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Physical Compliance and the Compliance Illusion: The Importance of Action for Perception

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***Abstract*—The perception of an object's compliance can be manipulated using the grain-based vibrotactile compliance illusion. Despite the growing interest in creating *virtual compliance* using this method, its perceptual mechanism is poorly understood. To address this gap in knowledge, we present a detailed analysis of compliance estimates and pressure profiles of exploration behaviors of 12 participants while perceiving both *physical* and *virtual* compliance. Our results indicate that the experience of virtual compliance provided by the compliance illusion is distinct from that of physical compliance and that these experiences are mediated by distinct sensorimotor processes. This is evident in the non-additive nature of both real and illusory compliance perceptions and the separable exploratory actions of the participants in response to real and illusory compliance. These insights affect the design of augmented and virtual tactile reality systems, shed light on the mechanisms of compliance illusion, and provide data in support of closed-loop theories of tactile perception.**

***Index Terms*—compliance, grain-based compliance, illusion, haptic, softness, hardness, Shore-A level, magnitude estimation**

I. Introduction

Designing rich haptic experiences is becoming increasingly important in virtual/augmented reality (VR/AR) [1], consumer products [2], gaming and entertainment [3], automotive manufacturing [4], medical and healthcare technology [5], robotics [6], teleoperation [7], wearables [8], [9], and many other fields. From smartphones to gaming controllers, haptic technology improves on intuitive and engaging user interfaces [10], [11]. Haptic designers can access a wide range of well-established heuristics, methods, and illusions to create haptic experiences [10], [12]–[14]. One widely studied example is the grain-based compliance illusion, which creates a sense of compliance in rigid objects and is used to create responsive tangibles [15], augmented input devices [16], and tactile VR/AR systems [8], [9].

Kildal [16] presented an early implementation of the compliance illusion. He induced an experience of compliance in participants by providing vibrotactile pulses to their fingertips as they exerted varying pressure on a rigid object. Since then, this illusion has broadly captured the interest of researchers in both the haptics [15], [17], [18] and human-computer interaction (HCI) [8], [9], [16], [19]–[24] communities. Kildal [15] also designed a compliance rendering system for a handheld pen, where friction grains were played as short pulses distributed over the range of applied force. Kildal studied four design parameters: number of grains, amplitude of vibration, grain distribution along the range of force, and regularity of amplitude. This approach did not clearly identify which parameters influence an object's mechanical properties.

Researchers have explored applications for the grain-based compliance illusion in various contexts. Ahmaniemi [17] used the compliance illusion to investigate potential improvements in joystick controllability. Kim and Lee [25] used the grain-based method to design haptic feedback that simulated the feeling of a mechanical button on a touchscreen. In another study, Kim et al. [26] used a similar approach to provide a button-like haptic feeling when a button was pushed on a touchscreen. Researchers have used a similar vibrotactile rendering approach to generate virtual materials in shoes [9], [23] and to investigate the perception of ground surface compliance using a grounded system [27]. Heo et al. [22] extended the use cases of the grain-based method to elicit sensations of stretching, bending, and twisting a rigid object. Recently, Vega et al. [8] proposed a back-of-the-finger device that could create a grain-based compliance illusion felt on the fingertips. Overall, these studies illustrate the utility and broad usage of the grain-based compliance illusion.

The grain-based *compliance illusion* is well established but not well understood. To understand this illusion, one might investigate the better-understood experience of *physical softness*, which relies on the integration of kinesthetic and cutaneous cues [28], [29], with cutaneous cues providing the majority of the information [30], [31]. The experience of compliance arises from the relationship between user-applied force and

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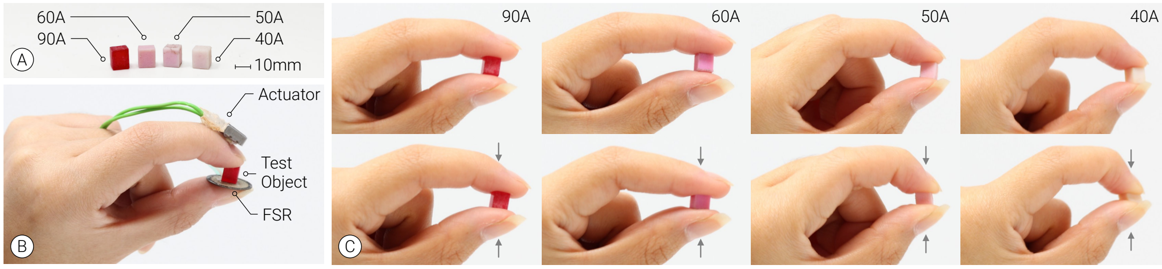

Fig. 1. A) The four 3D-printed samples used with known Shore-A levels. B) Participants pressed the samples with their index finger and thumb to estimate compliance. The applied pressure was measured using an FSR sensor. C) Illustrations of the physical softness of the 3D-printed samples.

its effect on the user's body. Such feedback is received in the form of cutaneous cues (e.g., fingertip deformation) and kinesthetic cues (e.g., strain on muscles and displacement of joints). Researchers have demonstrated that the reverse is also true: manipulating finger deformation can also affect softness perception [20], [32]. However, this perceptual model cannot fully explain our participants' experiences of the *compliance illusion* based on grain-based vibrotactile feedback.

To better understand the grain-based *compliance illusion* and how it is related to perception of *physical softness*, we collected data from participants interacting with objects that had varying *physical softness* and *compliance illusions* with varying grain count. We collected magnitude estimations of softness from participants to understand their subjective experiences. We also recorded the pressure applied by participants during exploratory acts to better understand the motor activity that leads to the experience, in consideration of closed-loop theories of perception [33], [34]. The magnitude estimates confirm the effectiveness of the grain-based compliance illusion, as also shown by Mun et al. [35]. However, our data indicate that *physical softness* and the *compliance illusion* are distinct experiences, mediated by different perceptual mechanisms.

Our study highlights three core insights regarding the perception of *physical softness* and the *compliance illusion*: 1) they are non-additive; combining them does not increase the perceived compliance of objects, 2) they emerge from different perceptual mechanisms; systematic changes in pressure maxima in exploratory actions correlate with specific experiences that participants focused on, 3) the data suggests *physical softness* and the *compliance illusion* are two distinct experiences; in our experiments, participants' behaviors and responses emerged as clusters based on one of the experiences. These insights enhance our understanding of the mechanisms of the compliance illusion and empirically support active perception theories [33], [34], [36], as our data indicate that sensory feedback received by the participants from exploratory actions influences how these actions unfold.

II. Material and Methods

We performed a factorial experiment combining 4 levels of *physical softness* and 4 levels of *grain count* (Fig. 1). We recorded the reported compliance estimates of the participants together with the applied pressure profiles to capture the dynamics of the participants' exploratory behavior.

A. Participants

We had 12 healthy participants (9 males, 3 females) aged 24–35 (M=27.25, SD=3.46). Before the experiments, they provided informed consent. They received compensation of 12 € for their participation and were free to withdraw from the study at any time for any reason.

B. Algorithm

We used the grain-based compliance illusion (cf. [16], [37]) based on the method demonstrated by Vega et al. [8]. This approach triggered short vibrotactile pulses (grains) whenever specific pressure thresholds were crossed. These thresholds were evenly distributed across the pressure-sensing range. Consequently, the pressure that the individual applied determined the occurrence and density of rendered grains (Fig. 2).

C. Stimuli

As shown in Fig. 1A, we fabricated 4 cuboids (6×6×7 mm) with known Shore-A levels (90A, 60A, 50A, and 40A) using a 3D printer (J826 Prime, Stratasys Inc.). The cuboid with the Shore-A level of 90 was rigid and incompressible. Therefore, it served as a baseline condition in the experiment. These 4 cuboid objects were crossed with 4 levels of *grain count*: a non-augmented condition (0 grains) and 3 conditions with increasing grain count (10, 20, and 40 grains).

D. Experimental Procedure

Participants were seated at a desk with a display and a numeric keypad. Their dominant hand was hidden behind a curtain so visual information would not influence their sensory perception. With that hand, they explored objects by applying pressure and rated the softness of each object [38].

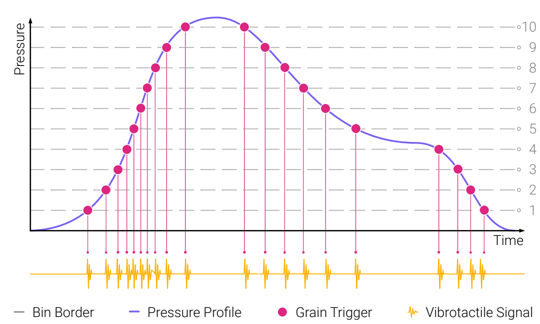

Fig. 2. Visualization of the compliance illusion algorithm. Vibrotactile pulses (grains) are rendered at the intersections of predefined bins evenly distributed over the pressure range. This plot shows the condition with 10 grains.

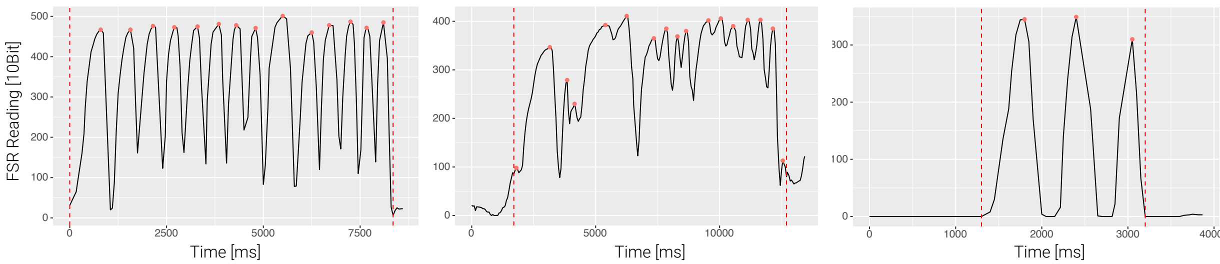

Fig. 3. Example pressure-time profiles of 3 different participants. The orange-colored dots represent pressure maxima. The participants showed various approaches to assess the compliance of an object.

During the experiment, participants held the objects between their thumb and index finger (Fig. 1B). An actuator to deliver the grain-based compliance illusion was attached to their index finger's nail with medical-grade double-sided tape. The vibrotactile signals for creating the compliance illusion were generated by a microcontroller (Teensy 4.1) with a 16-bit stereo DAC (PT2811, Princeton Technology Corp.). The signals were amplified using a stereo amplifier (AMP 2.2 LN, Visaton GmbH & Co. KG) to drive the linear resonant actuator (LRA) (VLV101040A, Vybronics Inc.) attached to the participant's nail (Fig. 1B).

During the exploration, we recorded two variables: 1) magnitude estimations of the perceived compliance and 2) applied pressure on the samples (until participants reported their estimates). We recorded the pressure-time profiles at 20 Hz as 10 bit integers sampled from an FSR sensor (FSR06BE, Ohmite Mfg Co.) placed underneath each object in contact with the thumb (Fig. 1B).

Participants underwent 3 sessions of 18 trials (4 objects $\times$ 4 renderings + 2 dummy trials to keep participants engaged). We counterbalanced the order and combination of Shore-A levels and granularity using the Latin square method. In total, we recorded 648 responses (12 participants $\times$ 3 sessions $\times$ 18 trials). Removing data for the dummy tasks resulted in 576 pressure-time profiles (12 participants $\times$ 3 sessions $\times$ 16 trials (4 objects $\times$ 4 renderings)).

E. Data Preparation

For estimation data, we aligned all scales so that higher estimates refer to softer experiences and lower estimates to harder experiences. This alignment accounted for two participants who used inverted scales in their magnitude estimates. As we intended to focus on changes in individual estimates based on changes in stimulus, all estimates were transformed to z-scores per person. The resulting score provided a measure of the magnitude of a given estimate relative to all other estimates provided by that participant. For example, a z-score higher than one suggested that this value was at least one standard deviation from the participant's mean, or higher than 84.1% of that participant's estimates based on the cumulative probability of a normal distribution.

For pressure profiles, we identified 39 trials where the recorded data was either too short to conduct analysis (10 trials) or too long to see which parts of the recording were relevant (25 trials). We removed these from the dataset before further analysis. An initial observation of the remaining 537 trials showed a large variability in exploratory behaviors. Fig. 3 shows sample pressure-time profiles of 3 participants. The number of applied presses varied widely by participant. Moreover, the amount of the applied pressure also varied between the participants. Despite high behavioral variability, prior research found links between material softness and pressing behavior [39]. This leads us to believe that maximum applied pressure might vary based on perceived softness. Therefore, we extracted pressure-maxima (orange dots in Fig. 3) and calculated their average for each trial. As with the estimation data, these averages were also transformed to z-scores.

It should be noted that Shore-A is a hardness measure. The numerical value of Shore-A increases with hardness and decreases with softness. When we refer to"increasing softness" in this paper, we also are referring to decreasing Shore-A levels. We do not refer to the levels of the compliance illusion since illusion is a subjective experience. Therefore, we use the term *grain count*, which is a controllable physical parameter.

III. Results

A. Magnitude Estimation

The magnitude estimation results are shown in Fig. 4. We found a linear positive effect of grains on perceived compliance. On average, each grain increased the estimate by 0.03 and *grain count* explained 60% of the variability of participant estimates (Fig. 4A). Although this relationship does not appear linear, we also found a positive relation between increased *physical softness* and participant estimates. Estimates increased by 0.02 per lower Shore-A level, explaining 47% of observed variability (Fig. 4B).

We performed a repeated measures ANOVA with *grain count* and *physical softness* as independent variables and the participant's standardized estimate as the dependent variable. Both *grain count* ($F_{(3,33)} = 18.445, p < 0.001, \eta_p^2 = 0.626$) and *physical softness* ($F_{(3,33)} = 11.649, p < 0.001, \eta_p^2 = 0.514$) had a significant main effect. We did not observe significant interaction effects ($F_{(9,99)} = 0.321, p = 0.966$). For *grain count*, all Bonferroni-corrected pairwise comparisons of adjacent levels were significant (Fig. 4A). For *physical softness*, differences between Shore-A levels higher than 50A were significant, but the comparison between 50A and 40A was not (Fig. 4B). Within-participant variability showed a significant linear relation of estimates and *grain count* ($p < 0.001$) with a large effect size ($\eta_p^2 = 0.659$). There was also a significant

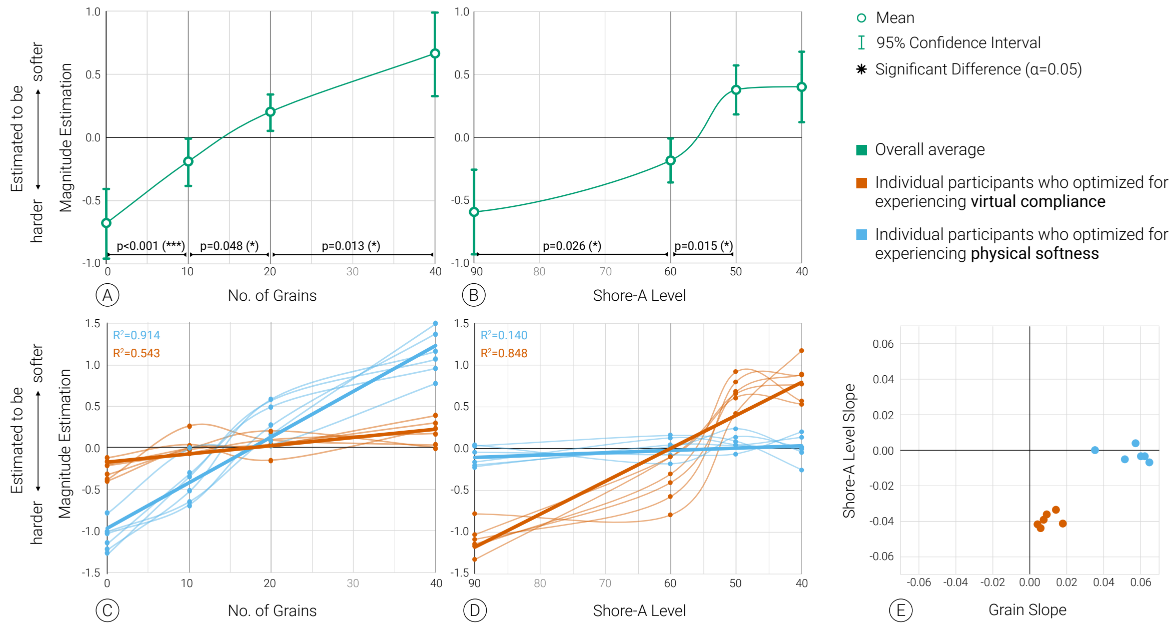

Fig. 4. Average magnitude estimations of the participants with their 95% confidence intervals as a function of A) number of grains (*compliance illusion*) and B) Shore-A level (*physical softness*). Response curves of magnitude estimations as a function of C) number of grains (*compliance illusion*) and D) Shore-A levels (*physical softness*). The orange and blue lines in C and D represent the regression lines per group. Measurements have been standardized (z-score) – a value of 1 indicates one standard deviation. E) Shore-A level slope of every participant from D with respect to their grain slope calculated from C, illustrating two approaches of compliance estimations.

($p = 0.004$), albeit weaker ($\eta_p^2 = 0.539$) linear relation with Shore-A level.

Our results do not capture the full complexity of the underlying data. The per-participant data in Fig. 4C and D show that participants for whom we observed a large effect of *grain count* (blue), estimated a small effect of *physical softness*. Conversely, those for whom we measured a small effect of *grain count* (orange), estimated a large effect of *physical softness*. Plotting each participant's slope for the effect of *grain count* against their slope for Shore-A levels revealed two clusters (see Fig. 4E).

In addition to the ANOVA, we performed a regression analysis and the correlation coefficients provided the predictive strength of *grain count* (Fig. 4C) and *physical softness* for each sub-group (Fig. 4D). For the blue group, *grain count* explained 91% of the observed variability in the average estimates, while *physical softness* only explained 14%. For the orange group, we found the inverse pattern. *Grain count* explained 54% of the observed variability while *physical softness* explained 85% of the observed variability (Fig. 4C and D).

To understand whether the differences between groups were statistically significant, we compared their slopes using a t-test. We found significant differences between blue and orange sub-groups for *grain count* ($t_{(44)} = 10.95, p < 0.001$) and for *physical softness* ($t_{(44)} = 9.64, p < 0.001$).

It appeared that, in our sample, half of the participants based their responses on *grain count* while the other half based their responses on *physical softness*. Both aspects influenced perception to some degree, in that grain count still explained 54% of variability even for the physical softness group. However, participants clearly preferred one cue rather than integrating both. These results suggest that the experience created by the *compliance illusion* is a distinct sensory experience from *physical softness* and that the two types of sensory experience are non-additive–in other words, they do not interact to create a greater magnitude estimation.

B. Pressure Profiles

If *physical softness* and the *compliance illusion* lead to distinct sensory experiences, do they also come with unique exploratory behaviors? To answer this question, we analyzed the applied pressure by the participants to better understand the full sensorimotor loop of active exploration and experience. We performed a repeated measures ANOVA with *grain count* and *physical softness* as independent variables and the standardized applied pressure delivered by the participants as the dependent variable. Results are shown in Fig. 5.

We found a negative effect of *grain count* on applied pressure. On average, each grain decreased the z-scores of applied pressure by 0.028 and *grain count* was able to explain 49% of the variability in pressure scores (Fig. 5A). Interestingly, we found the opposite effect for physical softness. With each increase in softness on the Shore-A scale, participants increased their applied pressure by 0.005. However, this correlation was weak; Shore-A levels could only explain 14% of the variability in our data (Fig. 5B).

Even though correlations were weaker, a repeated-measures ANOVA, with Greenhouse-Geisser correction, revealed a significant effect of *grain count* on maximum applied pressure ($F(1.31, 14.40) = 4.86, p = 0.036, \eta_p^2 = 0.306$) and a significant effect of *physical softness* on maximum applied pressure ($F(1.98, 21.75) = 5.81, p = 0.010, \eta_p^2 = 0.345$), with no significant interaction effect ($F(4.41, 48.51) = 0.27, p =$

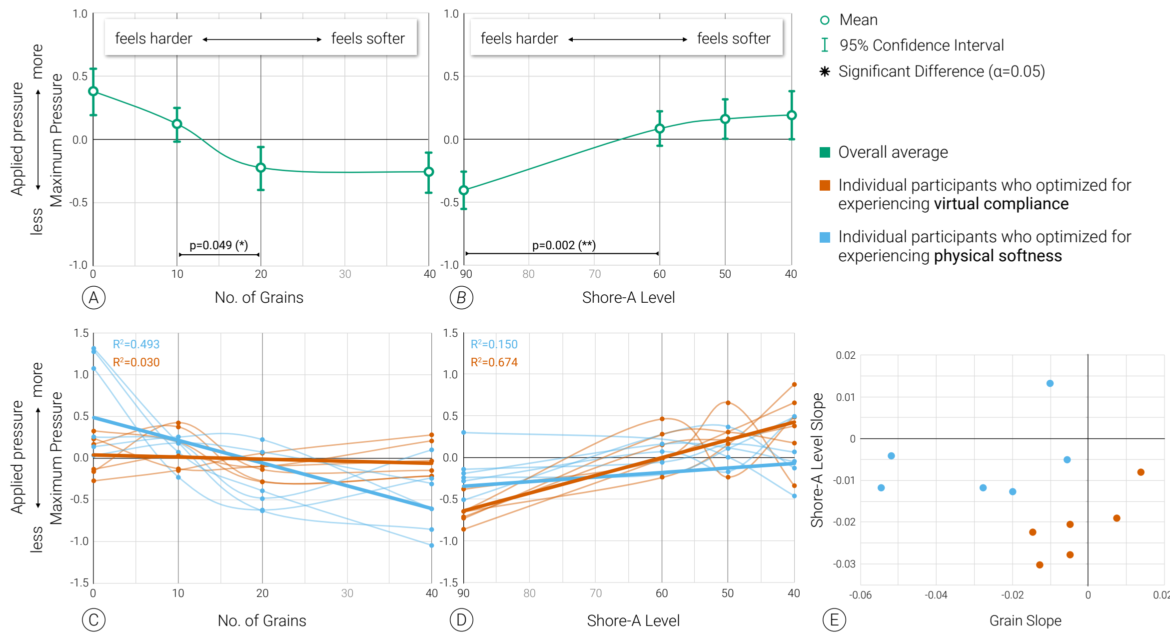

Fig. 5. The average maximum applied pressure by the participants with their 95% confidence intervals as a function of A) number of grains (*compliance illusion*) and B) Shore-A levels (*physical softness*). Subfigures A and B have annotations of perceived softness based on the magnitude estimation results. The maximum applied pressure to the overall average with respect to C) the number of grains used for compliance illusion, and D) the actual softness of an object (Shore-A levels). The orange and blue lines in C and D represent the regression lines per group. Measurements have been standardized (z-score) – a value of 1 indicates one standard deviation. E) The Shore-A level slope of every participant calculated from D with respect to their grain slope calculated from C.

$0.910, \eta_p^2 = 0.024$). Significant differences between adjacent stimuli, as identified in a Bonferroni-corrected post-hoc test, are shown in Fig. 5A and B. Bonferroni-corrected pairwise comparisons found significant differences in pressure between 10 and 20 grains, and between Shore-A 90 and Shore-A 60.

To reveal differences in behavior between the clusters identified in user estimates, we used the same participant color coding in Fig. 5C-E as Fig. 4. As with the magnitude estimation, we performed a regression analysis on the pressure profiles. The observed negative trend for grain count seems driven by the blue group, where grain count accounts for 49% of the observed variability in pressure, compared to only 3% in the orange group (Fig. 5C). Conversely, the orange group drives the effect of Shore-A level, where Shore-A level explains 67% of the observed variability, compared to only 15% in the blue group (Fig. 5D).

Plotting individual slopes for grain count against slopes for Shore-A levels does not reveal a clustering as distinct as in the estimates (Fig. 4E). However, the resulting points can still be clearly linearly separated (Fig. 5E). Differences in slopes between the blue and orange groups were significant for both grain count ($t_{(44)} = -3.75, p < 0.001$) and for Shore-A levels ($t_{(44)} = 3.75, p < 0.001$).

IV. Discussion

A. Perceiving Compliance

The **magnitude estimation** results showed limitations in human ability to perceive physical softness. In our experiment, participants could not systematically discriminate Shore-A levels below 50 (Fig. 4B). This nonlinear behavior is consistent with prior research findings [40], [41]. This suggests that human sensitivity to softness is constrained to a specific range. There may be a threshold at which people can no longer feel increases to softness or hardness due to limitations in human skin mechanics [42] or the density of mechanoreceptors [43]. An alternative explanation could be that the vibratory cue interferes with the extraction of the physical softness. However, most probably, this is not the case in our study, as we also had conditions without vibrotactile feedback.

Similarly, while grain count appeared to linearly influence participant estimates in the current experiment (Fig. 4A), diminishing returns likely occur at higher grain counts, as observed by Strohmeier et al. [9]. It is also intuitively obvious that there must be nonlinear effects at very low grain counts. One of the most intriguing observations is that we did not find an interaction effect; *physical softness and softness induced by the grain-based compliance illusion appear non-additive.*

B. Distinguishing Compliance Illusion and Physical Softness

The observations of **pressure profiles** appear paradoxical. Increases in perceived softness were associated with both increasing and decreasing pressure, which seems contradictory. However, this paradox is easily resolved when looking at the data of individual participants, which shows that participants *either* decreased their pressure with an increasing number of grains (blue) *or* increased their pressure with increasing physical softness (orange) (Fig. 5 C and D).

We posit that this behavioral difference is due to differences in how participants attended to the stimuli. The participants shown in blue – who adjusted their pressure based on grain count – primarily based their estimates on grain count. Conversely, participants indicated in orange – who adjusted their pressure based on physical softness – primarily based their

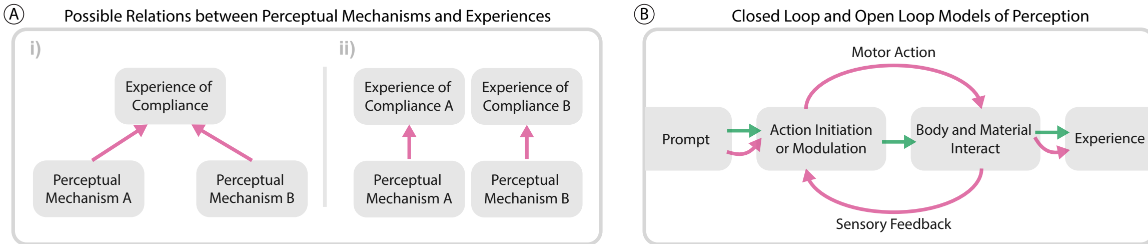

Fig. 6. A) Two separate perceptual mechanisms might allow a shared experience to emerge (i) or might lead to two distinct experiences (ii). B) Closed loop (green) and open loop (pink) models of perception.

estimates on physical softness. This suggests that *physical softness and the softness induced by grain-based illusion are mediated by distinct exploratory behaviors.*

These findings lead to a question: Is compliance a single experience mediated by two perceptual mechanisms (Fig. 6A-i) or are there two separate but similar experiences (Fig. 6A-ii)? If there were two perceptual mechanisms that led to the same experience of compliance, participants would predictably use the optimal perceptual mechanism based on the stimulus. This would result in similar behaviors and estimates for all participants. However, we found that two distinct clusters of participants emerged from our experiment. While it should be noted that this clustering does not necessarily mean that the cues were never integrated – it might reflect individual differences in cue weighting among the participants and their attempt to prioritize one cue over the other – it appears that *physical softness and softness induced by the grain-based illusion are distinct experiences.*

C. On the Nature of Perception

A traditional open-loop account of the experiment might include the following steps: (1) the participant is prompted to touch the object, (2) the participant touches the object, (3) the participant receives sensory feedback, and (4) the participant reports their estimation of experienced softness (Fig. 6B-green). Such open-loop accounts are common in the literature on visual experience [44] but can also be found in accounts of tactile perception [45]. Such simplified models can provide insight. However, ignoring the motor aspect of perception from models may obscure key dynamics of perception.

Our findings reinforce the idea that perception is a closed-loop process. We find that actions at step (2) in which the participant touches the object are shaped by sensory feedback at step (3) when the object gives sensory feedback to the participant (Fig. 6B-pink). Participants adjust their behavior in real time according to the sensory feedback they receive. This aligns with closed-loop models of perception. For example, O'Regan and Noë [33] suggested that perception is a skill and is based on our knowledge of law-like contingencies between motor activities and sensory responses. Ahissar et al. [34] suggested that perception is a closed-loop convergent dynamic from which experience emerges. Both emphasized the tight integration of sensory and motor processes.

An interpretation of our results is that exploratory behaviors are shaped by user attention. We speculate that participants who paid attention to physical softness optimized their exploratory behavior differently than those who paid attention to the grain-based illusion.However, even if *the sensorimotor perceptual process is shaped by participants' attention, this occurs pre-reflectively.* Based on previous qualitative explorations [37], we believe that participants were not conscious of their changing behavior, but only of the resulting experience.

V. Conclusion

We present a detailed analysis of compliance estimates and pressure profiles of the exploratory behaviors of 12 participants at the time they perceive both *physical softness* and the *compliance illusion*. As expected based on prior literature, we found a nonlinear relationship between perceived compliance and Shore-A levels (Fig. 4B). Within the measured range, grain count had a linear effect on compliance. However, we caution that this is unlikely to hold across a broader parameter range. An unexpected finding was that *physical softness* and the *compliance illusion* are not additive. Instead, participants consistently reported the effects of either one stimulus or the other (Fig. 4C and D).

This paper provides the first comparative exploration of exploratory acts in perceiving compliance. We present evidence that different behaviors mediate the perceptual mechanisms underlying *physical softness* and the *compliance illusion*. We speculate that these behaviors may depend on the participants' attentional focus on one of the stimuli, leading to distinct sensory experiences (Fig. 5C and D). Furthermore, because sensory feedback modulates exploratory behaviors, our data support closed-loop theories of perception.

The results of our study imply that haptic researchers and designers should not equate the experience of the *compliance illusion* with that of *physical softness*. In particular, the non-additive nature of these two experiences presents both a significant design limitation and a potential design opportunity. This is especially true in extended reality, where users may need concurrent information about both the real and virtual worlds. Another key implication is that designers should pay close attention to the actions users perform to access haptic feedback. Finally, we emphasize that in tactile perception, it is crucial to consider not only the experiential aspects of perception but also the underlying sensorimotor behavior.

Dataset

The dataset for this study is available through an Open Science Foundation (OSF) repository:
https://doi.org/10.17605/OSF.IO/4Z3M7.

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