Using Pseudo-Stiffness to Enrich the Haptic Experience in Virtual Reality

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ABSTRACT

Providing users with a haptic sensation of the hardness and softness of objects in virtual reality is an open challenge. While physical props and haptic devices help, their haptic properties do not allow for dynamic adjustments. To overcome this limitation, we present a novel technique for changing the perceived stiffness of objects based on a visuo-haptic illusion. We achieved this by manipulating the hands' Control-to-Display (C/D) ratio in virtual reality while pressing down on an object with fixed stiffness. In the first study (N=12), we determine the detection thresholds of the illusion. Our results show that we can exploit a C/D ratio from 0.7 to 3.5 without user detection. In the second study (N=12), we analyze the illusion's impact on the perceived stiffness. Our results show that participants perceive the objects to be up to 28.1% softer and 8.9% stiffer, allowing for various haptic applications in virtual reality.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; **Haptic devices**.

KEYWORDS

haptic illusions, pseudo-haptics, virtual reality

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1 INTRODUCTION

From checking the ripeness of fruit to choosing a suitable mattress, we often rely on our abilities to discriminate between different stiffnesses of materials and objects when assessing the physical world. While this haptic sensation of stiffness is a natural aspect of how we experience the physical world, today's virtual reality (VR) environments are dominated by visual and auditory stimuli, neglecting the haptic aspects. Hence, a fundamental part of our experience is lost, compromising the realism and, thus, the immersion of VR.

To mitigate this limitation of the missing haptic experience of object stiffness, research explored active systems that can emulate a variety of stiffnesses, such as robotic devices [43] or hydraulic and pneumatic interfaces [62, 64, 78]. However, such active systems are often expensive, bulky, and complex, hampering their broad applicability. As another solution, research explored passive props to provide haptic feedback. As a prominent example, Insko [31] showed that large-scale passive haptics could increase the presence and spatial navigation in virtual environments. White et al. [72] proposed a hand-held passive prop that significantly increases the game experience and performance over regular controllers when resembling the virtual object's properties. While these works did not investigate stiffness, they show that passive props can provide realistic haptic experiences if they closely resemble the virtual objects they represent. However, they cannot dynamically adjust their properties, such as stiffness, on demand, restricting their versatility to specific predefined use cases. As one solution to address this lack of adaptability of physical props, research explored using visuo-haptic illusions to alter the perception of static physical stimuli based on discrepant visual stimuli. Such visuo-haptic illusions have been proven to be effective in altering the perceived haptic properties of objects and materials, such as shape [7, 8], size [11, 66], weight [34, 56], surface textures [22, 38] and, also, stiffness [37, 49, 74]. However, these approaches to altering the perceived stiffness of objects rely on visually deforming the surface texture to evoke the illusion, restricting the flexibility and applicability of the approach.

In this work, we go beyond the state-of-the-art in stiffness feedback for VR systems by presenting a novel method to alter perceived stiffness through a visuo-haptic illusion that remains undetected by users. For this, we propose varying the Control-to-Display (C/D) ratio during the movement while pressing down on a physical object, causing the virtual hand in VR to travel more or less distance compared to the hand in the real world. We hypothesize that a greater visual distance of the hand will lead to the sensation of a softer object and vice versa, while the physical stiffness remains

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the same. To test our hypothesis, we contribute the results of two controlled experiments, assessing the detection thresholds and illusion's impact on the perceived stiffness. We found that an increase of up to 3.48 times and a decrease to 0.66 times the actual movement of the hand remain undetected by participants. Staying within these boundaries, we found the illusion to be able to alter the perceived stiffness of objects to feel up to 8.9% stiffer and 28.1% softer.

2 RELATED WORK

Our work was strongly influenced by a large body of related work on rendering stiffness using 1) active haptic devices and 2) passive systems, which we present in the following. Further, we 3) present a background on stiffness illusions.

2.1 Active Haptic Devices for Rendering Stiffness

In the area of robotic technologies, devices such as Geomagic touch[1], Omega[2], and Novint Falcon [43] allow for rendering realistic stiffness experiences. However, these interfaces have a very limited working space and are often extremely costly for common users. To overcome this, several attempts have been performed to render stiffness using vibrotactile feedback [4, 15, 42, 68, 69, 76], however, vibrotactile actuators cannot generate a realistic stiffness sensation given the physiological mechanisms underlying compliance perception [32]. In recent years, other options have been proposed; These alternatives vary from bulky hydraulic or pneumatic interfaces [62, 64, 78] to wearable gloves [26, 29] and finger-mounted devices [55, 65], to hand-held devices [50, 51, 58]. Within this spectrum, we can find jamming tubes to restrict finger movement by inflating the tubes. Although it is effective for stiffness rendering, such interfaces are slow and cumbersome [78]. As an alternative, the use of gloves presents practical advantages. For example, the ExoTen-Glove employs twisted string actuation to offer force feedback in gripping tasks [29]. However, the arm straps render it cumbersome to wear, hindering broad applicability. In the same line, Hinchet et al. [26] presented DextrES, a promising electric-brake-based glove that provides force and cutaneous feedback. Unfortunately, DextrES runs at voltages over 250V, ruling out usage at home. As an inexpensive and straightforward approach, research proposed finger-mounted devices. In this spectrum, Schorr and Okamura [57] developed a device mounted directly to the fingertip to produce both shear and normal skin deformation to the fingerpad. Alternatively, Salazar et al. [55] extended the work of de Tinguy et al. [17] to render stiffness and softness sensations using a device mounted on the user's proximal phalangeal finger. More recently, Tao et al. [65] presented a device to adjust the apparent softness of hand-held props in virtual reality by restricting the deformation of the fingerpad. Lastly, cutaneous deformations have also been integrated into hand-held devices to render stiffnesses in tool-mediated scenarios by applying shear forces to the contact area during probing of simulated compliant objects [50, 51, 58]. Although all these methods effectively stimulate the user's mechanoreceptors to render stiffness sensations, they require the addition of hardware, limiting the possible user interactions and range of haptic experiences to the device's capabilities. In general, while rendering stiffness with active haptic devices has reached maturity in terms of stability and dependability, the required hardware introduces severe restrictions in various dimensions.

[1]https://de.3dsystems.com/haptics-devices/touch-x, last accessed: 2023-02-15
[2]https://www.forcedimension.com/products/omega, last accessed: 2023-02-15

2.2 Passive Haptics

To overcome the limitations of active systems, research proposed the usage of physical objects for passive haptics in VR. These physical props offer high-fidelity feedback regarding the geometric and material properties of the objects they were designed to represent. Insko [31] showed that the inclusion of large-scale passive props can increase the sense of presence and spatial way-finding. Similarly, White et al. [72] showed a passive prop with haptic properties resembling the virtual object (e.g. a similar weight) to outperform regular controllers or passive props with differing properties. However, passive approaches severely limit the systems' scalability because they cannot change their position or haptic properties, such as stiffness. To mitigate the positional restrictions, research proposed solutions by redirecting the user's walking [53] or grasping [6, 14]. However, changing these objects' haptic properties, including stiffness, remains an open challenge.

2.3 Visuo-Haptic Stiffness

While active and passive systems are able to present an objective stiffness, the subjective perception of this stiffness is flexible, as it depends on both the perception of force and displacement [36]. Klatzky and Wu [36] discuss that while force is generally sensed haptically, displacement can additionally be (often better) perceived visually. Ernst and Banks [21] stipulate that haptic and visual cues are combined to a resulting percept based on a maximum-likelihood model, in which the weights of the senses are determined by their reciprocal variances. Therefore, both senses have a certain influence on the resulting perception based on how reliable they are in the respective task. Drewing et al. [19] demonstrate the contribution of vision on stiffness perception by showing that objects were perceived to be softer when participants were allowed to see the object and hand during exploratory tasks. Consequently, discrepant visual cues may have an effect on the perception of stiffness. For instance, it has been shown that a delay of the visual or the haptic cues while pressing a rendered virtual spring results in an increased or decreased perceived stiffness respectively [18, 75].

Srinivasan et al. [60] and later Lecuyer et al. [39] exploit the visual dominance over proprioception when judging the displacements to alter the perceived stiffness of rendered virtual springs. They asked their participants to press on a physical spring while looking at a visual representation of the compression on a computer screen. They report that altering the visual compression magnitude affected the participants' judgment of the spring's stiffness, with higher visual displacements resulting in the springs being perceived as softer and vice versa. While these approaches to changing perceived stiffness show the viability of visuo-haptic illusions, they required participants to watch their interaction on a separate screen while having no vision of their hands and the actual object during the interaction. Other works use a different approach, instead relying on visual texture deformations to create a pseudo-haptic sensation of stiffness. Argelaguet et al. [5] generate this illusion

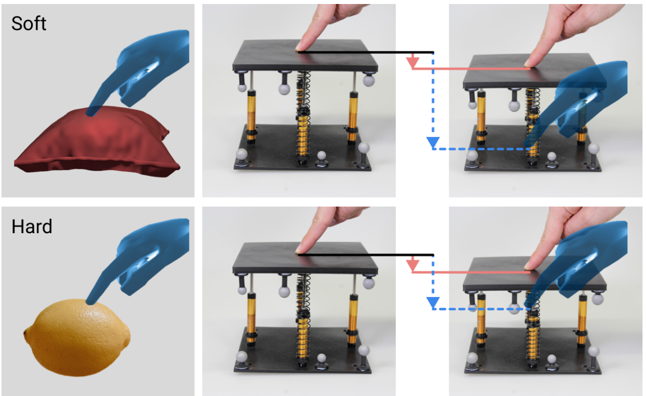


Figure 1: We modulate the ratio between the actual hand movements of the user (pink arrow) and the resulting change in the position of the hands' virtual representation in VR (dotted blue arrow). When users aim to explore a physical object's stiffness by pressing down on it, the movement gains are adjusted in accordance with the desired perception of stiffness for the virtual object.

by deforming a two-dimensional texture when participants click with a mouse on a computer screen. Kawabe [35] solely relies on visual cues by tracking the hands in mid-air and deforming a texture on a screen behind them accordingly. However, both of these indirect approaches do not conform with how people usually interact with their environment. Other research employed a more natural approach, where the texture was deformed when and where participants were pressing with their fingers onto a surface [27, 37, 49, 74]. In the case of Kokubun et al. [37], this was done on a rear touchscreen of a mobile hand-held device. Wolf and Bäder [74] and Punpongsanon et al. [49] instead projected the texture respectively onto a rigid table or on soft objects and deformed it visually when participants pressed them. Lastly, Hirano et al. [27] superimposed deformations while pressing using a video see-through mixed reality system. While these approaches allow for more natural interaction with objects, these setups only work in a limited workspace and completely change the visual experience in favor of inducing the pseudo-haptic effect. Additionally, most of these approaches were only able to achieve objects being perceived as softer.

To extend the capabilities of active and passive devices regarding the rendering of different stiffnesses and to mitigate the limitations of current approaches relying on illusions, we propose a novel method to modulate perceived stiffness based on a visuo-haptic illusion in which manipulations remain undetected by users.

3 CONCEPT: VISUO-HAPTIC ILLUSION FOR STIFFNESS SIMULATION

Our proposed technique modulates the perceived stiffness of objects by dynamically manipulating the Control to Display (C/D) ratio of users' hand movements while interacting with objects in VR (see Figure 1). C/D ratio describes the relationship between actual inputs, such as movements, and the resulting change in the display. Adjusting the C/D ratio has already been investigated before the emergence of VR. For instance, Lécuyer et al. [38] induced the sensation of textures on a flat desktop screen by manipulating the ratio of actual mouse movement to the cursor movement on the screen. In VR, this method was mostly adopted to redirect users' hands. This is made possible by the phenomenon of visual dominance over proprioception when judging the positions and movement of one's limbs in space. One of the first reporting of this phenomenon was made by Botvinick and Cohen [12] during their investigation of the Rubber Hand Illusion. They hid one of the participant's hands and instead laid a rubber hand onto the table in front of them, simultaneously and congruently stroking the fake and the hidden hand with a brush to elicit the adoption of the alien limb into one's own body representation. In addition to showing that the tactile sensations applied to the real hidden hand are misperceived to originate from the rubber hand, Botvinick and Cohen reported a proprioceptive drift of participants' perceived hand positions in space towards the fake rubber hand. This effect has been replicated in VR numerous times, replacing the rubber hand with a virtually generated one [41, 48, 59]. VR allows the virtual hand to be spatially co-located to the real hand [41, 59] but also enables artificial displacements of the hand [48]. This deliberate redirection allows a single physical object to stand in for multiple virtual ones by redirecting users' grasps to the same passive prop [6] or a specific part of it [14]. Additionally, the manipulation of the C/D ratio has been used to enhance the performance of active devices, such as the speed and workspace of encounter-type displays [23] and the perceived resolution, pin speed, and size of shape displays [2]. Recently, Samad et al. [56] characterized how C/D ratio manipulation of the user's hand in VR while lifting an object affected the subjective perception of its weight and showed that increasing and decreasing this ratio resulted in objects feeling lighter and heavier, respectively.

In our technique, we modulate the ratio between the actual hand movements of the user and the resulting change in the position of the hands' virtual representation in VR. While users' are not engaged in any interaction with an object, the C/D ratio remains at 1, resulting in no discrepancy between actual and virtual movement. However, when users aim to explore a physical object's stiffness by pressing down on it, the movement gains are adjusted in accordance with the desired perception of stiffness for the virtual object, i.e., if the object is meant to feel stiffer, the movement gains of the virtual hand pressing down are reduced (C/D ratio < 1). Alternatively, if a more compliant object is desired, movement gains during pressing are increased (C/D ratio > 1).

In this paper, we characterize the illusion in two psychophysical studies. First, we explore the detection thresholds of the illusion to find out whether the range of the C/D ratio can be increased and decreased while avoiding detection by users. Second, we analyze the impact of the illusion on stiffness perception by comparison to physical stiffness changes.

4 STUDY I: BOUNDARIES OF THE ILLUSION

We conducted a controlled experiment to establish the upper and lower detection thresholds of the illusion. While the detection thresholds of hand redirection have been explored before [2, 77], it is an open question how pressing on physical objects affects the illusion boundaries. In addition to visual and proprioceptive information, such objects allow us also to perceive tactile and kinesthetic information. Consequently, we aim to characterize the detection thresholds of the illusion when pressing on compliant objects of various stiffnesses. We used the Method of Constant Stimuli to assess how much the movement gains of the virtual hand representations can be increased and decreased during pressing without being detected. For this, we presented different fixed values of C/D ratio manipulations above and below the estimated detection thresholds in randomized orders and asked participants the following question: "Did the movement of the virtual hand match the movement of your real hand during pressing?" Participants were only able to answer "*Yes*" or "*No*" to this question and were forced to decide between these two answers.

4.1 Apparatus

We used a Novint Falcon for rendering forces to simulate stiffness. For this, we fixed the device to a wooden base which, in turn, was fixed facing upwards onto a desk with adjustable height. We replaced the Novint Falcon's end-effector with a 9cm x 9cm square wooden board attached to a custom 3D-printed connector. A piece of paper was glued on top of the wooden board to guarantee a uniform surface texture throughout the experiments. We tared this setup empirically to ensure accurate rendering of stiffnesses. We built the virtual environment in Unity3D and deployed it to a Gaming Laptop with an Intel Core i9, 32GB RAM, an NVIDIA GeForce GTX 1650 Ti graphics card, and a connected HTC VIVE Pro. To track and display the users' hand and finger movements in real-time, we attached a Leap Motion Controller to the front of the HMD. In the virtual environment, the end-effector is represented by a plain white cube with the same dimensions. The location of the physical and virtual contact surfaces are synchronized using a VIVE Tracker. We track positional changes of the end-effector during pressing using the Novint Falcon's internal positional tracking. No tactual or visual deformation of the surface is presented. The participant's dominant hand is represented by a low-poly hand model provided by Ultraleap. To mitigate some of the inaccuracies of the optical hand tracking of the Leap Motion Controller, we overwrite the hand position during contact with the end-effector to correspond to the more accurate tracking of the Novint Falcon. This ensures the virtual hand does not clip through the virtual object while pressing down. Participants interacted with the system using their dominant hand. We also gave them a wireless presenter in their non-dominant hand that they used to answer the questions during the experiment. Figure 2 depicts the apparatus for our experiments.

Figure 2: The experimental setup consists of the Novint Falcon haptic device with a custom-built end-effector, a Head-Mounted Display with an attached Leap Motion Controller to track participants' hands, a Gaming Laptop running the virtual environment, and a wireless presenter for participants to give their answers. Participants pressed down on the center of the provided touchable surface with their index fingers to displace the end-effector.

4.2 Procedure

First, we welcomed participants, informed them about the study's aim and data processing, and asked them to sign a consent form. To reduce the potential confounding influence of different visual perspectives in relation to the object and the kinematics of participants' arms, we adjusted the table, so the touchable surface was located at the same relative height for each participant. We chose to set the touchable surface's initial position to 40cm below a participant's total height to avoid the possible strain on participants from needing to bend over or lift their arms above their shoulder height (cf. [20, 47]). We discuss this choice and the possible effect of other interaction heights in more detail in Section 7.1. Participants were standing in front of the table on a standing desk mat. Then, participants put on the HMD, and the virtual and physical surfaces were synchronized using the VIVE Tracker. Participants could only see their dominant hand represented in virtual reality while holding the presenter in their non-dominant hand. We informed participants about their task, which consisted of pressing down the virtual object using the index finger of their dominant hand until the object turned green, signaling that the object had been pressed down far enough. This threshold was reached when the physical device's end-effector was pressed down 30mm. When the object turned green, the participants were instructed to remove their pressure, resulting in the physical and virtual object bouncing back to its original position. The participants initially ran through a short training session consisting of three pushes. The first push did not include any manipulation of the C/D ratio, so the visual and physical movement matched. The second and third pushes respectively increased and decreased the movement gains of the virtual hand far beyond the detection thresholds to showcase the illusion participants are tasked to detect. After the training session, the trials started. Each trial consisted of one press without time restrictions. When the pressing and releasing were completed, the question asking whether their perceived hand movements matched was prompted. The answer options ("*Yes/No*") were shown in the virtual environment. Participants chose their answer by pressing the left ("*Yes*") or right ("*No*") arrow button on the provided wireless presenter. After answering, the physical and virtual objects were reset to their starting point, and the next trial was started. No feedback about the correctness of the answer was given. After 75, 150, and 225 trials, participants took a break without any time limitations. Overall, participants took 40 minutes on average to finish the study.

4.3 Pilot Study

We conducted a pilot study using an (Ascending) Method of Limits to find a rough estimate of the detection thresholds of the manipulation. These rough thresholds were then used to inform the selection of adequate points to evaluate in the Method of Constant Stimuli. The pilot study used the same apparatus and followed a similar procedure, but the table was kept at a constant 76cm height, and the training session was skipped. During the trials, we continuously increased (or decreased for lower boundary detection) the manipulation of the C/D ratio while participants answered "*Yes*". As soon as a participant answered "*No*", the trial block was ended, and the next condition was started. We tested a total of six conditions resulting from the combination of three stiffnesses (Soft (249 N/m), Medium (363 N/m), and Hard (544 N/m)) and either increasing or decreasing the C/D ratio. The order of these conditions was counterbalanced between participants. 6 participants (3 female and 3 male; all right-handed; Age: M=28.83, SD=3.08) took part in this pilot study. We calculated the detection thresholds for each individual by taking the mean value between the last undetected point and the first detected point. The average detection thresholds across participants and stiffnesses occurred at ratios of 4.93 (SD=1.38) and 0.78 (SD=0.15) times the actual hand movement. We used these estimations of the illusion's boundaries to inform the scale and step sizes of the Method of Constant Stimuli.

4.4 Study Design

During the main study, two independent variables were varied: The reference stiffness (STIFFNESS) the haptic device was rendering and the C/D RATIO of the physical to virtual hand movements.

- **STIFFNESS** For our independent variable STIFFNESS, we selected three levels to be rendered by the haptic device in line with prior work by Lecuyer et al. [39]: Soft (249 N/m), Medium (363 N/m), and Hard (544 N/m).
- **C/D RATIO** As our second independent variable, we derived fixed values of C/D RATIO manipulations to evaluate based on the detection thresholds found in the pilot study. The pilot study indicated that the boundaries for detecting reduced and increased hand movement gains are not equally spaced. Therefore, the evaluation of detection thresholds was split into two separate parts. The C/D RATIO values for the first part comprised: 0x, 0.25x, 0.5x, 0.75x, and 1x the actual movement of the physical hand during pressing. The C/D RATIO values for the second part comprised: 1x, 2x, 3x, 4x, and 5x of the actual movement of the physical hand during pressing. The first and second parts were tested successively and their order was counterbalanced between participants.

Each combination of STIFFNESS and C/D RATIO was repeated 10 times. This resulted in a total of 300 trials per participant (3 STIFFNESS × 10 C/D RATIO × 10 repetitions). The order of trials in each of the two parts was randomized. For each trial, we measured the participant's response ("*Yes/No*"). Additionally, in each of the three breaks and after the last trial, we asked participants to fill out a raw NASA-Task Load Index (NASA TLX) [25] to assess their subjective workload.

4.5 Participants

We used convenience sampling to recruit 12 participants (1 female and 11 male). The age of the participants was between 26 and 36 (M = 29, SD = 2.6). 11 participants were right-handed, and 1 participant was left-handed. All participants had experienced virtual reality before (1 participant below 2h, 6 participants between 2h and 20h, and 5 participants above 20h). All participants had normal or corrected-to-normal vision and no known issues that might affect the tactile or kinesthetic perception of the hand. We offered 10€ as compensation.

4.6 Results

For each participant, we calculated the ratio of detection of the illusion for each point (pair of STIFFNESS and C/D RATIO) by dividing the number of times the illusion was detected by the overall number of trials for this point (10 trials per point). We considered the illusion as detected if a participant answered "*No*" to the question of whether the virtual hand's movement matched their real hand's movement. We then averaged the detection rates of all participants.

4.6.1 Reduced C/D Ratio. In line with prior work [2, 63], we fitted the results of the experiment on reduced C/D ratios to psychometric functions of the form:

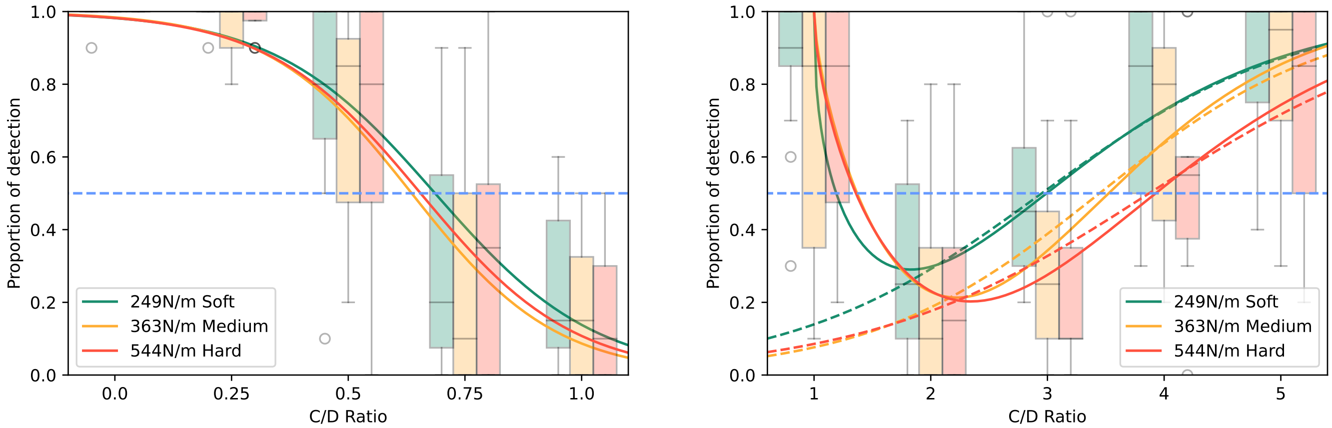
$$f(x) = \frac{1}{1 + e^{ax+b}}, \tag{1}$$

where the parameters a and $b \in \mathbb{R}$. Figure 3a shows the fitted curves for the Soft (a = 5.83, b = -4.00), Medium (a = 6.46, b = -4.11), and Hard (a = 6.13, b = -4.02) conditions. We calculated the detection threshold (DT) of the illusion as the C/D ratio that would be detected 50% of the time. We found DTs for the three STIFFNESS conditions ranging from 0.69x for Soft over 0.64x for Medium to 0.65x for the Hard condition. The mean DT of the three STIFFNESS conditions is 0.66 (SD=0.02).

4.6.2 Increased C/D Ratio. When assessing the data for increased C/D ratios, we observed that the detection rates do not follow the same expected trend we found for the reduced C/D ratios. Participants consistently reported detecting the illusion at a C/D ratio of 1, even though physical and virtual hand movements objectively matched. Instead, participants felt that their physical and virtual hand movements matched more often at higher movement gains. Due to this surprising phenomenon consistently observed across participants, the commonly used psychometric functions (such as Equation 1) are not sufficient to display this trend accurately. Thus, another function is needed, that better describes these findings. As the trend seems to follow the regularly expected monotonous increase beyond the second evaluated point, we, therefore, aimed to find a better fit that does not neglect the surprising phenomenon or the monotonous increase afterward. For this, we looked at a different commonly used function, the *Weibull probability density function* [71] of the form:

$$w(x) = \frac{k}{\lambda} * (\frac{x}{\lambda})^{k-1} * e^{-(x/\lambda)^k}, \tag{2}$$

where, $\lambda > 0$ is the scale parameter, and $k > 0$ is the shape parameter ($\lambda, k \in \mathbb{R}^+$). Moreover, in line with prior work, we used a more parameter version of the Weibull function (cf. [16, 45]). In detail,



(a) Reduced C/D Ratios

(b) Increased C/D Ratios

Figure 3: Fitted functions for proportion of detection of reduced (*a*) and increased (*b*) C/D Ratios for the Soft (*Green*), Medium (*Yellow*), and Hard (*Red*) conditions. A blue dotted line indicates the detection threshold (probability of 0.5). Alternative fitted functions for increased C/D Ratios are shown as dotted lines in (*b*).

we used an inverse version with amplification which describes this trend better than Equation 1. Therefore, we fitted Equation 3 with the form:

$$w'(x) = 1 - a * w(x), \tag{3}$$

where $a > 0$ is the amplitude parameter ($a \in \mathbb{R}^+$). Figure 3b shows the fitted curves for the Soft ($\lambda = 1.99$, $k = 1.41$, $a = 1.92$), Medium ($\lambda = 2.12$, $k = 1.67$, $a = 2.16$), and Hard ($\lambda = 2.47$, $k = 1.60$, $a = 2.58$) conditions.

Our findings and resulting fitted curves suggest that the DT of 0.5 is being crossed twice, once between a C/D Ratio of 1 and 2 and once at a much higher C/D Ratio. However, to inform the chosen values for C/D Ratio for the second experiment, we are only interested in the latter, because we hypothesize a higher C/D Ratio to result in a greater effect on perceived stiffness (see Section 5).

We found DTs of the illusion for the three Stiffness conditions from 2.99x for Soft over 3.52x for Medium to 3.93x for the Hard condition. The mean DT of the three Stiffness conditions is 3.48x (SD=0.38). To test the validity of the DTs ascertained through our function for increased C/D ratios, we additionally fitted the data to Equation 1, ignoring the values given at C/D Ratio of 1 (see Figure 3b, dotted lines). This revealed negligible differences between the respective curves beyond the second point evaluated (C/D Ratio of 2), resulting in very similar calculated DTs (the deviation of the mean DT is 0.06). Therefore, we consider our functions and the calculated mean DT (3.48x) correct.

4.6.3 Subjective Workload. We analyzed the TLX scores participants reported to find potential workload effects of the conducted tasks which might have to be considered. The raw TLX scores for each subsequent block were M=20.14 (SD=12.99) for the first, M=14.99 (SD=11.04) for the second, M=16.94 (SD=13.55) for the third, and M=16.68 (SD=11.69) for the fourth. A one-way repeated measures analysis of variance (RM-ANOVA) revealed no significant effect. Therefore, we assume that the workload caused by the tasks did not considerably influence our results.

4.7 Discussion

In the presented study, we determined the detection thresholds for changes in the C/D ratio when pressing on simulated objects with different stiffnesses. In this section, we will discuss these results in relation to our research question.

4.7.1 Reduced C/D Ratios are Easier to Detect. Across all three Stiffness conditions, we observe that a reduced C/D Ratio is detected earlier than an increased C/D Ratio. While a reduction in the C/D Ratio was detected on average at a difference of -33% (0.66x), increasing the ratio was, on average first detectable when reaching a difference of +248% (3.48x). We attribute this finding to multiple effects: First, we observed that people tend to overestimate their hand movements while pressing, which we discuss deeper in Section 4.7.3. This may have affected the detection because lower values would then be considered less realistic. Second, we associate this finding with the easier detection of extremes. While the C/D ratio could theoretically be increased indefinitely, it can only be reduced to the zero point where the virtual hand completely stops moving. The high detection rates at the zero point show that it is much easier to detect whether a movement of the hand should take place than to judge the extent of the movement.

Previous evaluations of hand redirections by Zenner and Krüger [77] did not show any significant difference between upward and downward displacements of the hands. Additionally, they reported an earlier detection of increased movement gains over reduced movement gains, which they evaluated in a task where participants reached horizontally. Therefore, we assume our contrasting results originate from pushing down on a compliant object, showing that this affects the detection thresholds of C/D ratio manipulations. This is further supported by the finding that the stiffness of an object affects the illusions detection rate, which is discussed in the following Section 4.7.2.

Overall, these outcomes demonstrate we can greatly increase the C/D ratio to create our visual-haptic illusion, while we must remain conservative when using decreasing values.

4.7.2 Effect of Physical Stiffness on Illusion Detection. While DTs for reduced C/D Ratio remain fairly close, we see a larger effect of rendered Stiffness on the illusions detection when using increased C/D Ratio. The C/D Ratio at the DT of the illusion was 11% higher in the Hard condition (DT=3.93x) and 15% lower in the Soft condition (2.99x) compared to the Medium condition (3.52x). In total, the increase of the DT from the Soft to the Hard condition was 31%. These findings imply that the physical stiffness affects the detection of the illusion, with harder objects allowing bigger C/D ratio values to remain undetected by users. When using this illusion to interact with different objects with varying stiffness, these differences must be considered. Tailoring the gain to the physical object would allow for the greatest possible manipulation. When trying to choose a general value that can be used for many objects, a more conservative value should be chosen, such as the average of the three DTs (3.48x).

4.7.3 Overestimation. We observed a general overestimation of participants' hand movements when pushing compliant objects in VR. We base this on the results that non-manipulated hand movements were more often classified as incorrect than higher gains in hand movements. The effect of overestimating one's hand movements because of visual manipulation has been shown in Lecuyer et al. [39], where some participants were asked to draw their perceived push distance and tended to overestimate the actual physical distance. However, as far as we can tell, there have been no efforts so far to characterize this phenomenon further. We aim to provide the first step towards this by quantifying the distance between actual movement and the discrepant movement gain, which felt the most natural to participants while they were pressing on the compliant objects in VR. Figure 3b shows that the detection rates of the illusion in our experiment were lowest at the 1.8x point for the Soft, 2.22x for the Medium, and 2.34x for the Hard condition. These low points correspond to the amount of C/D Ratio that was perceived to match the actual hand movements most often. This results in a mean C/D ratio manipulation of 2.13x (SD=0.22). Because we did not see the consistent rejection of a C/D Ratio of 1 (no illusion) in the first block investigating reduced ratios (see Figure 3a), we suspect this bias to originate from the addition of larger C/D Ratio options and therefore be dependent on the frame of reference. As we know from prior literature [70], proprioception tends to drift without visual calibration over time. Furthermore, by measuring overshooting and undershooting during reaching tasks, Caballero [13] showed C/D ratio manipulations to contribute to this proprioceptive gain, which subsequently requires time to be thoroughly washed out when movements are again matching. However, in Caballero's work, increased and decreased C/D manipulations both caused this recalibration. We did not observe a proprioceptive gain during the decreased C/D ratio block. Nevertheless, the large amount of time spent in VR with often incongruent visual hand positions and movements might have played a role in the resulting overestimation. However, as our aim for this first study was to provide detection thresholds to inform the second evaluation of how the illusion affects stiffness perception rather than investigating this surprising phenomenon, our findings are not yet sufficient to draw final conclusions about the exact characteristics of this phenomenon.

Nevertheless, this overestimation might have effects beyond the detection of our investigated illusion. While it increases the viability of the proposed illusion, it also affects VR experiences that do not make use of any manipulation, as an objective match of movement was judged to be discrepant. Our finding that approximately double the movement gains feel more coherent than a true match of physical and virtual hands during pressing needs to be considered when designing any VR application containing compliant objects. Consequently, further research is required to gain deeper insights into the characteristics and origins of this phenomenon.

4.8 Summary

In the first study, we found three main effects. First, we found that a reduction of the C/D ratio was more easily detectable than increasing the ratio with respective detection thresholds of 0.66x and 3.48x the actual movement of the hand. Second, we showed that the stiffness of compliant objects has an effect on the detection rates of the illusion with harder stiffnesses resulting in a less detectable illusion. Third, we observed a general overestimation of hand movements in VR while pressing on the compliant objects, with a C/D ratio manipulation of 2.13x feeling more coherent to participants than no manipulation of hand movement gains.

5 STUDY II: MANIPULATION OF STIFFNESS

In the second study, we quantify the illusion's effect on perceived stiffness, determining how much softer or stiffer an object is perceived when applying the illusion. We are utilizing the Method of Constant Stimuli in a two-interval forced choice (2IFC) task using the same apparatus from the first study. This time, in addition to the C/D ratio manipulations, we also varied the actually rendered stiffness by predefined offsets (in %) from the reference stiffness. Pressing on the device two times in succession, participants were tasked to find out **"Which of the two objects felt stiffer?"**. One of the objects was rendered in the reference stiffness without C/D ratio manipulation, while the other had a variable C/D ratio and physical stiffness offset.

5.1 Procedure

The setup of the procedure remained the same as in the first study: We again adjusted the table for each participant (40cm below a participant's total height) and participants were standing in front of the haptic device on a standing desk mat, being able to see their dominant hand in the virtual environment. The training session consisted of two pushes without any C/D ratio manipulation. For the first push, the stiffness was set to the soft stiffness (249 N/m), and for the second push was set to the hard stiffness (544 N/m). Participants were then asked to compare the two stiffnesses and select the one they perceived to be stiffer. After confirming that they understood the task, the trials began. Pink noise was played over the headphones of the HMD. Each trial consisted of two sequential pushes, following the same process as in the first study. After the second push, a question was displayed, asking which of the two objects felt stiffer to them. Following the 2IFC paradigm, participants had to answer either *"First"* or *"Second"* by pressing the left or right button on the wireless presenter, and no other selection options were given. After answering the question, no feedback on the correctness of the answer was given, and the subsequent trial started. After 105, 210, 315, and 420 trials, participants took a break without any time limitations. The overall duration of the study was 81 minutes on average.

5.2 Study Design

The two objects of each trial that participants were asked to compare consisted of a reference object and a tested object. The physical stiffness was offset from the reference object, and the C/D ratio while pushing was manipulated. We varied three independent variables throughout the experiment:

Reference Stiffness The same three stiffnesses from the first study were picked as the stiffnesses of the reference object. These were Soft (249 N/m), Medium (363 N/m), and Hard (544 N/m).

Stiffness Offset For each Reference Stiffness, we considered seven values of stiffness for the test object that should be compared to the reference object. The seven values were -75%, -25%, -12.5%, 0%, 12.5%, 25%, and 75% of the respective Reference Stiffness. These offset percentages were determined by preliminary testing.

C/D Ratio Lastly, we also varied the C/D ratio when participants were pushing the test object. In addition to the threshold values found in the first study, we also considered intermediary values in the center between the thresholds and the value for no manipulation (C/D Ratio of 1). To be able to determine the effect of C/D Ratio on perceived stiffness, we also evaluated perceived stiffness with no manipulation (C/D Ratio of 1). This resulted in the following five C/D Ratio values being evaluated: 0.66x, 0.83x, 1x, 2.24x, and 3.48x the actual movement of the physical hand.

Each combination of Reference Stiffness, Stiffness Offset, and C/D Ratio was repeated 5 times. This resulted in a total of 525 trials per participant (3 Reference Stiffness × 7 Stiffness Offset × 5 C/D Ratio × 5 repetitions). All trials, as well as the order of reference and test object in each trial, were randomized.

For each trial, we measured the response of participants about which object they perceived to be stiffer (*"First/Second"*). We again asked participants to fill out a NASA TLX during each of the four breaks and after the last trial to assess their subjective workload. After the experiment, participants were asked to fill out a short questionnaire relating to their self-perception of their use of vision and haptics in the stiffness judgment tasks. They were asked to indicate their agreement with 6 statements on a 7-item Likert scale, going from 1 ('Do not agree at all') to 7 ('Completely agree'). The statements were presented to participants in randomized orders.

5.3 Participants

12 participants (5 female and 7 male) were recruited using convenience sampling. The participants' age was between 22 and 29 (M=25.9, SD=1.9). All participants were right-handed and had experienced VR before (2 participants below 2h, 4 participants between 2h and 20h, and 6 participants above 20h). They all had normal or corrected-to-normal vision and no known condition affecting the tactile or kinesthetic perception of the hand. We offered 15€ as compensation.

5.4 Results

For each participant and combination of conditions, we calculated the ratio of the test object being perceived as stiffer than the reference. For this, we divided the number of times the test object was picked as the stiffer object by the total number of repetitions for this combination (5 repetitions per combination). We averaged these rates across participants and plotted the results. We fitted the *Weibull cumulative distribution function* [71, 73] of the form:

$$w''(x) = 1 - e^{-(x/\lambda)^k} \tag{4}$$

Figure 4 shows the resulting functions for the different C/D Ratio values concerning the Soft (left), Medium (center), and Hard (right) Reference Stiffness. The Point of Subjective Equality (PSE) represents the point at which a test stimulus is subjectively judged to be equal to the reference stimulus. In our case, this is defined as the point where the tested object was judged to be stiffer or less stiff than the reference object with equal probability, which occurs at the 50% probability. Table Table 1 provides the PSE values for each C/D Ratio in relation to Reference Stiffness. The Constant Errors (CE) can be seen for the C/D Ratio of 1, where no illusion was added. The CE describes the offset between the actual objective equality of the test and the reference object and the subjective judgment of equality without the added stimulus. In our case, this is the offset between the point where a C/D Ratio of 1 (no illusion) was perceived to be equal to the reference and the point of actual equal stiffness (i.e., where Stiffness Offset was 0%). The CE is assumed to be present in every condition. Therefore, the actual effect of the illusion is shown by the distance between the respective PSE and the CE. We observed the largest increase of perceived stiffness in the Soft condition, where the PSE of a C/D Ratio of 0.83x and the CE (C/D Ratio of 1) differed by 8.91% (22 N/m). The largest decrease in perceived stiffness occurred in the Hard condition, in which a C/D Ratio of 3.48x was perceived to be 28.05% softer (-153 N/m). The averaged maximum increases and decreases of stiffness across the three Reference Stiffness conditions were 4.15% (at 0.83x) and -23.39% (at 3.48x), respectively.

The Stiffness Offset (in percent) of each PSE from the CE are shown in Figure 5. We fit a linear function for each Reference Stiffness ($f_{Soft}(x) = 10.69x - 13.18$, $f_{Medium}(x) = 6.15x - 4.90$, and $f_{Hard}(x) = 10.80x - 12.05$) and show the average trend ($f_{Avg}(x) = 9.21x - 10.04$) across all three.

5.4.1 Self-Perception of Senses Used in Stiffness Discrimination. Figure 6 shows the results of the subjective questionnaire regarding participants' self-perception of how they relied on their different senses when discriminating the stiffnesses. Q1 (M=6.17, SD=0.83) and Q2 (M=5.66, SD=1.30) both relate to the haptic perception being primarily used to discriminate the stiffness during the tasks. In contrast, Q3 (M=1.92, SD=1.31) and Q4 (M=2.17, SD=1.70) relate to vision being used primarily over haptics. Here, we can observe a clear preference toward the haptic sense rather than visual, meaning that participants think they primarily used their haptic sense over vision when judging the stiffness of the objects. Q5 (M=2.50,

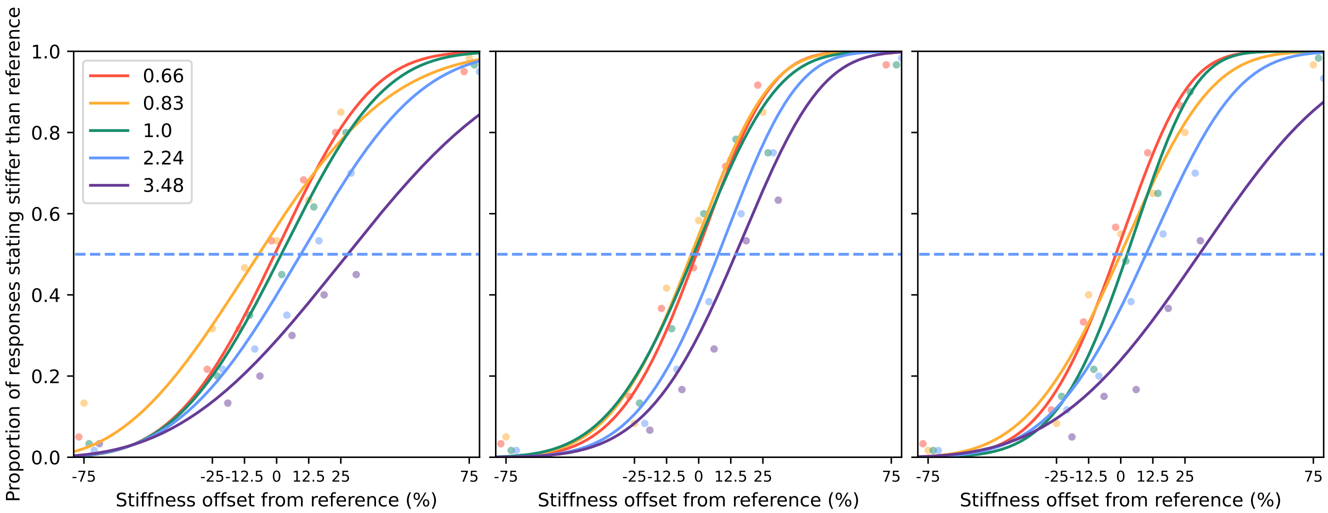


Figure 4: Fitted functions for the proportion of responses stating the manipulated object was stiffer than the reference object at different physical stiffness offsets (in %) for the different C/D Ratio values concerning the Soft (*Left*), Medium (*Center*), and Hard (*Right*) Reference Stiffness. The level for PSE (probability of 0.5) is indicated by a blue dotted line.

SD=2.02) shows low agreement with the statement that haptics and vision were used equally, while Q6 (M=4.25, SD=2.09) indicated a higher agreement with solely using one sense for stiffness judgment.

5.4.2 Subjective Workload. We again analyzed the TLX scores participants reported to find potential workload effects of the conducted tasks which might have to be considered. The TLX scores were M=26.60 (SD=15.17) for the first block, M=23.82 (SD=13.34) for the second, M=23.13 (SD=13.39) for the third, M=22.85 (SD=13.57) for the fourth, and M=22.57 (SD=16.61) for the fifth. The one-way RM-ANOVA revealed no significant effect, which leads us to assume that the workload caused by the tasks did not affect the results.

5.5 Discussion

The findings of the second study show a clear effect of the illusion on the perceived stiffness of compliant objects in VR. We can adjust the perceived stiffness to be softer to a higher degree than making it feel stiffer. We attribute this finding to the amount of C/D ratio manipulation that can be induced before detection, which we found to be a lot higher for increased gains than for reduced ones in the first study.

The subjective assessment of how participants thought they were discriminating stiffness during the experiment revealed the haptic sense to be clearly preferred over vision. This means that participants still thought they were judging stiffness primarily via haptic feedback rather than visual cues. This supports the idea

Table 1: PSE values (as stiffness offsets in % from the Reference Stiffness) for each C/D Ratio. The values for C/D Ratio of 1 correspond to the CE. The largest PSE distances are -7.06 for a C/D Ratio of 0.66x and 30.56 for a C/D Ratio of 3.48x.

C/D Ratio	Soft	Medium	Hard
0.66x	−0.74	−0.88	−1.88
0.83x	−7.06	−2.88	−0.06
1.00x	1.85	−1.92	2.51
2.24x	9.38	7.69	9.84
3.48x	27.64	14.41	30.56

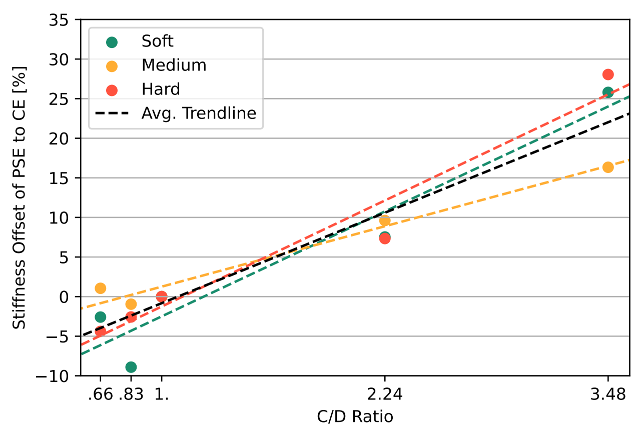


Figure 5: Fitted linear functions for the relation between C/D Ratio and the Stiffness Offset of their PSE from the CE (C/D Ratio of 1) for the Soft (*Green*), Medium (*Yellow*), and Hard (*Red*) condition. The vertical axis describes how much increased (+) or decreased (-) physical stiffness was necessary to compensate for the illusion and achieve the same perception of stiffness as the no illusion (CE) condition.

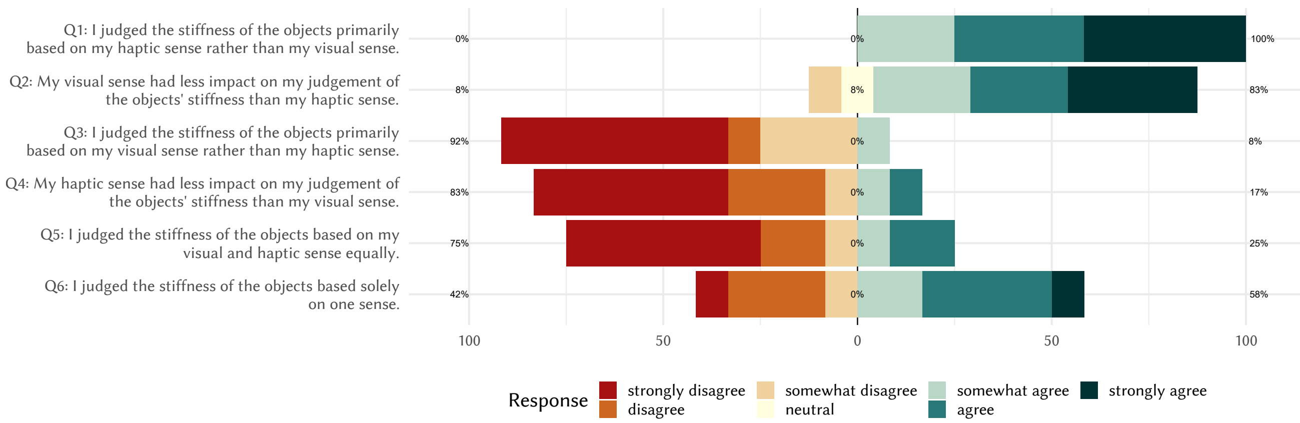


Figure 6: Results of the 7-item likert questionnaire regarding the self-perception of which sense(s) participants used primarily when judging the stiffnesses. On the left, the 6 posed statements are shown. On the right, the corresponding responses of participants are shown. The given values on the left, center, and right sides of the plot show the amount of negative, neutral, and positive answers.

that the found effect on stiffness is caused by an altered haptic perception based on the integration of vision and haptics (i.e., a haptic illusion), rather than a visual judgment of stiffness.

We found the highest increase of perceived stiffness for a C/D ratio of 0.83x the actual movement, rather than the ratio of 0.66x, in which the virtual hand moved even less. A possible reason for this might be that the illusion at a C/D ratio of 0.66x, being right at the determined DT of the illusion, still may have been detected in some cases, resulting in the visual perception being trusted less. Therefore, participants would have judged the stiffness more based on their haptic perception in those cases, whereas a C/D ratio of 0.83x still induced the illusion successfully. To verify if and how much occasional detection affects the overall effect on stiffness perception requires further investigations.

The overall trends displayed in Figure 5 allow us to map the effect of the C/D ratio on stiffness perception. This allows designers of VR experiences to modulate the stiffness of objects based on their needs by applying the respective C/D ratio manipulation. For a general approximation, designers can follow the averaged function $f_{Avg}(x) = 9.21x - 10.04$. For instance, if an object is required to be 10% softer, this results in a needed C/D ratio manipulation (x) of 2.18 the hand's actual movement. For more accurate calculations based on the physical stiffness of the initial object, one can refer to the individual functions for each Reference Stiffness provided in Section 5.4.

5.6 Summary

In the second study, we showed that the illusion affects the stiffness perception of compliant objects in VR. We showed that participants perceived the objects to be up to 28.1% softer and 8.9% stiffer with the application of the illusion. Furthermore, we provided a model to map the manipulation of C/D ratio to the perceived offset in stiffness, allowing designers of VR experiences to adjust the stiffness of objects based on their individual needs.

6 GENERAL DISCUSSION & GUIDELINES

In our two experiments, we have shown that our proposed illusion is able to change the perceived stiffness of objects without being detected by users. This opens up many possibilities for improving passive and active systems and enables wide applicability. In this section, we discuss the implications of our results together with guidelines for future use.

6.1 Enhancing Maximum Stiffness of Low-Force Devices

To date, visual-haptic illusions were only used to *decrease* the perceived stiffness of objects [37, 49, 74]. While we also saw a larger effect for decreasing stiffness in our experiment, the results still proved an *increase* of up to 8.9% for the softer condition. Since the illusion can be applied without many constraints, this could, for example, increase the maximum stiffness of active devices which, by design, can produce no or only low force. One example of such devices is ungrounded encounter-type interfaces, such as safe-to-touch drones [1, 3, 28]. These are very mobile, but the lateral forces they can apply are very limited. Another example is mid-air interfaces, where tactile feedback is provided by ultrasonic arrays [52]. However, further research is needed to determine how the complete lack of kinesthetic feedback in these systems would affect the illusion and vice versa.

6.2 Use with Everyday-Life Objects

To show the applicability of the illusion for passive everyday-life objects and to provide a frame of reference to the stiffnesses we investigated and the changes our approach can induce, we collected and calculated the stiffnesses of some commonly available materials (see Table 2). For the simulation of stiffnesses in our experiment, we employed a spring model with a constant ratio of input force

Table 2: Reference and sample stiffness values: Stiffnesses were calculated for a hypothetical 10cm object height with a cross-sectional contact area similar to the fingertip contact area [44]

Element	Stiffness (N/m)	E (Mpa)
Brain [54]	33.40	0.01
Pillow [54]	180.36	0.05
Skin Tissue [24]	200.40	0.06
Foam (Polyurethane) [46]	233.80	0.07
Reference Soft	249.00	0.07
Reference Medium	363.00	0.11
Human Finger [30]	400.00	0.12
Reference Hard	544.00	0.16
Soft Plastic (Nylon) [30]	760.00	0.23
Wood [30]	5600.00	1.68
Steel [30]	120000.00	36.00

to displacements (N/m). We chose the approach to minimize possible confounding variables and to enable meaningful comparisons. However, everyday-life objects cannot be fully represented by these models. To nevertheless enable a comparison to materials for which we found no stiffness in the literature, we calculated their stiffness based on their Young's modulus (E) by assuming an object of 10cm height which is pressed with a contact area resembling the area of a fingertip [44].

As is apparent from the table, the physical stiffnesses that we simulated as references in our experiment are fairly soft. We opted for this approach so that participants would not get too fatigued (or even injured) throughout the numerous trials. Additionally, increasingly hard materials become less and less distinguishable. An example of this is Wood (5600 N/m) and Steel (120000 N/m). Although their objective stiffness values differ by order of magnitude, it is difficult to distinguish them in real life on the basis of stiffness alone.

6.3 Range

In situations where a wide range of possible stiffnesses is desired, we recommend the use of props or devices that provide stiffness in the upper range of the required range. The illusion can then simulate objects that are up to 28.1% softer. When multiple props with different stiffnesses are used, the combined effect of increasing and decreasing the stiffness of each prop can fill a larger gap between physical stiffnesses through the illusion. The provided function allows calculating offsets of stiffness that can be achieved by the illusion ($f_{Avg}(x) = 9.21x - 10.04$). This can be used to approximate the needed number and predefined stiffness of props to cover a specified range of stiffnesses completely.

For example, to cover the whole range between our Soft (249 N/m) and Hard condition (544 N/m), we only require the use of 3 physical props. Since we aim to cover the biggest possible range while the illusion should remain undetected, we choose the lower (0.66x) and upper (3.48x) detection thresholds we found in our first study, which results in a stiffness offset of 3.96% stiffer and 22.01% softer for each physical object. Using these, we can then find adequate physical stiffnesses to cover the gaps between them, resulting in 3 required physical props with stiffnesses of 319 N/m, 426 N/m, and 567 N/mm. Similarly, we can determine that a single physical object made of Polyurethane foam could be altered to also simulate the stiffnesses of a Pillow and Skin Tissue as presented in Table 2. To bridge the gap between Foam and Soft Plastic, which is over 3 times stiffer, we instead would require 4 physical props (303 N/m, 409 N/m, 551 N/m, 744 N/m). While we can also speculate about the relationship between much stiffer and softer ranges, we only evaluated the illusion's effect in a specific space. The lowest and highest stiffnesses, which were perceived to be equal to the respective reference stiffnesses were 226.81 N/m and 696.59 N/m. The illusion's effects beyond these limits require additional investigations. The ranges we showed demonstrate the wide applicability and range of stiffnesses that can be simulated using the technique we proposed and evaluated. This gives designers of VR applications greater freedom and opportunities to enhance the haptic experience in VR.

Figure 7: Examples of possible setups where the proposed illusion may be applied.

6.4 Real-World Applicability

The presented illusion can be applied to a variety of haptic feedback devices to enrich the haptic experience in VR. As one example, the illusion can enhance the variability of custom-build passive devices (see Figure 7 left). We used off-the-shelf dampers, which can be adjusted to different stiffnesses by preloading the contained springs. We 3D-printed custom plates that allowed us to add dampers in variable numbers and constellations, resulting in a wide range of possible predefined stiffnesses. For usage in VR, we added reflective markers and an optical tracking system to allow for more precise calculations of pressing distance. Second, we can leverage the illusion in combination with common everyday items (see Figure 7 middle) to stand in for a variety of virtual objects. For this, the contact with the physical object and the pressing distance is calculated using the positional information of the optical hand-tracking system. While this tracking might be less precise, this approach does not rely on any additional hardware being added other than the chosen passive objects, allowing for rapid and easy development of haptic VR experiences. Finally, our presented illusion can enhance active haptic devices by applying it to a grounded encounter-type haptic device in the form of a serial manipulator arm (see Figure 7 right). These devices can position their end-effectors accurately and are able to produce constant forces. However, their motors lack the refresh rate to simulate convincing stiffnesses. We compensate for this by using the illusion to apply the sensation of different stiffnesses while pressing against the robot's end-effector.

7 LIMITATIONS & FUTURE WORK

While we are confident that this work provides valuable insight into the efficacy and applicability of the presented visuo-haptic illusion for altering the perceived stiffness of objects in VR, the design of our experiments imposes limitations that raise important questions for future research and development.

7.1 Interaction Task

In this work, we limited the exploration task for discriminating stiffness to the index finger of the dominant hand. We opted for this approach as it is one of the main ways we distinguish stiffnesses in our everyday lives [40]. However, we acknowledge that other ways to discriminate stiffness might yield other results. These include pinching with the thumb and index finger or pressing with multiple fingers. These will add new levels of complexity, such as the pressure distribution between the various fingers.

Additionally, for the scope of this work, the height of the interaction platform was kept constant in relation to participants' heights to minimize confounding factors. Zenner and Krüger [77] showed hand redirection in the direction of gaze to result in higher detection thresholds in comparison to vertical or horizontal redirection. Consequently, we assume that different visual angles resulting from different platform heights could affect the detection and efficacy of the investigated illusion. The lower the interaction takes place, the closer the angle of interaction becomes to the gaze direction, which in turn could potentially increase the detection thresholds and the resulting impact of this illusion. Similarly, proprioceptive localization of hand positions has been shown to be more precise closer to the shoulders than at more distant points [67]. We, therefore, assume the detection of the location offset caused by the illusion to be harder to detect at lower positions further away from users' shoulders. However, these hypotheses on the impact of the height of the interaction on detection rates as well as the resulting effect on stiffness perception require further study.

7.2 Additional Influences on Stiffness Perception

We deliberately excluded visual and tactile deformation cues from our investigation to focus solely on the (undetected) hand displacement. This was done to provide a solid baseline of the effect of this illusion without too many additional confounding factors. However, prior work has already demonstrated that the addition of visual deformation can influence stiffness perception outside the context of VR [37, 49, 74]. We assume that the integration of visual deformation cues into our approach will similarly cause the interacted objects to be perceived as less stiff, thus enabling the stiffness simulation of even softer objects. The interplay and resulting effective range of the combination of these visuo-haptic illusions warrants further investigations. Furthermore, tactile deformation cues, i.e., the skin deformation occurring during the indentation of a surface, may additionally affect the stiffness perception and discrimination. Srinivasan and LaMotte [61] and Bergmann Tiest and Kappers [10] showed that tactile cues alone are not sufficient for accurate discrimination of stiffnesses of objects with rigid surfaces, such as is the case in our conducted experiments. They attribute this to the fact that the pressure distribution over the contact area of the finger does not change when there is no surface indentation. However, they found tactile information to dominate over kinesthetic information for the accuracy in discriminating stiffnesses of objects with deformable surfaces. The addition of tactile deformation would therefore increase the reliability of the haptic sense in discriminating stiffness. Following Ernst and Banks [21], who showed haptic and visual cues to be combined based on a maximum-likelihood estimate, the higher reliability (less variance) of tactile information in this discrimination would lead to a lower weighting of the visual perception in the combined percept. As we are manipulating visual representations to induce the illusion, we, therefore, assume the effectiveness of the illusion to be lowered by the addition of tactile deformation cues. However, because the provided illusion does not impede the users' hands and fingers directly, it is possible to integrate it with methods simulating deformation and nominal forces using cutaneous deformations [50, 51, 55, 57, 58]. Overall, the inclusion of tactile and visual deformations corresponding to either the actual physical properties or the targeted manipulated perception could lead to many new insights for researchers and opportunities for designers of VR applications.

Additionally, the surface topology may have an influence on stiffness perception. Consequently, during our experiments, the surface texture was not altered to prevent any possible confounding effects. Bergmann Tiest [9] speculated that a rougher surface might slightly increase its perceived stiffness, due to more intense sensations during pressure exertion caused by the sharp points on the material. However, Kang et al. [33] did not find a clear tendency of rougher surfaces to be perceived as more or less stiff across participants but did show that the perception of stiffness changed. Future research into this relationship between surface properties and stiffness perception would be valuable.

7.3 Overestimation Effect

Finally, our initial investigation of detection rates and thresholds of the presented illusion revealed an interesting and surprising phenomenon. Participants appeared to overestimate their performed hand movements in VR, rejecting congruent visual hand movements in favor of larger C/D ratios. Because we did not aim our studies at finding this effect, the detection rates we observed around these C/D ratios might potentially be inaccurate and could have been influenced by our study design choices. Therefore, we can only provide a first step towards characterizing this phenomenon and can only speculate about its origin. Future research may focus on gaining deeper insights into this by adjusting the maximum and minimum C/D ratios being provided, the amount of time being spent in VR, and the duration of the training phase. Additionally, more values around the actual area where this phenomenon was observed (between a C/D ratio of 1 and 2) should be tested and the results may be compared to ones obtained by other psychophysical methods. This overestimation effect occurred in participants irrespective of whether they started with the reduced or increased C/D ratio block (see Section 4.4) and prior work solely evaluating increased C/D ratios did not find a similar effect [2]. Nevertheless, combining or alternating reduced and increased C/D ratios might reveal further insights into this phenomenon.

8 CONCLUSION

In this paper, we presented a novel approach to altering the perception of stiffness by manipulating the C/D ratio of users' hand movements while pushing on compliant objects. Through two controlled experiments, we assessed the detection ranges and the impact of the visuo-haptic illusion on the perceived stiffness. We found that we can alter the perceived stiffness of objects to be up to 28.1% softer and 8.9% stiffer without the illusion being detected by users. Therefore, our work contributes to the body of work on haptic stiffness and can be used as a low-cost option to extend the range of applications of active or passive haptic feedback systems.

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