Manipulating Stiffness Perception of Compliant Objects While Pinching in Virtual Reality

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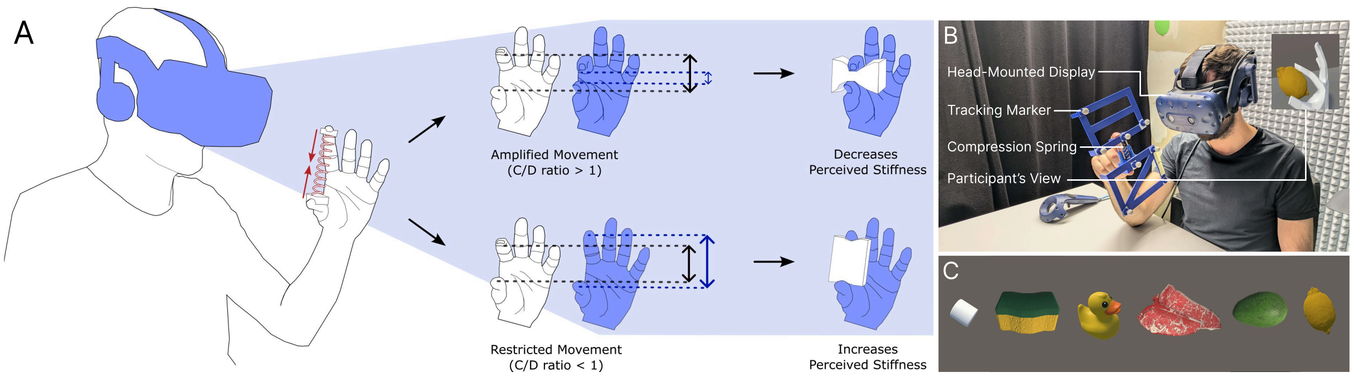

Figure 1: We investigate a visuo-haptic illusion to alter the perceived stiffness of objects in VR. (A) By amplifying or restricting the visual representation of users' index finger and thumb movement during the pinching of a compliant object, we can create the sensation of a softer or harder virtual object. To evaluate this concept, we built an experimental setup (B) consisting of three custom 3D-printed physical prototypes with compression springs, an optical tracking system, and a VR system. We applied this illusion to a variety of virtual objects (C) determined through a pre-study survey.

Abstract

Providing users with realistic sensations of object stiffness in virtual environments remains challenging due to the intricacies of our haptic sense. We investigate the use of a visuo-haptic illusion to alter the perceived stiffness of hand-held objects in virtual reality. We manipulate the Control-to-Display ratio of the index finger and thumb movements during pinching to make virtual objects feel softer or harder. We evaluated this approach on a variety of haptic representations and visualizations we selected through a pre-study survey (N=24). Results of our user study (N=20) demonstrate that this method effectively and reliably modifies stiffness perception, bridging gaps of 50% in physical stiffness without adversely affecting the visuo-haptic experience. Our findings offer insights into how different visual and haptic presentations impact stiffness perception, contributing to more effective and adaptable future haptic feedback systems.

CCS Concepts

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

Keywords

haptic illusions, pseudo-haptics, virtual reality, pinching

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1 Introduction

In our daily lives, we highly rely on our perception of stiffness, from checking the freshness of fruits and vegetables, wringing out a wet sponge, to adjusting our grip to a plastic or glass bottle. While current virtual reality (VR) and extended reality (XR) systems offer exceptional visual and auditory experiences, this fundamental haptic aspect is generally absent or substituted by simple vibrations, compromising the overall experience with these systems. To overcome this limitation, researchers devised grounded robots [48], hand-held devices [8, 18], and wearables [14, 30] that try to emulate various stiffness levels accurately. Due to the intricate nature of object compliance, these systems are often expensive, bulky, and complex, making them less practical for widespread use and constraining the user's interactions. Another approach involves using physical props to provide haptic feedback in virtual environments [34, 66]. While they can offer realistic experiences when resembling virtual objects closely, they lack adaptability and cannot dynamically adjust their stiffness for different scenarios, limiting them to specific use cases. To increase the variability of passive haptic props, researchers investigated visuo-haptic illusions (VHIs), which have been proven effective in adapting the perceived stiffness of virtual objects by adjusting visual stimuli, such as deforming surfaces [51, 67] or visually manipulating hand movements [65]. These approaches primarily focused on adjusting the perceived stiffness of objects when pressing from one side onto a surface. While this is a common method of testing the stiffness of larger or grounded objects, such as couch cushions or mattresses, this is not the main procedure to evaluate smaller objects or those held in hand, e.g., fruits and vegetables, cups and bottles, or flexible containers and packaging. These objects are typically evaluated by pinching them between the index finger and thumb [21, 46]. Prior work [13] adapted visual deformation cues to pinching, making hard objects appear more compliant through object and hand deformations. This shows the potential of VHIs for hand-held props. However, their technique only allows for reductions in perceived stiffness and is limited to fully rigid objects. Ban et al. [6] instead used semi-real-time (25 FPS) image detection and manipulation to apply visual object displacements and hand distortions on a screen covering the real interaction. Their findings demonstrated that such a VHI could both increase and reduce the perceived stiffness of a cuboid object with static compliance. However, it remains uncertain how well this method generalizes to immersive environments with direct (in-)hand interactions or realistic contexts with varied object appearances and characteristics. In general, the field still lacks a foundational understanding of how variations in visual and haptic representations influence the perceptual changes elicited by VHIs, which constrains the ecological validity of current techniques.

To address these gaps, we investigated the use of a VHI to both decrease and increase the perceived stiffness of pinched objects in VR. Our approach involved a diverse set of visual object appearances and physical base stiffnesses. To achieve changes in perceived stiffness, we manipulated the Control-to-Display (C/D) ratio of the index finger and thumb movements in VR during the pinch. This allowed us to increase or decrease the visually displayed pinch movement of both fingers relative to their real movements. Analogous to established approaches using screen-based systems [6, 45] or manipulations of the entire hand movements in VR [65], we expected these manipulations to influence the perceived stiffness of the object being pinched, with amplified and restricted movements eliciting a respective decrease and increase in stiffness.

We contribute the findings of an online survey with 24 participants (section 3) and an experimental user study conducted on 20 participants with diverse visual and haptic object representations (4 & 5), which show the VHI reliably modifies stiffness perceptions (6.1) without adversely affecting the virtual experience (6.2). Further, we provide general insights and recommendations for VHIs based on our discoveries relating to the confounding influences of more lifelike visualizations and haptic presentations, such as anticipatory biases and overestimation effects (6.3 & 6.4).

2 Related Work

Our work builds on extensive research in haptic rendering, particularly stiffness feedback. We review approaches using active devices (2.1), psychophysical studies on visuo-haptic stiffness perception (2.2), and VHIs for enhancing feedback in HCI (2.3).

2.1 Active Stiffness Rendering

With the ubiquity of vibrotactile actuators in modern devices and systems, many approaches to simulating stiffness naturally rely on vibration feedback to convey sensations of stiffness. These include vibration feedback applied to hand-held devices [2, 19], wearables [47], and grounded encounter-type devices [63, 64]. Rather than directly mapping vibration amplitude to force, Kildal [40] proposed rendering grain-like vibrations modulated by input force, an approach later extended to electrotactile stimulation [35] and deformation-based interactions [32, 33, 41]. While such methods demonstrate that vibration can modulate compliance perception, vibrotactile feedback alone cannot replicate high-fidelity stiffness due to the physiological mechanisms underlying force and stiffness perception [36, 42]. Realistic force and stiffness rendering is commonly achieved using grounded robotic devices such as the PHANToM [48], Touch X[1], and Omega[2]. These stationary systems deliver high-frequency force feedback via a handheld end-effector, enabling realistic haptic interactions but limiting mobility, workspace, and the ability to simulate soft object interactions in hand. To overcome these constraints, researchers have developed hand-held [8, 18] and wearable [14, 30] haptic devices that apply active forces to the fingers, offering richer feedback than vibrotactile systems. However, their bulky, tethered designs restrict interaction and obscure other tactile cues. Finger-mounted devices [53, 62] present a lighter, less obtrusive alternative by applying shear or normal deformations to the fingertips or phalanges. While less restrictive, these devices are limited to cutaneous feedback and still require continuous wear. To overcome the restrictions that added hardware inherently imposes, research increasingly investigates sensory illusions as an alternative approach to alter the subjective stiffness of objects.

2.2 Multisensory Stiffness Perception

We naturally rely on multiple senses during real-world object exploration, leading to crossmodal interactions. Ernst and Banks [23] describe this integration using a maximum-likelihood estimation model, where sensory inputs are weighted by their reliability. As a result, vision can influence or even override haptic perception when it provides more reliable information. Although the exact integration model remains debated [42], visual dominance is frequently observed in multisensory tasks [56]. Stiffness perception involves both force and displacement cues [42], with haptics better suited to force detection and vision often more precise for displacement. Consequently, visual input strongly affects perceived stiffness. In a magnitude estimation study, Drewing et al. [22] found that participants judged objects as softer when observing others' interactions compared to blindfolded self-touch, and self-observation produced intermediate ratings, slightly biased toward vision. This visual influence intensifies under incongruent conditions: Srinivasan and LaMotte [57] demonstrated that mismatched visual and haptic feedback led participants to rely heavily on visual cues when judging stiffness. These cross-modal interactions triggered research into the

[1]https://de.3dsystems.com/haptics-devices/touch-x, last accessed: 2025-01-30
[2]https://www.forcedimension.com/products/omega, last accessed: 2025-01-30

intentional manipulation of haptic information using of sensory illusions, often called pseudo-haptics.

2.3 Visuo-Haptic Stiffness Illusions

Lecuyer et al. [45] introduced pseudo-haptic feedback by visually modulating spring deformation on a screen, allowing users to perceive different virtual stiffnesses using a device with constant resistance. Since then, VHIs have been used to alter various haptic properties, including shape [7], size [10], weight [54], temperature [31], and surface properties [25] (see [44] for a comprehensive overview). For stiffness, a pervasive approach is manipulating visual deformation during object indentation [4, 39, 43, 51, 67], biasing perceived displacement and, consequently, stiffness. Alternative approaches rely on subtle manipulations of the Control-to-Display (C/D) ratio of users' movements in VR [13, 16, 27, 65], a technique also used to redirect hand motions in passive [5, 17] and active haptic systems [1, 29]. Building on this, Weiss et al. [65] adjusted the physical-to-visual movement ratio while users pressed a haptic device with constant stiffness, effectively altering perceived stiffness. Similar techniques have been applied to modulate perceived knob resistance [27] and terrain stiffness through foot displacement [16]. Across studies, users remain unaware of the distortions yet perceive altered object properties. While pressing is common for assessing stiffness [46], in handheld contexts, people typically use index-thumb pinching [21, 46]. Further, pinching has been shown to be an accurate and efficient general input method [55]. Visual deformation cues during pinching can make rigid props feel compliant [13], though prior work focused only on reducing stiffness in rigid materials. Similarly, Ban et al. [6] showed that visually distorting a pinched object and the corresponding hand pose altered stiffness judgments in a screen-based setup with compliant cuboids. Yet it remains unclear how such effects transfer to VR with direct in-hand interaction. More broadly, existing visuo-haptic studies have mostly examined abstract virtual objects, leaving the role of object appearance and users' expectations underexplored.

We extend prior work with a VHI that adjusts the C/D ratio of virtual finger movements during pinching of compliant materials, visually amplifying or restricting displacement to decrease or increase perceived stiffness [6, 45, 65]. To improve ecological validity, we test the illusion across diverse object visualizations and base stiffnesses, examining its impact on effectiveness, perceived congruency, and consistency with anticipations from real-life experiences.

3 Pre-Study - Stiffness Anticipations

To uncover how VHIs might fare in future realistic contexts, we sought to explore how they might be affected by users' expectations, as related studies predominantly focus on abstract settings. While objective metrics related to stiffness (e.g., Young's modulus) exist, they are not directly transferable to the human's subjective stiffness perceptions [9]. Further, expectations regarding the stiffness of different objects can vary greatly depending on human mental models and experiences [20]. Therefore, to provide a diverse representative sample of object appearances for the main study, we identified the stiffnesses expected of different everyday objects through an online survey. We selected 50 soft objects we commonly interact with in our everyday lives, such as fruits and vegetables, tubes and bottles, or objects made of foam or soft fabrics. These objects were carefully chosen during initial brainstorming sessions to represent a wide variety of items with various levels of stiffness with which people should have previously interacted. Each item was presented as a picture of a 3D-rendered model with a caption stating the item's name. 3D models were selected based on their render quality and details to achieve an approximate uniform level of abstraction among all objects. We then asked participants to rate how hard they expected the presented objects to feel when squeezed on a subjective scale from 0 (Soft) to 100 (Hard). All 50 objects were presented to each participant, and their order was randomized. We recruited 24 participants (18 female and 6 male), aged 18 to 68 ($M = 29.33, SD = 11.42$). Participants took an average of 6.56 minutes to complete the online questionnaire and received no compensation.

Results. The mean anticipated stiffness ratings spanned from 14.83 ($SD = 13.22$) for a marshmallow to 80.88 ($SD = 20.22$) for a bike tire. All 50 items were ranked according to their mean ratings and subsequently partitioned into groups. As the ratings were derived from prior experience rather than calibrated against an absolute reference, we did not apply fixed threshold values. Instead, to obtain a representative distribution across the stimulus set, the items were divided into three approximately equal groups: Soft (16 lowest-rated objects), Hard (16 highest-rated objects), and Medium (the remaining 18 objects). The distribution of expected stiffness of all objects is shown in Figure 2. From each of the three groups, we selected two items to include as virtual objects in the main study. When selecting the objects, we considered whether the objects would be comfortable to interact with by pinching with the index finger and thumb while remaining versatile in terms of texture, weight, and shape. The six virtual objects derived were a marshmallow ($M = 14.83, SD = 13.22$) and a sponge ($M = 20.08, SD = 19.09$) to represent the soft group, a rubber duck ($M = 49.92, SD = 18.72$) and raw meat ($M = 51.17, SD = 16.26$) to represent the medium group, and an avocado ($M = 59.13, SD = 22.13$) and a lemon ($M = 64.88, SD = 12.86$) for the hard group.

4 Study Design

We conducted a controlled experiment to evaluate the impact of C/D ratio manipulations of index finger and thumb movements during pinching in VR. Participants were tasked to pinch a virtual object between their fingers, which was haptically represented by a compliant prototype using compression springs. During pinching, we broke the one-to-one mapping of real and virtual movement by amplifying or decreasing the visual movement of the index finger and thumb. We employed this VHI on various visual and haptic representations of objects. With this, we aim to answer the following research questions: (**RQ1**) How do C/D ratio manipulations while pinching affect the perceived stiffness of compliant objects in VR? (**RQ2**) How do these manipulations influence the congruency and consistency of the visuo-haptic experience? (**RQ3**) How do different visualizations and haptic representations of objects influence the effect of the VHI?

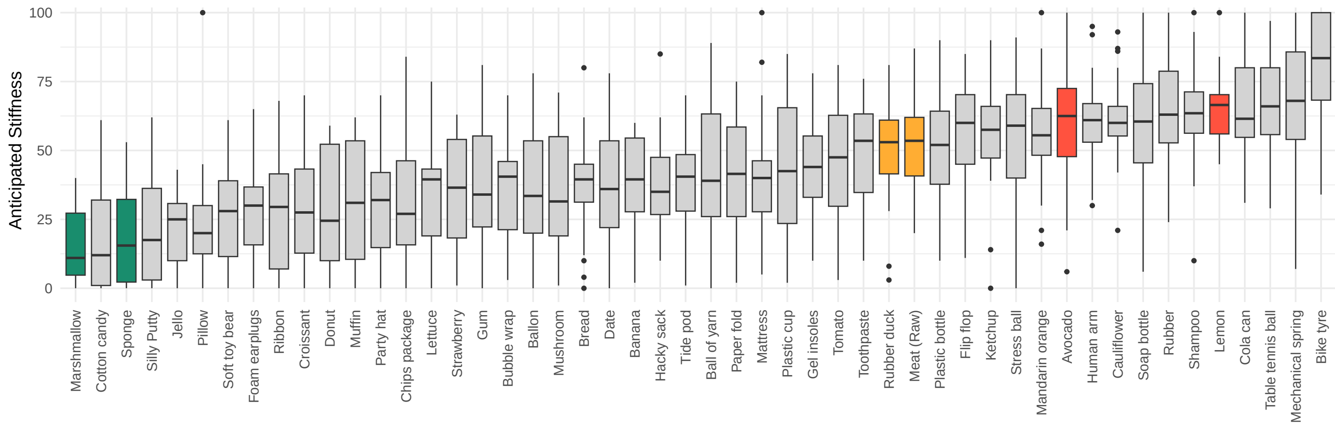

Figure 2: Anticipated stiffness ratings from 0 (Soft) to 100 (Hard) of the objects presented in the online survey. The objects chosen for the main study are highlighted in green (representing the soft group), orange (middle group), and red (hard group).

4.1 Stimuli

We employed a within-subject design and varied three independent variables: The visualizations of the virtual objects (OBJ), the actual stiffness of the pinched prototypes (PHYS), and the C/D ratio of the index finger and thumb movements during the pinch (C/D). Their combination resulted in a total of 90 conditions per participant (3 PHYS × 6 OBJ × 5 C/D). The order of trials was randomized.

OBJ. We use six different visualizations of virtual objects shown in Figure 1C. These were determined based on the pre-study (section 3) to evoke different levels of anticipated stiffness based on participants' prior experiences. These familiar visualizations may invoke biases that may impact the effect of the VHI, which would be overlooked in abstract settings using simple primitives. The visualizations are, in ascending order based on mean anticipated stiffness: (1) marshmallow, (2) sponge, (3) rubber duck, (4) raw meat, (5) avocado, and (6) lemon.

PHYS. To evaluate the impact of physical base stiffnesses on the VHI's effect, we selected three evenly distributed levels represented by mechanical springs: 1.085 N/mm for the soft condition, 2.170 N/mm (2x 1.085 N/mm) for the medium condition, and 3.255 N/mm (3x 1.085 N/mm) for the hard condition. These values were selected independently of the pre-study and were not intended to replicate the stiffness of the visualized objects, as complex geometries composed of heterogeneous materials cannot be adequately approximated by linear spring models. Instead, the chosen stiffness levels and the maximum compression depth (15 mm) were determined through preliminary testing to ensure that the conditions were perceptually distinguishable while avoiding excessive participant fatigue or discomfort. Our maximum required forces (3.255 N/m × 15mm = 48.825N) remain well below the average voluntary pinch strengths of adults (cf. [59]).

C/D. As our third independent variable, we modulate the C/D ratio of participants' finger movements during the pinch. While participants are compressing the physical object in their hand, we manipulate the hand poses by visually increasing or decreasing the index finger and thumb movement during the pinching motion. This results in the pinch being visually represented as stronger (i.e., index finger and thumb are visually closer together) or weaker (i.e., index finger and thumb are visually farther apart than they physically are). This concept is visualized in Figure 1A. For example, adjusting the C/D ratio to 2× and letting participants compress the physical object by 1cm results in the visual representation showing the hand compressing the object by 2cm. The deformation of the virtual object is adjusted accordingly so fingers do not cut inside or hover around the object. We determined our levels based on boundaries investigated in similar works on C/D ratio [10, 24, 26]. We evaluated two decreased (0.5× and 0.75×) and two increased C/D ratios (1.5× and 2×) in addition to a control condition in which physical and visual movements are congruent (1×). In total, we, therefore, included five levels of C/D ratios: 0.5×, 0.75×, 1×, 1.5×, and 2× of the actual finger movements.

4.2 Measurements

For each trial condition, we asked participants to rate the perceived stiffness, visual and haptic stimuli congruency, and consistency with real-life expectations. Because these aspects rely on subjective relative assessments, we used visual analog scales [37] without a reference, using the following questions and statements: (**Q1**) While squeezing, how hard did the object feel (*soft* to *hard*)? (**Q2**) While squeezing, the visual and haptic sensations matched (*completely disagree* to *completely agree*). (**Q3**) While squeezing, the object felt consistent with my real-life experiences (*completely disagree* to *completely agree*). After the trials, we invited participants to a voluntary semi-structured interview. We additionally asked participants to self-assess their reliance on vision and haptics during judgment (c.f. [65]). As these results were not central to our main analysis, we report them in the supplementary materials (see section 9).

4.3 Apparatus

To present accurate linear stiffnesses, we created three physical devices, each consisting of two 3D-printed frames with rounded indents to place the index finger and thumb. The frames are connected by three pistons, with either one, two, or three compression springs[3] attached depending on the PHYS conditions they represent. To provide reliable tracking of participants' pinch, we used OptiTrack[4], a highly accurate optical tracking system reporting errors of less than 0.1mm [55]. We attached eight retro-reflective markers to each device and set up an OptiTrack V120:Trio tracking system approximately one meter from where the interaction occurred. We created the virtual environment using Unity3D and deployed it to two computers[5]. The virtual environment was displayed on an HTC VIVE Pro at 90 FPS and synchronized with the tracking of the Optitrack system to ensure that virtual objects followed the physical devices. The virtual objects were presented to be located between the participant's thumb and index finger while holding the physical devices. The participant's right hand was shown as a low-poly hand model. After preliminary tests, we opted against using hand tracking to display participants' hand poses due to tracking inaccuracies of these systems. Instead, we manipulated the skeletal hand pose of the virtual hand representation based on the compression of the physical devices, which are tracked more reliably and accurately. Participants were seated in front of a table set to a height of 70cm and interacted with their right hand. An HTC VIVE controller was placed on the table, with which participants could answer the questions prompted during the experiment using a virtual laser pointer. The setup is shown in Figure 1B.

4.4 Procedure

After we welcomed the participants and informed them about the study's objective and data processing procedure, we asked them to sign a consent form and fill out a questionnaire regarding their demographics. Afterward, participants sat on a chair, which was adjusted for each participant to ensure they could comfortably interact with the physical prototypes. Then, participants put on the head-mounted display (HMD) and were informed about their task by text prompts in the virtual environment. Each trial consisted of the same steps: First, participants had to position their right hand on the table. The experimenter then placed one of the three physical devices directly into the participant's hand between the index finger and thumb. Participants saw a virtual object between their fingers and were tasked to lift it up and hold it in a predefined spot in mid-air. The correct position and pose had to be held for one second to control for lifting height and finger orientations, as these factors could affect stiffness perceptions. Afterward, the participants were instructed to squeeze the object fully once. During this pinch, the index finger and thumb of the virtual hand representation either moved congruent to the real fingers or had an increased or decreased movement depending on the C/D conditions. The virtual object deformed accordingly to ensure the fingers do not visually clip through the object or hover above its surface during the pinch. After the object was compressed by 15mm, the participants were prompted to release the pressure and return it to its original position on the table. Participants then released their grip from the physical device and picked up the HTC VIVE controller with the same hand. The three questions were displayed in front of the participants, each with a two-dimensional slider that could be adjusted using the laser pointer attached to the virtual controller. After submitting the answers, the subsequent trial was started. No time restrictions were given for each trial. Each participant started with a training session consisting of at least three trials to get accustomed to the procedure. Additional training trials were conducted if the participant struggled with the task procedure. Afterward, they proceeded by going through the 90 test trials. After 30 and 60 trials, participants were given a break with no time limitations. Following the experiment, participants were then invited to a voluntary semi-structured interview, which was audio-recorded and later transcribed. On average, participants took around 50 minutes (SD = 9 min) to complete all trials, including breaks. This study was approved by our institution's ethical committee.

4.5 Participants

We recruited 20 participants (9 female, 11 male) through university mailing lists. Participants were between 20 and 36 ($M = 26.00, SD = 4.63$). 18 had experienced VR before (7 below 2h, 7 between 2h and 20h, and 4 above 20h). 18 participants were right-handed, and 2 were left-handed. All participants reported normal or corrected-to-normal vision and no known conditions that may impact haptic or tactile acuity of the right hand. As compensation, we offered 10€ or university course credit (where applicable) commensurate with the time spent. No participant opted for course credits.

4.6 Analysis

We fitted generalized linear mixed models (GLMM) by maximum likelihood (Laplace Approximation) using a Poisson distribution with a log link function for all three dependent variables. We included PHYS, OBJ, and C/D as fixed effects, along with their interaction effects, and the participant ID and trial count as random effects to account for individual differences in subjective ratings and possible fatigue effects. We report the models' explanatory power using the marginal (R^2_m) and conditional (R^2_c) R-squared. We applied type III Wald chi-square tests for significance testing. Where we found significant main effects or interaction effects, we conducted post-hoc pairwise comparisons with Bonferroni correction.

5 Results

In the following, we present our results structured around the three investigated dependent variables, followed by the qualitative findings of our semi-structured interview.

5.1 Perceived Stiffness

In our GLMM, the fixed effects explained 68% of the variance (R^2_m= 0.6828), while the combined fixed and random effects explained 88% of the variance (R^2_c= 0.8829), which indicates very high explanatory power. The distribution of changes in stiffness ratings for PHYS and C/D averaged over all objects is presented in Figure 3. Perceived stiffness ratings display a clear trend with both PHYS and C/D levels, with distributions for the physical stiffnesses partially overlapping when increased C/D ratios were applied to the harder prototypes and decreased C/D ratios were applied to the softer prototypes.

[3]https://www.federnshop.com/en/produkte/druckfedern/vd-179j-02.html, last accessed: 2025-01-30
[4]https://optitrack.com/, last accessed: 2025-01-30
[5]A desktop computer with an Intel i7 processor, 16GB RAM, and an NVIDIA GeForce RTX 2070 Super graphics card, and a gaming laptop with an Intel Core i9 processor, 32GB RAM, an NVIDIA GeForce GTX 1650 Ti graphics card

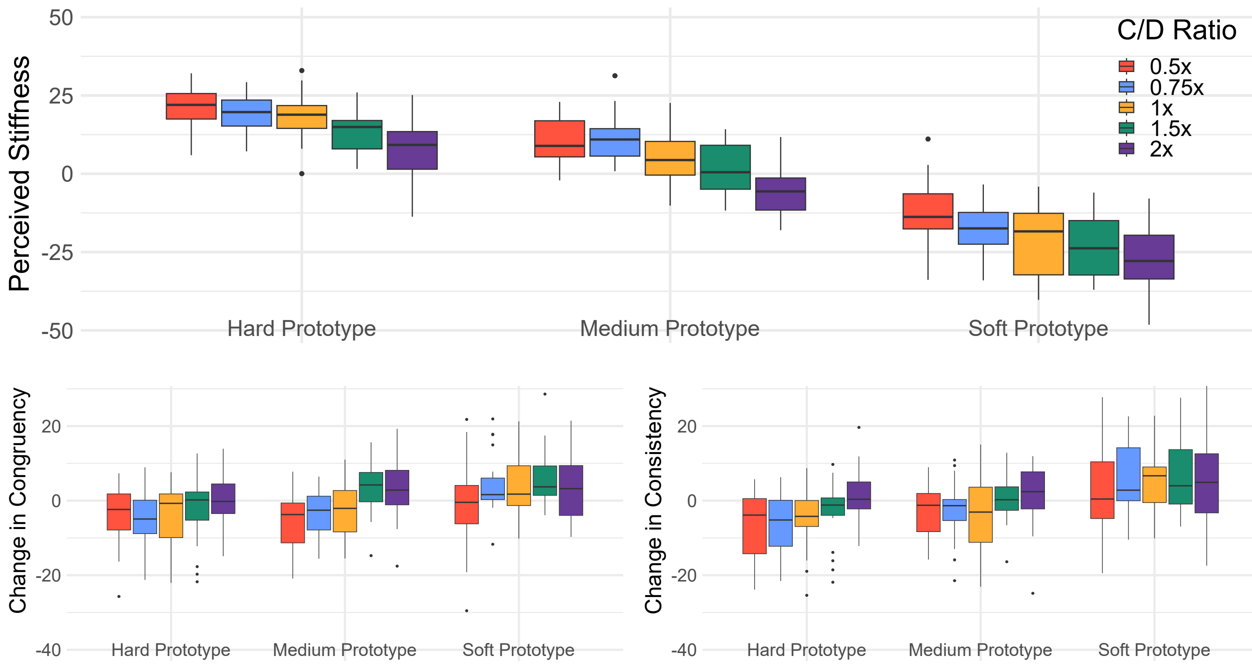

Figure 3: Change in ratings for (top) perceived stiffness, (bottom left) visuo-haptic congruency, and (bottom right) consistency with anticipations from real-life experiences. Changes are presented relative to participants' individual means.

We found significant main effects for PHYS ($\chi^2(2) = 260.17, p < .0001$) and C/D ($\chi^2(4) = 64.00, p < .0001$). Additionally, there were significant interactions between PHYS and OBJ ($\chi^2(10) = 46.10, p < .0001$), PHYS and C/D ($\chi^2(8) = 39.61, p < .0001$), OBJ and C/D ($\chi^2(20) = 37.62, p < .01$), and a three-way interaction among PHYS, OBJ, and C/D ($\chi^2(40) = 190.40, p < .0001$).

For PHYS, post-hoc tests reveal significantly ($p < .0001$) different stiffness ratings for all pairwise comparisons among the hard ($M = 74.9, SD = 17.3$), medium ($M = 63.3, SD = 20.5$) and soft ($M = 38.5, SD = 20.0$) prototypes with the hard condition having the highest perceived stiffness and the soft condition having the least perceived stiffness. Analogously, all levels of C/D are significantly different in perceived stiffness ratings from all other levels ($p \leq .0001$). Here, perceived stiffness decreases with C/D magnitude with 0.5× rated the hardest ($M = 65.3, SD = 22.9$), followed by 0.75× ($M = 63.1, SD = 23.4$), 1× ($M = 59.1, SD = 24.1$), 1.5× ($M = 56.1, SD = 24.7$), and lastly 2× with the lowest stiffness rating ($M = 50.4, SD = 24.9$). Regarding the interaction effect of PHYS and C/D, we observe that harder physical prototypes reduce the differences among ratings elicited by different reduced levels of C/D. Specifically, for the Hard prototype, we found no significant differences between C/D levels ×0.5, ×0.75, and ×1, while all other pairwise comparisons that include the Hard prototype and larger C/D ratios showed to be significant. Notably, the combinations of Medium/0.5× ($M = 69.8, SD = 16.4$) and Medium/0.75× ($M = 69.7, SD = 18.3$) both show higher mean perceived stiffness ratings than the Hard/2× group ($M = 66.2, SD = 21.0$). However, these differences are not significant. OBJ did not have an independent main effect on perceived stiffness, but we do see a slight trend towards objects anticipated to be stiffer based on our pre-study (e.g., lemon and avocado) to be rated as softer compared to other objects among groups where PHYS or C/D was constant. By observing the interaction of PHYS and OBJ, we found this effect was more pronounced with softer physical prototypes.

5.2 Perceived Visuo-Haptic Congruency

In our GLMM, the fixed effects explained approximately 12% of the variance for all distributions ($R^2_m = 0.1171$), while the combined fixed and random effects explained approximately 87% of the variance ($R^2_c = 0.8670$), showing that the inclusion of individual differences and possible fatigue greatly enhances the model's explanatory power. The bottom left side of Figure 3 presents the distribution of the change in average congruency ratings dependent on PHYS and C/D. We found significant main effects for PHYS ($\chi^2(2) = 73.01, p < .0001$), OBJ ($\chi^2(5) = 221.27, p < .0001$), and C/D ($\chi^2(4) = 14.86, p < .01$). Additionally, there were significant interactions between PHYS and OBJ ($\chi^2(10) = 184.43, p < .0001$), PHYS and C/D ($\chi^2(8) = 43.45, p < .0001$), OBJ and C/D ($\chi^2(20) = 144.52, p < .01$), and a three-way interaction among PHYS, OBJ, and C/D ($\chi^2(40) = 171.89, p < .0001$).

The perceived match of visual and haptic stimuli declines with the hardness of the physical prototypes. Post-hoc tests reveal significantly ($p < .0001$) different perceived congruency ratings for all pairwise comparisons among the soft ($M = 66.2, SD = 24.8$), medium ($M = 61.2, SD = 27.0$) and hard ($M = 58.9, SD = 28.7$) conditions of PHYS. The softest physical prototype achieved a significantly ($p < .0001$) better visual and haptic sensation match over the harder prototypes for all objects except avocado and lemon, for which the hardest prototype was rated higher. Regarding the overall visualizations, the objects anticipated to be softer based on the classification of our pre-study evoke worse perceived congruency of visual and haptic sensations. The sponge ($M = 57.1, SD = 30.0$) and marshmallow ($M = 59.7, SD = 29.7$) both result in significantly ($p < .0001$) worse ratings compared to the duck ($M = 62.7, SD = 26.7$), avocado ($M = 64.1, SD = 25.1$), meat ($M = 64.3, SD = 24.8$), and lemon ($M = 64.7, SD = 24.7$). Adapting the C/D ratio of finger movements also shows to have an effect on the congruency of visual and haptic sensations. Contrary to the expectation of the baseline without any distortions (C/D= 1×) receiving the highest ratings, the perceived match of visual and haptic stimuli increases with higher C/D ratios. While a C/D ratio of 0.5× ($M = 58.6, SD = 28.5$) evokes significantly ($p < .0001$) worse congruency ratings than no distortion ($M = 61.3, SD = 27.1$), C/D ratios of 1.5× ($M = 64.9, SD = 26.6$) and 2× ($M = 64.9, SD = 26.0$) both achieve significantly ($p < .0001$) better congruency ratings than baseline. Regarding the interactions of C/D and PHYS, we can observe that C/D ratios ≤ 1 applied to the soft prototype received significantly higher ratings than when applied to the medium or hard one, while amplified movements (C/D>1) resulted in similarly higher scores for the medium prototype and soft prototype, with only a significant reduction when their applied to the hard prototype. Furthermore, we found a C/D ratio of 1.5× was rated as the highest congruence for the soft and medium physical prototypes, while the C/D ratio of 2× achieved the best results for the hardest prototype. These differences between 1.5× and 2× are, however, not statistically significant. Lastly, while higher levels of C/D generally increase congruency, this effect is more pronounced for the OBJ levels anticipated to be softest, with the largest differences in ratings between the ×0.5 and ×2 groups of the marshmallow and sponge.

5.3 Perceived Consistency with Anticipations

For the perceived consistency with anticipations based on real-life experiences with the investigated objects, our GLMM model explained 41% of the variance with only fixed effects (R^2_m= 0.4090) and 86% with the addition of random effects (R^2_c= 0.8575), which indicates a very high explanatory power. The change in perceived consistency ratings in relation to PHYS and C/D averaged over all objects is shown in Figure 3 on the bottom right. We observe that the perceived consistency increases with the softness of the prototype and increasing C/D ratios. Analogous to the perceived congruency, we found significant main effects for PHYS ($\chi^2(2) = 43.04, p < .0001$), OBJ ($\chi^2(5) = 559.14, p < .0001$), and C/D ($\chi^2(4) = 17.09, p < .01$) and interactions between PHYS and OBJ ($\chi^2(10) = 504.98, p < .0001$), PHYS and C/D ($\chi^2(8) = 18.86, p < .05$), OBJ and C/D ($\chi^2(20) = 236.46, p < .0001$), and three-way interaction among PHYS, OBJ, and C/D ($\chi^2(40) = 287.53, p < .0001$). The consistency ratings exhibit similar trends to perceived congruency, with the harder physical prototypes receiving significantly ($p < .0001$) lower ratings compared to the next softer one (Hard: $M = 45.8, SD = 27.6$, Medium: $M = 48.4, SD = 25.6$, Soft: $M = 54.9, SD = 26.1$). The softer physical prototypes achieve significantly ($p < .0001$) higher consistency scores compared to the next harder prototypes for all objects except avocado and lemon, for which the order is reversed. Overall, sponge ($M = 42.2, SD = 27.7$) and marshmallow ($M = 46.9, SD = 29.1$) again result in significantly ($p < .0001$) worse ratings compared to all other objects. C/D ratios of 1.5× ($M = 51.1, SD = 26.6$) and 2× ($M = 52.2, SD = 26.7$) significantly ($p < .05$ and $p < .0001$) increase the perceived consistency compared to the baseline ($M = 49.1, SD = 25.9$), while 0.5× ($M = 47.4, SD = 27.8$) and 0.75× ($M = 48.8, SD = 27.0$) decrease this rating. However, interaction effects indicate that the perceived consistency for the different C/D ratios is affected by PHYS. With the softest prototype, a C/D ratio of 2× ($M = 54.9, SD = 27.7$) achieved slightly lower consistency ratings compared to a C/D ratio of 1.5× ($M = 56.5, SD = 26.6$) and the non-distorted baseline ($M = 55.0, SD = 25.4$), but these differences are not significant. Regarding the interaction of varying PHYS and C/D levels with individual objects (OBJ), we observed a shift in trends. For the objects anticipated to be softer based on prior experience (e.g., Marshmallow and Sponge), the perceived consistency increases with the softness of the prototype and increasing C/D ratios. For the objects that received higher expected stiffness ratings in the pre-study (e.g., Avocado and Lemon), this trend reverses.

5.4 Qualitative Findings

After the completion of the study, 18 participants agreed to a voluntary semi-structured interview. To gain deeper insights into their experiences, we asked participants about the sensations felt during the study, how they compare to their experiences in the real world, what differences they noticed between trials, and the uses they see in this kind of feedback. Interviews were audio-recorded, transcribed with $pyannote - audio$[15, 50], and manually corrected. We analyzed the interviews following the process outlined by Blandford et al. [12] using Atlas.ti[6]. Three researchers first open-coded three interviews (~ 16%) independently, then consolidated codes. One researcher applied the final code set to all transcripts. The following section is structured based on the main themes that emerged.

5.4.1 Anticipatory Contrast. A common theme among those interviewed was the anticipatory contrast before and during the interaction with the objects. Especially for the softer objects (i.e., sponge and marshmallow), participants noted that their anticipation due to the visual presentation had an effect on their stiffness judgments: *"Just the expectation of how the object should feel and should be able to be squeezed [...] changed my like initial reactionary thinking of how stiff it actually felt"* (P4). Similarly, participants noted that this contrast degraded the perceived realism: *"I expected it [marshmallow] to be soft, but it wasn't soft. So I was like, oh wait, okay. This feels not real"* (P8). And it might also affect the exploratory procedure itself: *"I would know, like if I'm going to touch the sponge, it's going to be that soft, that I don't have to squeeze it harder. So when I look at those objects in the VR, I wanted to only press that much [...] but sometimes it felt a bit harder"* (P20).

5.4.2 Noticeability of the Illusion. When asked about the changes that were introduced during their trials, participants generally only focused on the virtual objects and physical prototypes and did not mention any awareness of manipulations in hand and object behavior. During follow-up questions specifically targeting the manipulations, some participants reported apparent changes in the

[6]https://atlasti.com/, last accessed: 2025-01-30

visual deformation: *"I don't really have a pattern for that. But at some point, it felt like things were becoming more deformed. And sometimes they were not moving at all"* (P17). *"I felt like I should deform more. Or sometimes it deformed more than I expected it to"* (P19). However, the manipulation of the finger movement was noticed less and instead sometimes attributed to a physical change of pressing distance: *"The physical pressing distance was different, I would say, so for some it was possible to press them further for some it was not possible to press them that far together"* (P13).

5.4.3 Feedback & Interaction Fidelity. Regarding the fidelity of the feedback, participants mainly missed additional auditory feedback and tactile cues, such as texture, wetness, or stickiness of the objects' surfaces: *"When you squish a lemon, then you will have like sticky fingers afterward [...] it's not as realistic when you just squeeze an object out of plastic"* (P1). *"Meat should feel like it's a bit slimier"* (P5). They also mentioned an expected non-uniformity regarding the stiffness of objects such as a pitted avocado or the meat: *"Small disturbances [...] move the finger to some side because of the meat. [...] it's usually not a homogeneous material"* (P13). These expected changes in stiffness would constrain how participants would interact with these objects in reality: *"You wouldn't be able to press it [avocado] because there's a pit [...], so all of that wasn't really replicated. But for the things like the marshmallow or the sponge, you would be able to press it the entire way"* (P17).

6 Discussion

In the following, we discuss our findings in relation to the research questions and their implications for haptic feedback design.

6.1 The Haptic Illusion Changes Stiffness Perception Effectively & Reliably

Regarding RQ1 (*How do C/D ratio manipulations while pinching affect the perceived stiffness of compliant objects in VR?*), our study demonstrated a large effect of the VHI on the perceived stiffness of compliant virtual objects. Increasing and decreasing C/D of finger movements resulted in the respective softer and stiffer perceptions in line with prior work [45, 65]. From Figure 3, we can observe the strong correlation of C/D ratio and reported stiffness levels, even to the extent where ratings overlap among groups of different physical prototypes. The illusion effectively bridged the gap between the medium (2.170 N/mm) and hard (3.255 N/mm) prototypes with higher mean ratings for C/D ratios of 0.5× and 0.75× in the medium condition than the hard condition with a 2× C/D ratio. This demonstrates that a 50% (1.085 N/mm) difference in physical stiffness is mitigated by the visual manipulation, which means that we could reach any stiffness between these two physical stiffnesses purely through the use of this visual manipulation in our setup. We can observe a similar but less pronounced overlap between the softest (1.085 N/mm) and medium (2.170 N/mm) prototypes, which have the same absolute stiffness change (+1.085 N/mm) but a higher relative change (+100%). This aligns with established psychophysical principles (see Stevens [61]), which stipulate that absolute stimulus intensity and perceptual change are not linearly correlated. The perceived stiffness ratings additionally reveal that physical stiffness changes and C/D ratio adjustments are not entirely independent. The integration of both cues into a unified stiffness perception [23, 57] explains the apparent ceiling effects of decreased C/D ratios showing less effective change on higher physical stiffnesses following the same psychophysical principles [61]: Higher base stiffness levels require larger stiffness changes to become distinguishable, which would explain the fact that decreasing C/D levels did not significantly increase perceived stiffness on the Hard physical prototype, while they did for the Soft prototype. The effectiveness of the VHI in increasing perceived stiffness, thus, could have a diminishing effect, the harder the base material the VHI is applied to. Generally, the VHI is effective in expanding the range of stiffness achievable by compliant passive props. C/D ratio manipulation allowed us to bridge up to 50% stiffness gaps in our experiment, which can drastically lower the number of required physical props to display the same range of haptic sensations.

6.2 Manipulations Do Not Adversely Affect the Virtual Experience

Regarding RQ2 (*How do these manipulations influence the congruency and consistency of the visuo-haptic experience?*), we found that C/D ratio adjustments did significantly affect congruency. In contrast to expectations, they do not uniformly lower the perceived congruency of visual and haptic presentation. Instead, we see from Figure 3 that visuo-haptic congruency increased with higher C/D ratios. This means that amplified movements are judged to be more congruent than restricted and even unmodified presentations. These findings align with prior reports [45, 65], which found participants to overestimate their input movements in similar visuo-haptic tasks. While these had abstract, restrained visualizations, we show that this phenomenon remains present across various visual and haptic representations. This effect showed to be more pronounced for softer physical base stiffnesses and object visualizations that users may anticipate to be softer based on prior experiences. We paired hand-pose manipulations with visual object deformations. Interviews suggest these deformations were more noticeable than finger-movement changes, though participants felt their stiffness judgments relied more on haptics than vision. With the found non-adverse effect on congruency and largely altered perceived stiffness, this supports a multisensory integration of movement, deformation, and haptic cues instead of separated judgments, which aligns with theoretical foundations of stiffness perception [42, 57].

6.3 Effects Are Generalizable Across Individuals and Virtual Objects

Expectantly, subjective ratings generally show higher variances between subjects. Especially the ratings for congruency and consistency depend largely on individual baseline assumptions. We accounted for this in the analysis using the individual as a random effect in our GLMM. The strong fit of the GLMM with included random intercepts indicates it is possible to predict and consequently elicit changes in individual stiffness perceptions with a combination of physical prototypes, C/D ratio adjustments, and different visualizations of virtual objects. Regarding our third RQ (*How do different visualizations and haptic representations of objects influence the effect of the VHI?*), we observe that both physical stiffness change and the VHI were effective in altering perceived stiffness across visualizations. Regarding the consistency with their expectations from real-life experiences, we see correlations of higher perceived stiffness (as a combination of PHYS and C/D) being better suited for objects anticipated to be harder and vice versa. Here, participants reported anticipatory contrasts about stiffness expectations of the presented objects based on real-life experiences and the actually rendered stiffness when they started pinching. This can explain the interaction observed between physical stiffness and the visualized objects regarding perceived stiffness. For softer prototypes, we observe objects that people anticipate to be stiffer (i.e., avocado and lemon) to result in a softer perception than the same stiffness applied to visualizations of softer objects. This contradictory effect is consistent with phenomena in other areas of haptic perception, e.g., with the size-weight illusion [49], where people perceive an object to be lighter if it is larger than a smaller object of the same weight. Although the precise mechanisms underlying this phenomenon are not yet fully understood, a similar effect is observed for equally weighted objects made of different materials [52] or when judging collision forces with manipulations of visual speed [3]. Our findings suggest an analogous phenomenon present in stiffness perception, whereby an object that is anticipated to be stiff is judged to be softer than an equally stiff object that is visually presented as soft. Yet, the nature of this effect warrants further investigation.

6.4 Addressing Perceptual Biases Will Improve Haptic Rendering Approaches

Our investigation centered on modifying stiffness during pinching. However, we employed the VHIs in a wider context with a selection of visualizations that were distributed across their anticipated stiffness and varied in color, size, and shape. Our insights may, therefore, inform research on other multisensory illusions targeting stiffness or other aspects of haptics, or may be transferred to haptic rendering using active devices. Transitioning from abstract to realistic settings requires consideration of confounding effects, such as biases due to previous experience, which not only affect the perceived quality of the representation but can fundamentally influence haptic perception (see 6.3). Participants expected non-homogeneity and holistic, multisensory sensations (see 5.4.3), which cause difficulties when trying to scale to diverse objects and contexts. However, other aspects, such as the apparent overestimation of displacement movements (see 6.2) and prevalent psychological interferences (see 6.3), can be mitigated and adapted for by directing research accordingly.

7 Limitations & Future Work

Our work provides a more generalizable understanding of the efficacy of VHI by evaluating various visual and haptic presentations. Nevertheless, haptic perception comprises many aspects that cannot be fully accounted for without further investigations.

We focused on pinching as a primary exploratory procedure used to discern stiffness [21, 46]. Prior works have investigated procedures such as pressing onto an object from one side [16, 45, 65] or stretching, twisting and bending [33]. Yet, there remain many potential ways to interact with and assess a haptic object, such as two-handed interactions [60] or squeezing with more than two fingers, which has been shown to improve haptic stiffness discrimination [21] and, therefore, might lessen the effect of the visual manipulation.

Further, to mitigate confounding factors, we did not replicate the entire spectrum of sensations present during real-life interactions, such as cutaneous deformations [11, 58], surface textures [38], and auditory cues [28], which all impact stiffness perception and thus necessitate further investigations to gain a complete image of users' haptic experiences. For our visuo-haptic approach using C/D ratio, there are further aspects to consider. A steeper viewing angle, which we controlled for using enforced hand orientations, might lower the effectiveness of the visual manipulation due to less perceptible movement, analogous to the findings on C/D adjustments on different hand movement directions [68].

Additionally, if multiple senses are integrated according to their reliability [23], interpersonal or transient differences in visual, haptic, and proprioceptive acuity could skew users' perceptions in separate directions, which requires further study.

Lastly, our study focused on the effects of familiar visualizations and controlled linear stiffness on the VHI, rather than on how the illusion would manifest when applied to actual everyday objects. Given that the stiffness of complex, heterogeneous objects cannot be easily modeled, future work could explore applying VHI directly to real objects in mixed reality settings.

8 Conclusion

Our study demonstrates that the investigated haptic illusion is an effective and reliable method for modifying the perceived stiffness of objects in virtual environments. By manipulating the C/D ratio of finger movements during pinching, we successfully bridged significant gaps of up to 50% in physical stiffness without the need for multiple physical props. We showed this manipulation to not adversely affect the perceived visuo-haptic congruency or consistency with anticipations from real-life experiences. Our results indicate that the effects of the illusion are generalizable across different individuals and virtual objects. By adding this technique to conventional approaches, we expand the range of haptic sensations achievable with passive props or active devices, enhancing their practicality and flexibility to provide haptic feedback for a wider spectrum of VR experiences. Our findings also revealed perceptual biases and influences that point to a complex interplay between visual cues, haptic feedback, and expectations. These could impose considerable challenges or possible opportunities when integrating VHIs or other haptic rendering techniques into more lifelike scenarios, warranting further investigation to allow systems to adapt to users' circumstances more precisely.

Overall, our investigation demonstrates that VHIs offer an effective and versatile approach for haptic rendering in VR across individuals and contexts. These findings can inform future research and development for haptic feedback methods, particularly in creating more scalable haptic experiences that respond dynamically to user interactions.

9 Open Science

We make our project files, collected datasets, final codeset for interview coding, and data analysis scripts available on the Open Science Framework[7].

[7]https://osf.io/5btk4/?view_only=2865bfddaedc417ead8d105b5868c062

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