of subjective equality [30, 33]. The interleaved staircase uses both an ascending and a descending sequence, and randomly assigns the next trial to one of the sequences. The procedure increases the next stimulus in a sequence if a participant fails to detect the current stimulus in this sequence, and decreases the next stimulus if the user detects the offset. A directional change within a sequence is called a reversal point, which we used as a convergence criterion (r=4). Since we are the first to explore rotations, we used our preliminary experiment to determine range and start values for the procedure. We found a fixed step size (i.e., changes in the C/D gain) of 0.05 to be appropriate, and selected 1.0 and 0.5 as starting values.

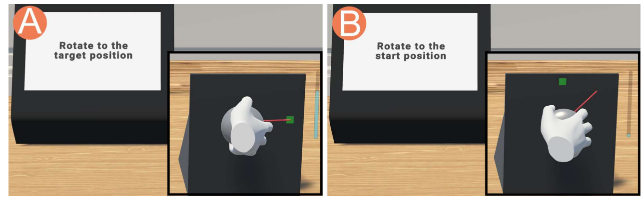

Figure 3: Threshold task.

Task. Participants were asked to rotate the (proxy) knob until the virtual knob matched a target position displayed in the virtual world (at 60 degrees)—thus, the virtual distance remained equal (see Figure 3). After they successfully established the position, a 1 second dwell-time indicator appeared, and they were required to maintain this position, before rotating the knob back to the start position. Next, a forced-choice ('yes' or 'no') question appeared, and they responded to the following statement: *"My real hand rotated further than my virtual hand"* [21, 44]. Participants were instructed to perform a 'normal' rotation of the knob at a comfortable speed. Participants were not allowed to repeat the rotation. The physical resistance of the proxy knob was kept the same throughout this part of the experiment.

4.0.2 How does changing the C/D gain affect the perceived resistance? We used a two-interval forced-choice procedure to determine the just-noticeable difference (JND) in resistance (**H3** and **H4**)[33]. We exposed participants to two successive stimuli (C/D gains), one being the baseline (C/D gain = 1.0) and a second stimulus being randomly picked from the range from 1.0 to 0.5 in 0.05 steps. Both stimuli were presented to the participant in a random order. The stimuli were generated using the 1-up-1-down interleaved staircase procedure outlined above. We kept step size, target probability (here: 50%-correct) and start values the same to ensure comparability.

Task. Similar to the above, participants were asked to rotate the (proxy) knob until it matched the target position. However, this time they had to repeat this interaction and then compare both rotations of the knob in terms of their physical resistance, i.e., one baseline (C/D gain = 1.0) and one stimulus (C/D gain <= 1.0). Because the physical resistance of the proxy knob was kept the same, participants rating the pseudo-haptic effect created by the C/D gain manipulation. Next, a forced-choice ('yes' or 'no') question appeared, and they responded to the following statement: *"The physical resistance of two knobs felt the same"*. Participants were prevented from repeating the rotation and could only explore each of the knobs once.

4.0.3 How do C/D gain and perceived resistance relate to each other? In the last part of our experiment, we used the method of adjustments to investigate how C/D gain and perceived resistance relate to each other (**H5**). To this end, participants experienced two knobs, initially not differing in their physical resistance, but only in their C/D gain [42]. We asked them to adjust the physical resistance of the (red) knob, with a C/D gain = 1.0, until it matched the resistance of the (blue) knob, with a C/D gain <= 1.0 (see Figure 4). Participants had 25 seconds to adjust the resistance following Samad et al. [42]'s methodology. After 25 seconds, the configured resistance

Figure 4: Method of Adjustments.

was logged and could not be changed anymore. However, we only continued with the next trial when participants confirmed that they felt ready, allowing them to take breaks in between. Please note that participants were informed that no physical difference between the two knobs is also a valid option, which was explained and shown to them during the warm-up. Nevertheless, each trial started with the base level, which is different from what was used by Samad et al. [42] and thus may have affected the results.

Task. In this part of the experiment, participants could rotate the (proxy) knob in whatever way they preferred. Yet, they could only switch between the two virtual knobs (red and blue) when the needle was pointing upwards. Initially, the physical resistance of the proxy knob was the same for both virtual knobs, as in previous parts of our experiment. A progress bar showed the possible range of physical resistance that could be configured, in 0.1 Nmm increments. We tested C/D gains ranging from 1.0 to 0.5 in 0.1 increments (i.e., 1.0, 0.9, 0.8, 0.7, 0.6, 0.5) in a random order. We decided on this after rigorous pilot testing, allowing us to collect more data points per participant to increase robustness. To do so, we repeated the procedure 3 times, resulting in $3 \times 6 = 18$ configurations each participant had to adjust.

4.1 Design

In this experiment we used a within-subjects design. We had four study parts: two times detection thresholds for rotating knobs with and without haptic tick marks, just-noticeable difference in resistance and a condition that studied how C/D gain affects the perceived physical resistance. We fully counterbalanced the conditions using a Latin square ($n = 4$).

4.2 Participants

We recruited 20 right-handed participants (9 female, 11 male), aged 20–38 ($mean = 26.42$; $SD = 3.65$) from the general public and the local university. This excludes one participant (P12), in whose case we had to stop the experiment due to system failure. Participants had a range of different educational and professional backgrounds including media informatics, computer science, education, pharmacy, anglistics, neuroengineering, embedded systems, data science and artificial intelligence. All participants reported normal or corrected-to-normal vision and did not report any known health issues which might impair their perception. 8 participants had never used VR before, 6 had used it a few times (1–5 times a year), no one reported using it often (6–10 times a year), and 6 others used it on a regular basis (more than 10 times a year). 10 participants reported that they had not played VR games before, 5 people responded 'sometimes' or 'infrequently' (1–5 times a year), 1 'often' (6–10 times a year), and 4 people 'on a regular basis' (more than 10 times a year). Participants not associated with our institution received €10 as remuneration for taking part in the experiment. The study was approved by the University's Ethics Board.

4.3 Apparatus

Our apparatus consisted of a HTC VIVE Pro Eye system and our implemented knob prototype shown above. The virtual scene was aligned based on the position of the physical knob using a Vive tracker, ensuring 1-to-1 mapping of the virtual- and real-world setup. On the software side, we used SteamVR (v.1.17) with the OpenVR SDK (v.1.1.4). We used a simple virtual scene, consisting of a table, the virtual knob, and an instruction screen, which was developed in Unity3D (v.2022.2.1f1) and was running on an Acer Predator Orion 5000 PO5-615s offering an Intel® Core i9 10900k CPU, 32 GB RAM, and an Nvidia® GeForce RTX 3080. We used a simple and fixed hand representation to prevent unwanted effects [40]. The experimental logic was implemented using the Unity Experiment Framework (UXF v.2.4.3) [9] and the Unity Staircase Procedure Toolkit [51]. Participants remained seated on a chair throughout the experiment, and we supported their arm position with a pillow to reduce fatigue. Participants' responses were collected using a keyboard. The default resistance of the knob was taken from our preliminary experiment.

Haptic tick marks. To ensure high synchronization, the haptic ticks were timed with the virtual marks. To achieve this, we had to scale them up/down, depending on the applied C/D gain. The tick marks were rendered by changing the proportional controller's setpoint value when the knob reached the point halfway between two tick marks.

4.4 Procedure

After giving participants a general introduction to the study and obtaining their informed consent, they filled in the demographics' questionnaire. Following this, we showed them the physical knob and explained how it should be used. Next, they were introduced to VR and the task through an open-ended practice round. Since all study conditions significantly differed, participants were given enough time to familiarize themselves.

Participants were instructed to grasp the proxy object as indicated by the virtual hand and were told to maintain this pose, not readjusting their grip, which was monitored by the experimenter. We instructed participants to respond to the question as quickly as possible by using a keyboard with their non-dominant hand. After completing all conditions, participants filled in a Simulator Sickness Questionnaire (SSQ) [31]. The total experiment took about 60 minutes per participant.

4.5 Data Collection

We collected data from six sources: a pre-study questionnaire for demographic information; the subjective responses to the forced-choice questions; the configured physical resistance; field notes and observations; a short post-study interview and a SSQ in VR using the VRQuestionnaireToolkit [20].

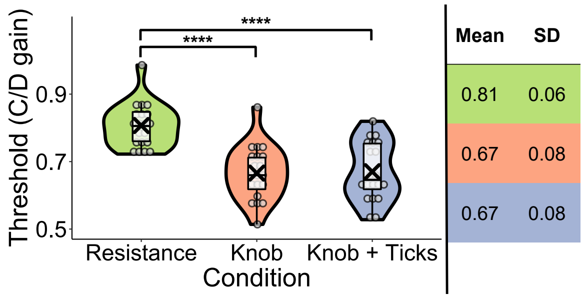

Figure 5: Results from our threshold experiments.

4.6 Analysis

We analyzed our data using a One-Way Repeated Measures ANOVA. First, we removed significant outliers using the box plot method and verified the normality assumptions at $\alpha = .05$, using a Shapiro-Wilk test. We checked the assumption of sphericity using Mauchly's test and applied Greenhouse-Geisser corrections when sphericity was violated. Post-hoc pairwise t-tests were corrected using Bonferroni-Holm adjustments.

To further investigate our data, we conducted a Bayesian analysis using the BayesFactors R package[1] with default priors (v.0.9.12+−4.4). ANOVA effects are reported as the Bayes factor for the inclusion of a particular effect (BF_{incl}), calculated as the ratio between the likelihood of the data given the model with the effect vs. without that effect [32]. Additionally, we performed paired Bayesian t-tests using default effect size priors. Results are reported as two-tailed Bayes factors BF_{10} and effect size estimates as median posterior Cohen's δ with a 95% credibility interval (95%CI) [32].

4.7 Results

In this section, we report our results. First, we look at the detection thresholds, comparing knob rendering with and without haptic marks to investigate **H1** and **H2**. Next, we analyze the results of just-noticeable difference and contrast them with the detection thresholds regarding **H3** and **H4**. Finally, we plot participants' perceived physical resistance against the tested C/D gains (**H5**). The SSQ results did not suggest simulator sickness caused by exposing participants to, sometimes, noticeable offsets above their thresholds (Total Severity (TS) score: $mean = 18.04, SD = 7.02$) compared to [1, 21]. For each participant, we computed detection thresholds by averaging the last three reversal points within the ascending and descending staircase sequence. All staircase plots are available in the appendix.

4.7.1 How much C/D gain manipulation goes unnoticed? Figure 5 shows that we could introduce substantial offsets between real and virtual rotations of the Knob ($mean = .67; SD = .08$) and Knob + Ticks ($mean = .67; SD = .08$), without participants noticing it, confirming **H1**. Our statistical analysis showed a main effect ($F_{(2,38)} = 21.96, p < .0001, \eta^2 = .431, BF_{incl} = 773384$); however, post-hoc analysis did not suggest a significant difference between the Knob and Knob + Ticks condition ($p = .861, \delta = -0.05$). In fact, our Bayesian analysis revealed evidence for the absence of an effect ($BF_{01} = 3.21$, with median posterior $\delta = .038, 95\%CI = [-.592, .509]$), suggesting that it is 3.21 times more likely to observe this data under the null hypothesis. Thus, we reject **H2**, because based on our collected sample, we could not identify an effect on the C/D gain tolerance caused by higher visuo-haptic congruence. Despite this not being reflected in the detection thresholds, participants frequently commented "This feels so satisfying" (P13), "So nice..so nice" (P19) or intentionally moved slower during the warm-up, noting "the ticks are in perfect synchronization" (P5).

4.7.2 How does changing the C/D gain affect the perceived resistance? Interestingly, the conservative detection thresholds for C/D manipulations found in the first part of the experiment are significantly greater than the just-noticeable difference ($mean = .81; SD = .06$) in resistance found in the second part ($p < .0001, Knob_\delta = 1.96, KnobTicks_\delta = 1.80$) (see Figure 5). This was supported by the Bayesian analysis, providing very strong evidence for the existence of an effect, both for Knob ($BF_{10} = 35600$, with median posterior $\delta = 1.824, 95\%CI = [1.049, 2.606]$) and Knob + Ticks ($BF_{10} = 8460$, with median posterior $\delta = 1.662, 95\%CI = [.907, 2.423]$) against the JND. Since the physical resistance did not change in this part of the experiment, we conclude that, similar to our preliminary experiment, participants in fact associate rotational C/D gain manipulations with changes in physical resistance (**H3**). Moreover, as a central finding, we could show that within the range of unnoticeable C/D gains, designers can effectively change the perceived physical resistance of the knob proxy (**H4**).

4.7.3 How do C/D gain and perceived resistance relate to each other? Finally, we looked at the resistances perceived when different C/D gains are applied. Initially, the resistance was set to 1.1 Nmm, which pilot study participants stated to be most realistic, given the visualization, form and feel of the knob, and the investigated interaction. In the last part of our experiment, we obtained 3 configured physical resistances per C/D gain, which were averaged for each participant and then statistically compared. The results can be seen in Figure 6, showing a robust baseline and an increase in configured physical resistance with decreasing C/D gains. We found very strong evidence for a main effect ($F_{(1.72,29.29)} = 27.34, p < .0001, \eta^2 = .441, BF_{incl} = 5.496e^{+16}$) of C/D gain on the configured resistance. Post-hoc analysis indicated that there exist many significant differences between C/D gains, demonstrating consistent and distinct configurations made by participants. In addition, we found a strong negative correlation ($r(351977) = -.68, p < .0001$) between C/D gain and configured physical resistance, meaning that lower C/D gains lead to higher physical resistances. This shows that participants were able to consistently assign a physical resistance to a C/D gain (**H3**) and that the effects of C/D gain manipulations were perceptually distinguishable for our participants (**H5**).

4.8 Summary & Discussion of Results

Our study confirms that substantial differences between the real and the virtual rotations of the knob can be introduced without users noticing (**H1**). Participants interpreted the pseudo-haptic effect triggered by C/D gain manipulation as physical resistance (**H3**). The JND in terms of physical resistance stays within the unnoticeable

[1] https://richarddmorey.github.io/BayesFactor/

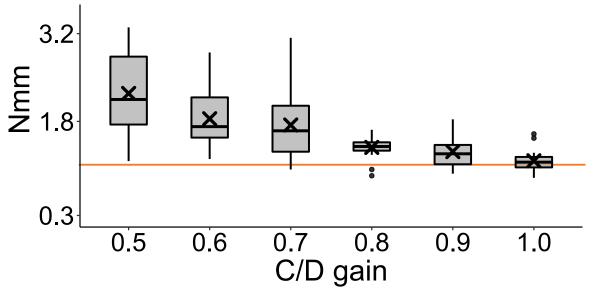

Figure 6: Participants adjusted physical resistance given the applied C/D gain. Orange line represents default resistance.

C/D	0.5	0.6	0.7	0.8	0.9	1.0
0.5	-	< .01	< .001	< .001	< .0001	< .001
0.6	137.10	-	.21	< .01	< .0001	< .001
0.7	2315.4	1.11	-	< .05	< .01	< .01
0.8	858.48	113.91	6.83	-	.349	< .05
0.9	3755.2	5719.7	105.47	0.36	-	.21
1.0	2139.1	1243.3	49.67	13.94	1.09	-

Figure 7: Bayes factors and p-values.

range of C/D gain manipulations, enabling designers to increase the perceived resistance (**H4**) without users noticing that they are being manipulated. The range of tested C/D gains created distinguishable levels of pseudo-haptic resistance and participants reliably assigned physical resistance to the presented C/D gains, with smaller C/D gains resulting in higher levels of perceived physical resistance (**H5**). However, we could not identify a shift in perceptual thresholds caused by higher visuo-haptic congruence (**H2**).

In the following, we outline important aspects and lessons learned when incorporating pseudo-haptic resistance in rotational interactions and discuss what could potentially break the illusion.

4.8.1 Towards Pseudo-Haptic Resistance. We found that selecting an appropriate base level of resistance, which is in line with participants' expectations, is crucial for our pseudo-haptic resistance illusions to work. Notably, in the preliminary experiment, participants immediately commented on the missing base resistance, which we intentionally kept low (0.3 Nmm). We changed this for the main experiment, and not a single participant commented on this. Following the method of adjustments, the first significant change in participants' configured resistance occurs at a C/D gain of 0.8. This is in line with our JND results, showing that participants notice a change in resistance at $mean$ = 0.81 compared to the baseline. However, it is unclear whether the C/D steps required to achieve perceptually different levels of resistance between two interactions follow a linear pattern [16].

With decreasing C/D gains, the amount of variance in the configured physical resistance became larger. This may be attributable to two things: (1) individual variances in participants' perceptual abilities and (2) the fact that for some participants, the illusion broke when being exposed to C/D gains above their detection threshold.

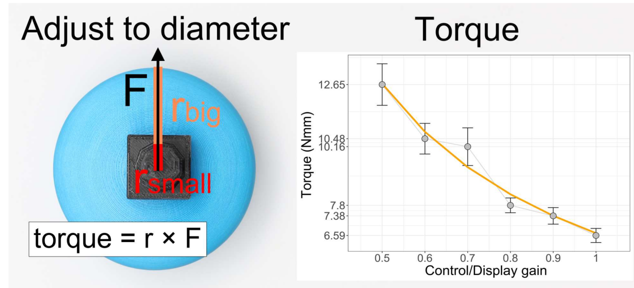

Figure 8: Left: Depiction of torque components on our 3D-printed knob. Right: Fitting for perceived torque by C/D gain.

This can be addressed by calibrating illusions to an individual's perceptual boundary [22].

4.8.2 Breaking the Illusion. We observed two different effects that occurred when the pseudo-haptic resistance illusion broke.

P8 stated, "my virtual hand moves slower than my real hand", which is the effect of a C/D gain $\leq$ 1.0. To our surprise, the participant did not change the default resistance of 1.1 Nmm to a C/D gain of 0.5, but selected 1.6 Nmm for C/D gain = 0.8. In the interview s/he said that when the virtual hand moved slower s/he closed his/her eyes during the procedure, because it "was so confusing to compare the resistances, when the dials moved at different speeds".

In contrast, P18 reached the maximum physical resistance that could be configured with our device and stated, "Can't I go higher with the resistance of the red dial?", followed by "I would need more resistance to match the blue dial" (i.e., C/D gain = 0.5). Thus, the participant still 'believed' the pseudo-haptic effect, but exhausted the physical scale. This happened all 3 times when the 0.5 C/D gain was presented to this participant. Please note, P4 and P18 were also identified as (the only) outliers, following the box plot method, and were therefore excluded from the analysis above.

5 A MODEL OF PSEUDO-HAPTIC RESISTANCE

Our goal is to provide a model for pseudo-haptic resistance that can be applied to new and exciting VR applications. Thus, we demonstrate how our results can be applied. Since the provided resistance depends on the radius of the knob, we compute the torque that the DC motor can produce using the following equation $\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$. As a result, depending on the designer's needs, they can derive the required size of the motor to produce the desired haptic resistance given the lever, or vice versa (see Figure 8).

Data from the method-of-adjustments experiment was fitted following a forced fusion procedure as indicated in Samad et al. [42]. Figure 8 shows the experimental data for perceived torque according to the veridical values rendered by our device per C/D gain, and the orange fitting curve of the model (R=0.96377). Additionally, the model in Equation 1 predicts the perceived torque in our VR knobs for a given C/D gain, which is parameterized with the variable CD. The resulting value unit is Newtons per millimeter (Nmm), representing the counterforce provided at knob rotation.

$$Torque(Nmm) = \frac{6.684}{0.054 + (0.946 * CD)} \tag{1}$$

Figure 9: (A) displaying Feick et al. [21]'s slider proxy next to our knob proxy. (B) shows a user's hand is redirected. (C) indicates the start position, while (D) shows the position of the hand after rotation in the real and virtual world.

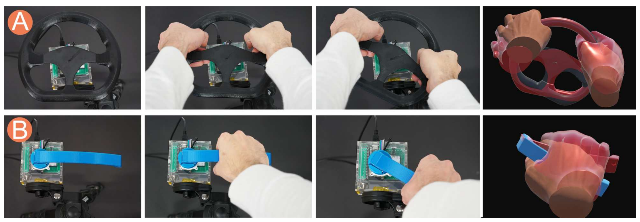

Figure 10: 3D-printed steering wheel (A) and door handle (B) connected to our prototype using the custom mount. *Pseudo-haptic Resistance* allows users to perceive changing levels of resistance during interaction. Red indicates displaced hand.

6 POTENTIAL USE CASES & APPLICATIONS

To illustrate how VR designers can use our findings on rotational offsets and the introduced pseudo-haptic resistance technique, we outline two potential use cases. We used the proxy knob hardware described above, and attached different 3D-printed objects using our custom mount.

6.1 Re-mapping 3D Interfaces

The ultimate goal of proxy-based haptics is that users only need a minimal set of physical props to simulate a large set of virtual objects. When also considering function, i.e., the different states that proxies can adopt, it becomes more challenging. Together with prior work, we push the current boundaries of re-mapped 3DUI [38]. To illustrate this, we re-implemented the DJ desk application from Feick et al. [21], and besides the virtual sliders we also re-mapped the virtual knobs on the DJ desk to a single physical proxy knob (see Figure 9). Depending on the selected virtual knob, the proxy knob resets itself to the corresponding state (e.g., the rotation limits or to align its haptic features). With only two functional proxies, slider and knob, we could, in fact, provide haptic feedback for the DJ desk's UI by seamlessly redirecting users [12], without them noticing (see Figure 9 B). This is possible because the different hand poses, when interacting with the UI elements, do not interfere with hand redirection [23]. Finally, interactions could even be improved by applying the *REACH++* technique [25].

6.2 Pseudo-Haptic Resistance Beyond Knobs

Our results may be used beyond knobs to create realistic haptic sensations without the need of large and expensive actuators. For example, other types of rotational manipulations could benefit from *Pseudo-Haptic Resistance*: for example, simulating different door handles and levers, or even bi-manual interactions with steering wheels. We also envision our technique at a smaller scale, e.g., single finger interactions with existing controllers. Often, they already host mechanical actuators to provide haptic feedback and their haptic resolution could further be improved. To showcase this, we implemented a set of these interactions, depicted in Figure 10.

7 DISCUSSION & LIMITATIONS

7.1 Limitations of Pseudo-Haptic Resistance

Our proposed pseudo-haptic resistance technique can be easily integrated, because there is no special hardware or knowledge required. However, as with any other vision-based approach, it only works when users directly look at the object or their hand during interaction. We also encountered this issue with one of our participants who closed her/his eyes in order to focus on the physical resistance. This poses some limits on the technique, as users sometimes solely rely on their proprioception, e.g., when interacting with devices while focusing on another, primary task. This is especially true for experts familiar with an interface.

We included a condition with haptic tick marks in order to improve visuo-haptic integration, hypothesizing that it should increase detection thresholds [14, 40] which would have enlarged the possible range of unnoticeable C/D gains for pseudo-haptic resistance. However, our results suggest that it did not have a measurable effect on the detection thresholds. Nevertheless, we believe it is an interesting area to explore in future work, since in this paper, we were focusing on the most conservative case, i.e., we told and showed participants the effect of C/D gain manipulation and their only task was to detect it [50]. VR experiences are much more complex, including distracting factors or tasks that require more attention—extending the range of unnoticeable C/D ratios [15].

In our preliminary experiment pilots commented on the physical resistance of the knob being 'too loose'. This suggests to us that there is a physical resistance, given the visualization, form and feel of the knob, that participants intuitively expect based on their everyday experience with similar interfaces in the real world. Hence, as with any other psychophysical experiment, our results may need to be adapted, depending on the VR application. To this end, it is unclear how different base levels of physical resistance might affect the presented pseudo-haptic resistance model.

7.2 Utility of Pseudo-Haptic Resistance

Our model of pseudo-haptic resistance is a simplification and cannot replace a more comprehensive multisensory integration model such as proposed by Ernst and Banks [14]. However, it still provides designers with a validated range of perceived torque (i.e., from 6.683 to 12.684 Nmm according to our tested C/D gains), reasonable for common VR interactions with 3DUIs. Our technique is applicable to existing systems and controllers and can be used to adapt interfaces to different users, e.g., based on their individual ergonomic preferences, without changing the hardware.

In this work, we were only interested in increasing the perceived resistance in order to improve the haptic resolution of new and existing devices. Still, we recommend that future work should investigate whether pseudo-haptic resistance works bi-directionally, i.e., if C/D gains ≥ 1.0 result in less perceived physical resistance. Similarly, the method could be used not only for rotations, but also for translations or even stretching [21]. The latter could be achieved by gradually changing the C/D gain.

7.3 Extending the Approach

We are also interested in situations where proxies cannot be used, and hence, the overall multimodal feedback relies on wearable haptic feedback and/or pseudo-haptics: for example mid-air knobs, where, similar to *Holitouch* [2], a holistic approach could be developed. Here, our pseudo-haptic technique provides the first puzzle pieces to achieve this, and we encourage the community to build upon it. Finally, we did not evaluate the presented use cases through a formal user study, but leave this for future work.

8 CONCLUSION

In this work, we presented a novel technique called *Pseudo-Haptic Resistance*, which grants the VR system control over the perceived resistance during proxy-based rotational interactions. We ran a 3-staged psychophysical experiment with 20 participants and found that we can introduce substantial offsets between real and virtual rotations of a proxy knob, without users noticing the manipulation. We report the corresponding detection thresholds, and demonstrated that the technique can effectively convey distinguishable levels of rotational resistance while staying within unnoticeable ranges of C/D gain. In addition, we provide a model that describes how C/D gains correspond to perceived physical resistances, and outline how our results can be translated to other rotational manipulations by presenting two use cases and applications. We believe that our results will help to overcome current limitations of proxy-based VR systems. At the same time, our technique can easily be deployed in new and existing VR applications.

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