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The effect of object compliance on the velvet hand illusion

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Abstract— Movement of a grid of bars between the two hands creates the tactile illusion of a velvet-like material, namely the velvet hand illusion (VHI). It was recently proposed that the VHI is caused by a *masking* effect; bar movement suppresses conscious perception of tactile inputs from the opposing hand. If this hypothesis sufficiently explains the VHI, the physical properties of the opposing hand should not affect the illusion. Another hypothesis suggests that the *integration* of inputs from the grid of bars *and* the hands plays a critical role in the VHI. To compare these two hypotheses, the VHI was elicited under two conditions; the grid of bars was between one hand and a soft texture or the grid of bars was between one hand and a hard texture. A hand was stimulated by moving bars while contacting the stationary texture held by the opposing hand. The grid of bars with the soft texture induced a stronger illusion and softer feeling than that with the hard texture. This result supports the integration hypothesis in which tactile inputs from both bars and textures attached to the opposing hand are integrated.

Index Terms— Somatosensory, tactile illusions, velvet hand illusion

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1 INTRODUCTION

Perceptual illusions have been studied for decades to understand the underlying perceptual mechanisms, to determine how different modalities influence one another, and to discover the neural bases of these processes [1], [2], [3]. Due to the dominance of vision and audition in our daily experience, most of the research is focused on visual, auditory, or audio-visual illusions [2], [4]. Thus, illusions involving somatosensory modalities (e.g. touch and haptic) are far less studied [5], [6].

The influential review by Lederman and Jones [5] (see also [6]) divided haptic and tactile illusions into different categories. One of the categories covered illusions related to material properties. Material properties can include roughness, smoothness, temperature, and weight perception [5]. For instance, the size and texture of an object can influence the perceived magnitude estimates of weight (size-weight or material-weight illusions) [7], [8],

[9], whereas the feeling of burning pain is produced by alternating touches of (non-painful) warm and cool bars (thermal-grill illusion) [10]. In contrast to weight and temperature, however, less is known regarding tactile illusions involving softness and roughness [5], [6].

In the present study, we introduce the velvet hand illusion (VHI) [11]. The VHI occurs when an individual rubs the palms of the hands on one or more grids of bars; this produces the illusory perception of a smooth velvet-like object between the hands (Fig. 1A) [1], [11], [12], [13], [14], [15], [16]. Although this illusion is not well-known in haptic research, many science museums include it in their exhibitions (e.g., the Exploratorium in San Francisco, Nagoya City Science Museum, the National Science and Technology Center in Canberra, and Bloomfield Science Museum in Jerusalem).

So far, most of the research focused on the optimal settings to elicit the illusion: the distance between the stimulating bars relative to the stroke of their movements (the R/D_v ratio), the velocity of the movement, and the relative suitability of passive or active touches [1], [13], [14], [15], [16]. Recently, a few studies have attempted to further explain the mechanism underlying this illusion. A study by Hidaka and colleagues [12] showed that rubbing the bars with the peripheral part of the palm not only induced the VHI, but also decreased the detection of vibrotactile stimuli delivered to the central part of the hand. The authors interpreted that the moving bars stimulating the hands degraded (‘masked’, [17], [18]) the sensitivity to

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other inputs delivered to the hands. The degraded sensation of the palms by bar movements is interpreted as the illusion. Therefore, the illusion is mainly elicited by the input from the bars.

In contrast, it is possible that the VHI is the result of the *integration* of all inputs delivered to the hands. In other words, all tactile inputs delivered to the hands, including the bars *and* their background (i.e., textures pertaining to the opposing hand), are combined to produce the velvet-like sensation without one input masking the others. Previous studies assumed that there was input integration to explain tactile perception [19], [20]. For instance, Kitada et al. found that humans can perceive a single object from multiple inputs to discrete skin areas [20]. This is analogous to the “common fate” in visual perceptual organization principles. Thus, authors interpret that inputs from discrete skin areas are combined to induce the perception of a single object. Moreover, in the case of the thermal grill illusion, interlaced grill of warm and cool bars causes heat pain. This illusion is explained by the integration of cold and warm sensory fibers, perhaps in the spinothalamic tract [19]. Collectively, the integration hypothesis predicts that the experience associated with the VHI is influenced by the properties of the bars *and* their background (i.e., the opposing hand).

One way to evaluate these two hypotheses (masking vs. integration) is to modulate the attributes of the background of the bars. Here, we used textures with different levels of compliance (hard and soft) replacing one of the hands of the participants. If the main mechanism responsible for the VHI is *masking* [12], then the attributes of the textures would have a negligible effect on the illusion. In other words, highly similar illusions should be induced regardless of the compliance of the textures (because this input would be masked by the input arising from the bars). Conversely, if the integration hypothesis explains the VHI, then, the illusion should be affected by the compliance of the textures (because this input would be integrated with the input arising from the bars). A previous study also showed that using rough material (sandpaper) reduces the perceived magnitude of the VHI [12]. However, using rough material such as sandpaper is likely to hinder the smooth movement of the hands (necessary for eliciting the VHI), which may be responsible for the reduced occurrence of the VHI. Thus, it may not be roughness per se that affects the experience of the VHI.

The purpose of the present study is to investigate the effects of object compliance (one of the main dimensions in tactile texture perception) on the strength of the VHI by manipulating the R/D_v ratio [1], [13], [16] and the laterality of hands. In order to ensure smooth hand movements, we used two different textures with different compliance, rather than roughness [12]. In particular, in this experiment we manipulated the hand used to rub the taut carbon bars (variable: Hand), the distance between bars relative to the extent of the stroke (variable: r/D ratio, or Frame), and the types of textures used during the VHI procedure (variable: Texture). We measured the subjective vividness of the illusion (VHI strength) and the softness of the *illusory* velvet (VHI softness). We predicted that

these variables would be affected by object compliance, especially that the perceived softness of the illusion becomes softer with softer textures.

A Velvet Hand Illusion (VHI)

B Experimental setup

C Frames

60 (Optimal for VHI)

60 mm

22.5 (Nonoptimal)

22.5 mm

D Textures

Hard texture Soft texture

Fig. 1: (A) Velvet hand illusion. When both hands are used to rub one grid of bars, one perceives the presence of a velvet-like object between the hands. (B) The setup used to induce the velvet hand illusion. (C) The two different frames used in the experiment. The 60-mm frame induces a stronger illusion than does the 22.5-mm frame. (D) The materials used in these experiments. Note that these materials were covered with the same fabric to control for roughness. The right part of the figure shows the 60-soft condition. The skin of the participant's hand contacts both the bars and material attached to the opposing hand, regardless of the material used.

2 Methods

2.1 Participants

A total of 28 naïve healthy participants were tested: 14 males [mean (M) age = 22.6 years, standard deviation (SD) = 2.0 years] and 14 females (M = 21.9 years, SD = 1.8 years). All participants were right-handed according to the handedness inventory administered at the end of the experiment [21]. Participants were recruited via email broadcast and flyer advertisement and received 15-20 SGD for their participation. None of the participants re-

ported finger or hand injury prior to the experiment. All participants provided written informed consent prior to their participation. The methods and procedures used in these studies were assessed and validated by the local ethics committee in the Division of Psychology of the Nanyang Technological University and were thus in adherence with the guidelines of the Helsinki Declaration.

2.2 Apparatus

We used the apparatus used in previous studies [1] (Fig. 1B). This apparatus allowed us to stimulate the hands of the participants while they remained still. We chose passive stimulation because it causes a stronger illusion than active touch [14], and it allows us to control the range of the movement of the bars and their speed. This apparatus consists of a disk attached to a shaft, which was connected to the frame to which the bars were attached. Each frame contained two horizontal and two vertical bars. The rotation of the disk causes a reciprocating motion of the frame along the horizontal axis. The disk contained holes that enabled the experimenter to manipulate the extent of horizontal movement (stroke, R).

Two different frames were used in this experiment: one where the amplitude of the movement of the bars (stroke, r) and distance between the two vertical bars (D_v) was equivalent ($R/D_v = 1$), and one where it was not ($R/D_v \neq 1$). Previous studies showed that the former frame induces stronger VHI [1], [13]. In this experiment, in one frame condition, *both* R and D_v were set at 60 mm ($R/D_v = 1$) and in the other frame condition, R was 100 mm and D_v was 22.5 mm ($R/D_v = 4.4$) (Fig. 1C). We termed the conditions involving the frames with 60- and 22.5-mm D_v “60” and “22.5,” respectively. The distance between the horizontal bars (D_h) was 60 mm. The instructions provided in illusion experiments can implicitly bias participants’ reports to inflate estimates of an illusion’s robustness [5], [22]. Thus, we used the 22.5-mm frame (less suitable to elicit the illusion) to confirm the presence of illusions in the 60-mm frame (i.e., the optimal one); if illusion strength ratings depend mostly on the actual strength of the illusion, there should be an influence of R/D_v [1].

The software Presentation™ 20.0 (Neurobehavioral Systems Inc., USA) was used to visually guide the experimenter during the experiment. Specifically, the program presented the time left before the onset of the trial and then a circle orbiting a larger circle after the onset of each trial on a computer screen. The experimenter manually rotated the disk by following the small circle rotating around at two angular velocities on the screen. The angular velocity was $8.5 (2.7 \times \pi)$ rad/s in the $R/D_v = 1$ condition (or “60” condition), while it was $5.0 (1.6 \times \pi)$ rad/s in the $R/D_v = 4.4$ condition (or “22.5” condition). Therefore, the mean speed of the object on the screen was maintained at approximately 80 mm/s for both frame conditions (velocity = radius of the disk $\times$ angular velocities; 30×2.7 for the $R/D_v = 1$ condition vs. 50×1.6 for the $R/D_v = 4.4$ condition). This speed was chosen because it produces the strongest VHI illusion [16].

Two different materials were used in the experi-

ment: soft and hard. The soft material was made of sponge, while the hard material was made of wood (Fig. 1D left). The materials had the same dimensions and approximately equal weights: 20 cm $\times$ 12 cm $\times$ 2.3 cm and 243.7 g for the soft material and 246.2 g for the hard material. Both materials were covered with the same smooth fabric material to control for the smoothness variable, because this experiment tested the compliance variable only. The compliances of the human palm (RK’s hand), soft object, hard object, and bar, which were measured by a force tester with 1-cm diameter cylindrical probe (KES-G5; Kato Tech Co., Ltd., Kyoto, Japan), were 2.50, 2.13, 0.31, and 0.43 mm/N, respectively. When used during the experiment, the materials were attached to customized gloves using Velcro. Gloves were worn by participants, so that the soft or hard material could be maintained on one side of the bars and the “free” hand (without glove) on the other side (Fig. 1D right). The participant could feel the softness of the material with the free hand even when the bars moved between the hand and the material. This is because a part of the free hand contacts the material before and after the vertical bars stimulate this part of the hand.

2.3 Procedure

Participants sat down in front of the apparatus, read and signed the consent form, and received the instructions. To minimize the effect of visual information, participants were blindfolded during the experiment. There were 48 trials, with half (24) of the trials involving each hand. Each series of 24 trials contained 4 repetitions of six conditions in which the frame (60 vs. 22.5) and the texture (skin vs. soft vs. hard) were manipulated. The skin condition was introduced to allow the participants to compare the illusion produced with textures with the illusion produced with the conventional setting (i.e., rubbing bars with bare hands). Therefore, each repetition included 60-skin, 60-soft, 60-hard, 22.5-skin, 22.5-soft, and 22.5-hard conditions. For example, in the left hand, 60-soft condition, the left hand was placed on one side of the 60-mm frame and the right hand wearing the glove with the soft texture attached was placed on the other side; thus, the free left hand was paired with the soft texture. The order of hands was counterbalanced across participants and the order of conditions was pseudorandomized within each repetition. The first repetition was considered practice and excluded from statistical analysis.

When a trial started, the experimenter rotated the wheel, which produced the back-and-forth horizontal movement of the frame. The participant was instructed to maintain the same force between the two hands. After 20 s of the frame movement, participants verbally reported the strength of the illusion using a number between 0 and 10. Ten indicated that the illusory object felt like a real object, while 0 indicated that no illusory object was perceived. To evaluate the illusion the participant was instructed to evaluate “how much does it feel like there is a real object?” as in [1]. Likewise, *when* it was perceived, participants were asked to report the softness of the illu-

sory velvet using a number between 0 and 10. The participants were allowed to use decimals and fractions. Similar rating methods have been used in studies on haptic perceptual organization [20], [23], and studies on illusions [1], [12], [24], [25], [26]. Before the experiment, *all* participants saw and touched a sponge (6.47 mm/N) and metal (too high to be measured with the device) that differed from the stimuli used. The participants were instructed that 10 indicated the softness perceived by touching the sponge, whereas zero indicated the softness of the metal. The experimenter helped the blindfolded participants wear gloves, attach the tactile materials to the participants' glove, and remove them. This experiment lasted about 120 minutes.

3 Results

Initially, in order to replicate our previous finding [1], we examined the effect of the frame on illusion strength when the palms of the two hands were in direct contact with each other (skin condition). We then examined the effect of texture on VHI strength and VHI softness (dependent variables) with the Hand (left vs. right), Frame (60 vs. 22.5), and Texture (soft vs. hard) as independent variables.

3.1 VHI strength

3.1.1 Skin condition

All participants experienced the illusion in the 60-mm frame condition, whereas 25 (out of 28) participants experienced the illusion in the 22.5-mm frame skin condition. Because the skin conditions were identical between the left- and right-hand conditions, we statistically evaluated the VHI strength averaged over both hands. Kolmogorov-Smirnov tests used to examine the normality of these data showed no significance (p values > 0.19). A Student's t -test showed a significantly stronger illusion in the 60-mm frame ($M = 6.28$, $SD = 1.68$) than in the 22.5-mm frame ($M = 3.92$, $SD = 2.70$) conditions [$t(27) = 4.93$, $p < 0.001$, $d_z = 0.93$], which confirms our previous finding [1].

3.1.2 The effect of texture

A majority of the participants (18 out of 28) reported the presence of the illusion in soft and hard texture conditions with the 60-mm frame (i.e., the VHI strength was above zero), whereas fewer participants (11) reported the presence of the illusion when the 22.5-mm (non-optimal) frame was used.

The first goal of this study was to examine the effect of texture on illusion strength. Thus, we included the data of all participants in this analysis. Kolmogorov-Smirnov tests used to examine the normality of these data showed significance in the following conditions: left 22.5-soft [$D(28) = 0.167$, $p = 0.044$], left 22.5-hard [$D(28) = 0.225$, $p = 0.001$], right 60-hard [$D(28) = 0.189$, $p = 0.011$], right 22.5-soft [$D(28) = 0.205$, $p = 0.004$], and right 22.5-hard [$D(28) = 0.263$, $p < 0.001$]. To our knowledge, there is no nonparametric test for 3-way repeated-measures ANOVA. As we

had specific a priori hypotheses for our data, we conducted nonparametric tests (Wilcoxon signed-rank test) with Bonferroni corrections. This approach has been used in many neuroimaging studies (e.g., linear contrasts in mass univariate analysis of functional MRI data) [1], [20], [28], [29]. The scores of the left and right hand data were averaged after confirming that there was no significant difference (p values > 0.99 , Bonferroni corrected).

Fig. 2A and Table 1 show the strength of the illusion. We confirmed the effects of Frame for the soft texture (signed rank = 342, $p = 0.003$ Bonferroni-corrected, $r = 0.60$) and hard texture (signed rank = 314.5, $p = 0.005$ Bonferroni-corrected, $r = 0.57$). Wilcoxon signed-rank tests on the strength scores showed that the score in the 60-soft condition was greater than that in the 60-hard condition (signed rank = 357, $p < 0.001$, $r = 0.76$) and that that the score in the 22.5-soft condition was greater than that in the 22.5-hard condition (signed rank = 280, $p = 0.003$, $r = 0.60$).

A. Strength of the illusion (n = 28)

B. Softness of the illusion (n = 10)

Fig. 2: (A) The strength of the perceived illusion and (B) The softness of the perceived material using two types of frames and two types of textures (data are collapsed over the variable Hand). The data are presented as boxplots where the box indicates the interquartile range [IQR, from 25th percentile (Q1) to 75th percentile (Q3)] and the thick line in the box indicates the median. Whiskers indicate the maximum and minimum value. Circles and notches of the boxes indicate data points and 95% confidence level, respectively.

In the analyses above, responses of zero were included in the data. Thus, it was not clear if there was an

effect of texture on the illusion strength when participants could experience the illusion with both textures. In order to examine this, we conducted an additional analysis using the data of the participants who experienced the illusion in *all* 60-mm frame conditions (18 participants). Nevertheless, the same non-parametric test confirmed that there was a significant difference (signed rank = 140; $p = 0.003$; $r = 0.71$). Thus, these results indicate that, compared to the soft texture, the hard texture reduced the strength of the illusion even if the participants experienced the illusion.

Table 1 Means and standard deviations (SD) of VHI Strength and Softness ratings (ranged from 0 to 10). Data are collapsed over the variable Hand. Note that “n” in the softness rating indicates the number of the participants who reported the presence of the illusion in *all* conditions.

	60 mm		22.5 mm	
	Soft	Hard	Soft	Hard
Strength (n = 28)				
Mean	4.42	3.15	3.10	2.11
SD	2.59	2.82	2.86	2.58
Softness (n = 10)				
Mean	6.51	4.58	6.04	4.18
SD	1.63	1.95	1.40	1.96

3.2 Perceived softness of the VHI

To further investigate the effect of texture, we analysed softness ratings of the illusion. For this analysis, we only included participants ($n=10$) who experienced the VHI in all texture conditions (soft and hard). Fig. 2B and Table 1 show the VHI softness. Kolmogorov–Smirnov tests performed to examine the normality the VHI softness data in each condition showed no significance (p values > 0.19). Thus, we used 3-way repeated measures ANOVA for the VHI perceived softness with the Hand (left vs. right), Frame (60 vs. 22.5), and Texture (soft vs. hard) as independent variables. The variable Texture showed significance, with the soft texture producing a softer illusory object ($M = 6.27$, $SD = 1.36$) than did the hard texture ($M = 4.38$, $SD = 1.90$) [$F(1, 9) = 14.89$, $p = 0.004$, $\eta_p^2 = 0.62$]. By contrast, no other main effect was observed: Hand ($p = 0.86$; $M = 5.29$, $SD = 1.76$ for the left hand; $M = 5.37$, $SD = 1.51$ for the right hand); Frame ($p = 0.18$; $M = 5.55$, $SD = 1.50$ for the 60-frame; $M = 5.11$, $SD = 1.56$ for the 22.5-frame). No other interaction effect was significant (all p values > 0.3).

A possible issue with the analysis above is that this result may be explained by the weakness of the illusion. If participants only experienced a weak illusion, they may have reported the softness of the textures rather than the softness of the illusion. Moreover, as soft textures showed greater illusion strength than did hard textures, this difference may have contributed to the observed texture effect. In order to address these points, we conducted the

following two analyses. In both analyses, we excluded the participants who experienced no illusion or weak illusion (i.e., scores lower than 3).

First, we compared the 60-soft and 60-hard conditions after excluding the participants who experienced no illusion or weak illusion (i.e., scores lower than 3). We defined the texture effect of VHI softness by subtracting the VHI softness of the 60-hard from that of the 60-soft condition. One sample t -tests showed that the texture effect was significantly greater than zero, regardless of the hand [$t(10) = 2.98$, $p = 0.028$ for the left hand; $t(10) = 5.78$, $p < 0.001$ for the right hand, Bonferroni corrected]. This result indicates that the texture effect on VHI softness was present for participants who did not experience the illusion very weakly.

Second, we conducted a linear regression analysis for the texture effect on VHI softness by treating the texture effect on VHI strength as an independent variable. Here, we defined the texture effect on VHI strength by subtracting the VHI strength of the 60-hard condition from that of the 60-soft condition. If the texture effect on VHI strength could actually explain the effect on VHI softness, the effect on VHI softness (the intercept of the fitted line) should be no more than zero after the texture effect on the VHI strength was included in the analysis. This analysis showed that the intercept of the fitted line was significantly above zero in both the left [$t(9) = 2.19$, $p = 0.028$ one-tailed] and right hands [$t(9) = 5.43$, $p < 0.001$ one-tailed]. The same analysis showed that the slope of the fitted regression line was significantly above zero for the left hand [$t(9) = 1.84$, $p = 0.050$], but not for the right hand ($p = 0.40$). These analyses therefore suggest that softness ratings are considering the velvet hand illusion rather than the softness of the textures.

4 Discussion

The main purpose of the present study was to test if the VHI can be explained by the integration hypothesis. We found that the strength and perceived softness of the illusion were affected by the textures attached to the opposing hand. This result indicates that the properties of the bars and the texture on the opposing hand affected the VHI, supporting the hypothesis.

4.1 The task design

In our experimental design we included skin conditions because none of the participants was familiar with the VHI, and we had to ensure that they could compare the illusion produced with textures (soft and hard) with the illusion produced with the conventional setting (i.e., rubbing bars with bare hands). One of the major differences between this skin condition and the other texture conditions is the area of contact. More specifically, the conventional VHI condition involves the skin of both hands, an area twice as large as that of the texture conditions. Because of this reason, the skin condition was not directly comparable with the other two conditions (soft and hard) and thus was analysed separately. However, a compari-

son between soft and hard textures was sufficient to test our hypotheses concerning the underlying mechanism of the VHI.

The soft and hard materials used in the present study were covered with the same textile (Fig. 1D), whereas weights were matched between them. Therefore, it is unlikely that perceptual dimensions such as roughness and weight could explain the observed difference between the soft and hard textures.

4.2 The effect of textures

The soft texture induced a stronger illusion and greater perceived softness of the illusion than did the hard texture, although both textures induced the illusion (with the 60-mm frame). This result is difficult to explain using the masking hypothesis; because the same movement of bars stimulated the participant's palms, such stimulation should cause the same masking effect regardless of the textures attached to the opposing hand. One possibility is that this was caused by the principles of perceptual organization. For instance, similarity of textures between an object and the background structure affects the perception of a single object (as opposed to just the background structure), indicating a grouping principle of similarity [23], [30], [31]. However, in the present study, the compliance of the hard texture was more similar to that of the bars than that of the soft textures. Therefore, the mechanism of this illusion may not be easily explained by this principle.

Alternatively, the bars and background texture may be integrated in the following manner. The movement of the bars induces a smooth sensation with low friction and hence renders the source of the sensation unclear. This may be because movement of the bars may saturate the activity of peripheral afferents. As a result, the brain assumes that such input originates from an illusory object on the palm. Then, the soft material held and pressed by the opposing hand is deformed such that the soft material and bars are placed on the same plane against the stimulated hand. This further renders it difficult to distinguish between the bars and the soft texture as the source of the tactile input. Thus, in this condition, the inputs from the bars and opposing hand are integrated. Consequently, tactile inputs originating from the soft texture may be misattributed to the illusory object, strengthening the illusion and creating the impression that the illusory object is soft. By contrast, because the hard texture is not deformed and hence remains away from the bars, inputs can be more clearly distinguished as segregated from each other. This may result in a weaker illusion than that produced with the soft texture, although information of the hard texture is misattributed to the illusion. It is necessary to further investigate how the inputs from the bars and opposing hand are integrated to produce the illusion.

The illusion ratings in the conditions with textures were not high, close to half of the canonical skin condition (6.28). This is partly because in the texture conditions, the stimulated skin area became half and the illusion was tested in a controlled manner. Even so, the main goal of

the experiment was to examine the effect of textures on illusion strength and perceived softness of the illusion. Thus, even if the participants did not feel a strong illusion, examining the effect of textures would still address our empirical question. One potential issue with the low rating of the illusion strength is the possibility that softness ratings are just ratings of textures held by the opposing hand and not of the illusion. However, the effect of texture on softness ratings was present after excluding the participants who very weakly experienced the illusion (score lower than 3). Therefore, it is reasonable to assume that the texture effect on the softness ratings is related to the illusion rather than to the texture.

Moreover, the simple regression analysis indicated a positive correlation between softness and strength ratings in the left hand (i.e., positive slope of the fitted line). The masking hypothesis cannot predict such correlation, because the texture effect on the strength rating should be negligible under the hypothesis. This also favors the integration hypothesis in which the difference in strength ratings between the two textures can be co-varied with the difference in softness ratings.

The neural mechanism underlying this illusion is not well understood. Previous neuroimaging studies have shown that texture processing involves the secondary somatosensory cortex and insula where neurons can have receptive fields covering the whole palm [28], [29]. Thus, it is possible that inputs from the bars and background texture of the opposing hand are integrated in these regions and then sent back to the primary somatosensory cortex for awareness of new textures. This speculation is consistent with our recent fMRI study on the VHI; activity in the primary somatosensory cortex is associated with the strength of the illusion and such activity is related to activity in brain regions including the secondary somatosensory cortex [1]. Future studies are needed to examine this speculation.

4.3 Implications for applications of VHI

Tactile displays, haptic devices using micro-actuator arrays, have been developed to generate surface pressure distribution caused by virtual contact. However, the ability to present a variety of realistic textures on the human skin remains limited. A previous study attempted to develop a tactile display that produces the VHI [25] with piezoelectric actuators. In this context, the result of the present study provides three findings that are potentially important to consider for future applications.

First, the strength of the illusion depended on textures attached to the hand. Thus, it is important to consider soft material (e.g., rubber) as a background texture to induce the illusion. Second, the illusion was weaker when the illusory object felt harder. One way to present illusory hard objects is to combine this illusion with other sensory modalities. For instance, visual input is used to induce the rubber hand illusion, where a rubber hand is perceived as being part of one's own body [24], [26]. Auditory input can change perception of the skin [32]. Thus, visual and auditory presentation of textures may be able

to maintain the strength of the illusion similar across conditions. Finally, we found no effect of the use of the dominant vs. non-dominant hand on the VHI; both the right and left hands showed highly similar illusion strength and texture effects. This result indicates that tactile displays using the VHI can present similarly soft textures to both hands at similar strength. This implication is especially relevant for devices that are used with only one hand (e.g., tactile mouse).

4.4 Limitations

There are four interpretational issues and limitations worth noting. First, the VHI occurrence was measured in terms of subjective ratings only, and future assessments should include the use of more *objective* measures of the illusion. For example, the physiological responses triggered by a threat to the rubber hand (skin conductance responses) were used to examine the intensity of the rubber hand illusion [26]. In our case, we could use real velvet [see 1] and ask participants to discriminate between the real material and the illusory one. In other words, the real material would act as a control condition for measuring the intensity of the illusion. It is also possible to use an electromyogram to measure activity of facial muscles (e.g., zygomaticus major), because these muscles are sensitive to the pleasant feelings that are frequently caused by the VHI [27].

Second, as in our previous study [1], we adopted manual rotation of the apparatus to induce the VHI. Therefore, speed variation was probably greater than it would be if bar movement was controlled by a motor [13], [14]. This should be further tested in a future study.

Third, we only instructed the participants to press their hands with the same force throughout the conditions. Unlike our previous study in which forces were measured, this study involved soft and hard textures which rendered accurate measurement difficult. It is important to examine in the future how forces exerted between the hand and the textures affect the VHI.

Finally, the participants may have expected some feeling of texture because they perceive texture before the onset of the illusion. Thus, it is possible that the change in perceived softness of the illusion can be partly explained by such an expectation. However, this expectation should not change the strength of the illusion because the expectation of touching soft or hard material does not predict the strength of the illusion. Thus, although the effect of texture on perceived softness of the illusion requires further investigation, our result favors the integration hypothesis rather than the masking hypothesis.

5 Conclusion

In conclusion, the present study showed that bars movement with a soft texture attached to the opposing hand elicited a stronger and softer VHI than did the same bars movement with a hard texture. This result supports the hypothesis that the VHI involves integration of tactile inputs from bars and background textures.

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