Describing the Sensation of the 'Velvet Hand Illusion' in Terms of Common Materials

Takumi Yokosaka, Scinob Kuroki, and Shin'ya Nishida

***Abstract*—When sandwiching two moving parallel metallic wires between both hands, one often experiences an unexpected tactile sensation known as the "velvet hand illusion" (VHI). Researchers have revealed the optimal conditions for inducing VHI, while the subjective nature of VHI remains obscure. In this article, we conducted a psychophysical experiment to investigate the quality and magnitude of the illusory sensation felt during VHI. Participants were asked to evaluate the tactile sensation of moving wires by giving tactile adjective and intensity ratings of the illusory sensation. In the same experiment, for the sake of comparison, participants also rated the sensation for various common materials one may encounter in daily life. We found that, as the intensity of the illusory sensation increased, the tactile sensation became softer, wetter, warmer, and more favorable. We also found that, when a strong illusion was reported, the sensation was similar to those for leather and fabrics rather than metallic wire, which suggests that the illusion indeed changes the perceived material category. These findings provide a better characterization of VHI as well as a better understanding of tactile texture perception.**

***Index Terms*—Material perception, tactile texture perception, velvet hand illusion.**

I. Introduction

We ARE surrounded by a number of textured surfaces and feel a variety of tactile sensations characterized by their materials: the softness of sponges, bumpiness of concrete, and smoothness of fur. It is known that the perception of a tactile texture remains stable despite changes in scanning speed [1], which is presumably related to our ability to estimate surface materials in a stable way (material constancy). However, we sometimes feel different materials even when touching the same object. A good example is the velvet hand illusion (VHI). The illusion occurs when sandwiching two moving parallel metallic wires between both hands (Fig. 1), and it induces "a strange velvety, slippery or oily sensation" [2] or the "sensation of rubbing a very smooth and soft texture like velvet" [3] even though metallic wire is physically very different from velvet. This is an important phenomenon for studying the tactile mechanism underlying texture and material perception since it is expected to provide researchers with a unique way of manipulating perceived textures and materials. An alternative and the standard way is to change the physical material itself, but as long as material X is perceived as material X, it is not easy to specify what factors lead to the perception of material X. Studies on VHI have been conducted in a variety of research domains; examples are the conditions required for inducing VHI in the realm of engineering [3]–[5], the relationship between VHI and tactile masking in the realm of psychophysics [6], and the brain region related to VHI in the realm of neuroscience [7]. Still, the subjective nature of VHI, i.e., the quality and magnitude of the illusory sensation felt during VHI, remains vaguely characterized. For example, the sensation felt during VHI has been described as velvety, "smooth and glistening," or oily [3]–[6], [8] as based on introspective reports, but the correctness and generality of these subjective descriptions have not been experimentally clarified. While some researchers investigated tactile ratings of smoothness, softness, and pleasantness experienced during VHI [7], [9], [10], there remains a possibility that the observed ratings might partially reflect the properties of the stimulus materials per se (e.g., materials moved between both hands, or materials placed on the other side of the wire from the hand). To validate, or update, the characterization of VHI in these studies, it is necessary to directly compare the tactile ratings and intensity ratings of the illusory sensation without changing the materials.

The aim of this study was to investigate the quality and magnitude of the illusory sensation felt during VHI. We wanted to capture the change in tactile sensations during VHI without changing the input stimulus as much as possible. To do so, we systematically modulated the intensities of the illusory sensation by changing only the wire intervals and movement directions, and we calculated the correlations between the obtained tactile sensations and the intensity of the illusory sensation. We adopted a rating task using six pairs of tactile adjectives (e.g., hard/soft and rough/smooth) that are known to be major components of the tactile texture perception space [11]. Also, the prefer'ence was measured. The evaluation task was performed under two conditions: touching wires in a variety of ways to elicit different magnitudes of VHI and touching materials one may encounter in daily life. With this, we tried to compare the sensation of VHI to those of common materials in the tactile texture perception space. Independently of this study, Komura and Ohka [12] reported a similar

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Takumi Yokosaka, Scinob Kuroki, and Shin'ya Nishida are with the NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 2430198, Japan (e-mail: yokosaka.takumi@gmail.com; shinobu@lab.ntt.co.jp; nishida.shinya@lab.ntt.co.jp).

Shin'ya Nishida is with the Graduate school of Informatics, Kyoto University, 36-1 Yoshidahon-machi, Sakyou-ku, Kyoto 6068501, Japan (e-mail: nishida.shinya@lab.ntt.co.jp).

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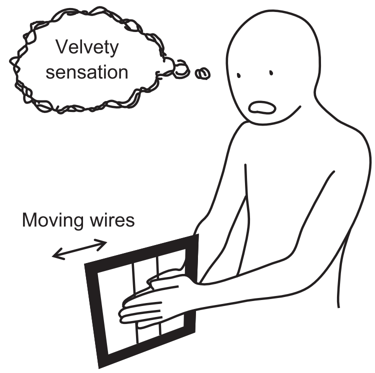

Fig. 1. Moving two parallel wires induces VHI. Sensation felt during VHI has been typically described as "velvety" in past studies.

experiment in a conference proceeding (at about the same time as we reported the preliminary results of this study [13]). Their experimental procedure was similar to ours in many aspects, and the general agreement of the two studies supports the robustness of the present findings. Unlike Komura and Ohka [12], however, we conducted a statistical correlation analysis between the intensity of the illusion and tactile adjective ratings by continuously changing the intensities of the illusory sensation. This continuous change allowed us to identify materials that are similar to each level of the illusion intensity. We predicted that when participants feel a stronger illusory sensation, the sensation would be evaluated as softer, smoother, slipperier, and more favorable and similar to the sensation for velvet material rather than metallic wires as subjectively described in past studies [2]–[6], [8].

II. Methods

A. Participants

Fifteen naïve volunteers (twelve females and three males) with an age range of 21-47 years participated in the experiment. All participants were right-handed and had normal or corrected-to-normal vision, had no known abnormalities with their motor systems, and did not know the "velvet hand illusion." They had no specialized knowledge about psychophysical experiments and were unaware of the purpose of the experiments. They gave written informed consent before the experiment began. The experimental protocol was approved by the NTT Communication Science Laboratories Research Ethics Committee and was performed in accordance with the ethical standards outlined by the Declaration of Helsinki.

B. Apparatus and Stimuli

In the experiment, the participants sat at a table on which a tactile stimulus was placed. A black curtain visually occluded the hand and tactile stimulus from the participants' view. We used two types of stimuli, one for the wire condition and one for the material condition. The stimuli of the wire condition were two parallel bronze guitar strings fixed to an aluminum frame (Fig. 2 a). The diameter of the guitar strings was 0.89 mm. The length of the wires was 250 mm. The stimuli of the material condition consisted of 30 different textured materials such as fabrics, woods, and metals (Fig. 2 b). All material stimuli were fixed on a wooden panel so that the total thickness became 30 mm. They were in the shape of 100 $\times$ 100 mm squares. We adopted material stimuli 100 $\times$ 100 mm in size since we confirmed that they spanned a wide range of perceptual qualities as shown in our previous studies [14]–[16]. A low-friction linear slider was used to guide the linear movement of the wire and material stimuli. The participants wore earplugs throughout the experiment to mask any noise made by the relative motion between the hands and stimuli.

C. Design and Procedure

At the beginning of the experiment, we let the participants experience VHI for the first time. We induced VHI by using different materials (metallic wire [4], nylon string [2], and cardboard [9]) so that they could understand the shared illusionary feeling as distinct from the physical properties of the material (e.g., wire). An experimenter told them that the sensation we targeted in this study is "a perceptual illusion on the fingers and palm/s[1] that is different from the normal tactile sensation of wires." Note that the experimenter did not use any particular words such as "velvet," "smooth," "soft," and so on to explain the illusion, as doing so could have affected the participants' rating.

The experiment consisted of three blocks, and each block consisted of 39 trials (each of 9 wire stimuli + 30 material stimuli was presented three times). The presentation order of the 39 stimuli was randomized for each block. Before the start of the experiment, the participants performed one block to familiarize themselves with the procedure of the session and to normalize the variation in their tactile adjectives ratings within our stimuli set (i.e., wire and material conditions). Each participant completed all blocks within four hours (including breaks). In each trial, participants kept their hands static, and an experimenter selected a stimulus from either the wire or material condition and moved it across the participants' palm/s and fingers for seven seconds. The mean speed of the stimulus was around 100 mm/sec. The movement direction (forward/back or up/down) of the stimuli in the wire and materials conditions was reversed every 0.5 sec (i.e., the stroking distance was 50 mm). The wire condition consisted of nine stimuli (four intervals between wires $\times$ two movement directions + one control condition; Fig. 2 a). We varied the interval between the wires and movement directions to modulate the intensity of VHI [2]–[5]. The interval of the two wires was 0 (i.e., one wire), 25, 50, or 75 mm. Participants held the wire stimulus between both hands, and the wires were repeatedly moved horizontally or vertically between their fingers and palms. We also tried a one-hand condition (control condition) wherein the participants touched horizontally moving wires (interval of 50 mm) with only the left hand. The stimuli of the material condition were moved horizontally, and the participants touched them with the left hand. Participants were asked to give ratings in terms of hard/soft, rough/smooth, sticky/slippery, cold/warm, bumpy/flat, wet/dry, and favorable/unfavorable on a seven-point scale for the tactile sensation on their hand/s. The first six adjective pairs are known to be major components of the tactile texture perception space [11]. The rating order of these seven pairs of adjectives was randomized in each trial. When touching a stimulus of the wire condition, the participants rated the intensity of the illusory sensation of VHI (see the definition of VHI in the previous paragraph) in addition to rating the

[1] Since the stimuli were applied to one hand in some conditions and to both hands in the other conditions, we use "hand/s" or "palm/s" for the latter.

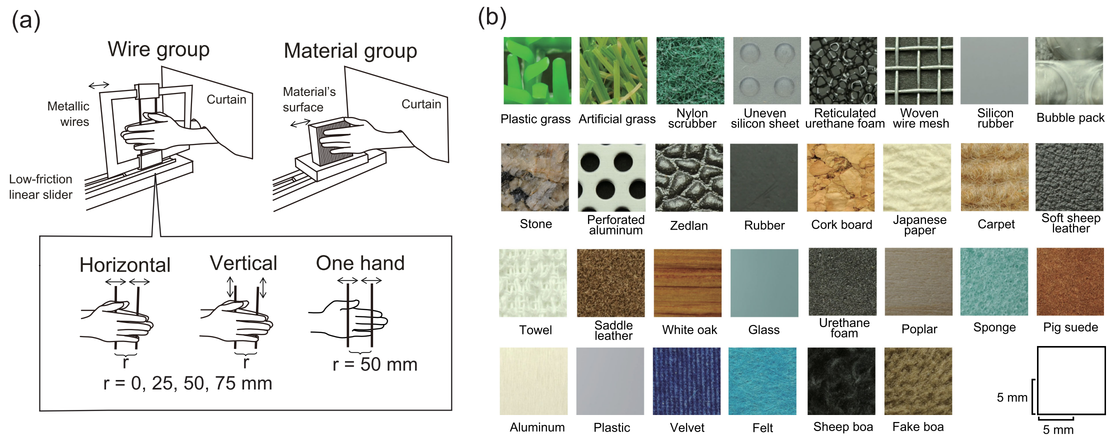

Fig. 2. Experimental setup. (a) Stimuli of wire and material conditions. (b) Magnified images of materials used for stimuli of material condition.

perceived sensation with the seven pairs of adjectives. An experimenter manually moved the stimulus horizontally along the low-friction linear slider on which the stimulus was mounted (Fig. 2 a). When moving the wires vertically, we used a standing linear guide for the motion of the wires. Participants were instructed to touch the stimulus with both hands just before the horizontal or vertical movement condition for the wire stimulus (except for the one-hand condition) was conducted and with the left hand just before the other conditions were conducted.

III. Results

First, we show the averaged intensity ratings of the illusory sensation for the stimuli of the wire condition (Fig. 3) to see whether we were able to modulate the intensity. A two-way repeated ANOVA with movement direction and wires' interval as factors shows that there were significant effects for the movement direction ($F(1,14) = 85.68, p < 0.01, \eta^2 = 0.22$), wire interval ($F(3,42) = 74.98, p < 0.01, \eta^2 = 0.42$), and interaction effect ($F(3,42) = 35.42, p < 0.01, \eta^2 = 0.11$). These results show that horizontally moving the wires tended to induce a stronger illusory sensation than vertically moving them and that the larger the interval between the two wires was, the stronger the intensity of the illusory sensation tended to be. These trends are in line with earlier reports [2], [5]. Taken together, we were able to modulate the VHI intensity by changing the stimulus condition.

Second, to investigate how the sensation was modulated during VHI, we show Spearman's correlations between the intensity rating and the other tactile ratings for the stimuli of the wire condition (Fig. 4). The intensity ratings of the illusory sensation had statistically significant correlations with the hard/soft, cold/warm, dry/wet, and favorable/unfavorable ratings (all $p < 0.05$), which indicates that the illusory sensation was evaluated as softer, warmer, wetter, and more favorable within the range of our material stimuli. However, our data did not show statistically significant correlations of VHI intensity with "rough/smooth" ($p = 0.36$), "sticky/slippery" ($p > 0.99$), and "bumpy/flat" ($p > 0.99$). Note however that the rating difference between the two extreme conditions (H75 and H0) was statistically significant for smoothness as well for hardness, coldness, and wetness (Fig. S1; see also Discussion for the reasons of this additional analysis).

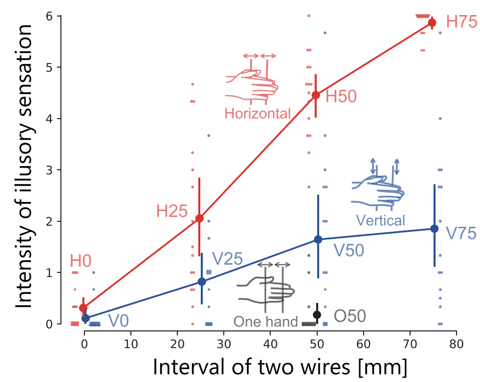

Fig. 3. Intensity ratings of illusory sensation for stimuli of wire condition. Error bars denote 95 percent confidence interval that were calculated by the bootstrap method [17]. Rating was averaged across repetitions for each participant. "H" and "V" in graph denote conditions wherein wires moved horizontally and vertically, respectively. "O50" denotes one-hand condition. Number after "H," "V," and "O" denotes interval between wires.

Here, to assess whether the illusory sensation felt with the wires moving in the horizontal direction was different from that felt with the wires moving in the vertical direction, we compared the shift in the tactile adjective rating from H0 to H75 (H75-H0) with the shift from V0 to V75 (V75-V0). Since the difference in intensity ratings between V75 and V0 was smaller than that between H75-H0 and similar to that between H25-H0 (see Fig. 3), we also calculated the values of H25-H0 for the sake of comparison. The results are shown in Fig. S2. We found that H75-H0 was judged as different from V75-V0 for hardness, roughness, and favorableness ratings. However, this discrepancy between the two directions (V and H) became small when matching the intensity of the illusory sensation; V75-V0 did not have a statistically significant difference from H25-H0 for the ratings. Our data therefore suggest that the illusory sensation is different in magnitude but similar in quality between the horizontal and vertical directions of wire movement.

Finally, to further evaluate the quality of the illusory sensation felt during VHI, we tried to find such textures that induce a similar sensation to VHI by mapping all of the stimuli in the wire and material conditions to a space consisting of six tactile adjective pairs regarding physical characteristics. The favorableness rating was not included in this analysis since it reflects an affective aspect rather than a physical one. We

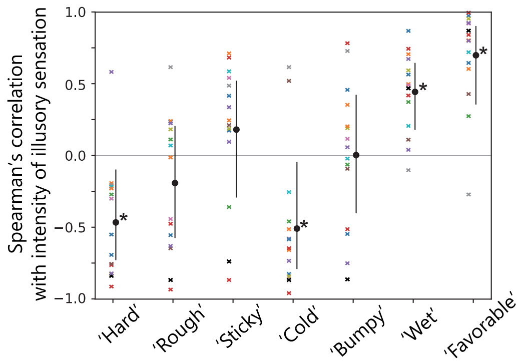

Fig. 4. Spearman's correlation coefficients between intensity and tactile ratings. Error bars denote confidence interval calculated by bootstrap method [17] and Bonferroni-corrected so that range was 95 percent in total. Each rating was averaged across repetitions for each participant.

conducted a multidimensional scaling (MDS) analysis by using a similarity matrix between all stimuli to construct a similarity space and reduce the redundancy. The Euclidean distances between all stimuli on the six-adjective-pair space were calculated to compute the similarity matrix. The similarities were visualized in three-dimensional space (Fig. 5) since the stress values showed that three dimensions were sufficient for representing the original space (Fig. S3). We found that saddle leather[2] was the closest stimulus to H75 (horizontally moving wires having 75-mm interval) that induced the strongest illusory sensation. The velvet material was the sixth closest to H75, which is neither very close nor far from H75 (see also Fig. S4). In addition, wire mesh was the closest stimulus to O50 (one-hand condition where the intensity ratings of the illusory sensation seemed to be zero). Cork board was the closest to all the other wire conditions that induced moderate sensations of illusion. Interestingly, even though we did not use the illusion intensity ratings in this analysis, dimensions 1 and 3 had high correlations with the illusion intensity ratings (Spearman's correlation coefficients with positions in dimensions 1, 2, and 3 were 0.75, -0.10, and -0.93, respectively). We can see that the nine wire condition stimuli from O50 to H75 are arranged on a straight line, roughly in the order of the intensity of the illusory sensation. Saddle leather (and velvet, too) is located around the end of this line. In summary, the results suggested that the sensation for the moving wires dramatically and continuously altered from the original wire mesh-like sensation to a saddle leather-like sensation as the illusion intensity increased, rather than the wire sensation changing to a completely different tactile sensation once the illusory sensation occurred. We also conducted a principal component analysis to visualize the relationships between the stimuli and found that the result was very similar to the MDS results (see Fig. S5).

IV. Discussion

In this study, we characterized the sensation felt during VHI with tactile adjective ratings by comparison with those for common materials in order to understand the quality and magnitude of the illusory sensation felt during VHI. Previous studies suggested that VHI may increase softness, smoothness, and pleasantness ratings [7], [9], [10]. These studies compared the ratings among a wire-touching VHI condition, wire-touching no-VHI condition, and real-velvet-touching condition, but it still remains obscure how much the estimated sensation reflected the effect of VHI itself and how much it was affected by the physical materials of the inducing stimuli (e.g., metallic wires). One previous study suggested that softness ratings correlate with VHI intensity ratings [10], but they did not provide clear evidence as stated in Introduction. Here, to characterize the VHI sensation itself, we examined how the tactile ratings changed with an increase in the intensity of VHI without changing the stimulus material.

First, we found that the intensity ratings of the illusory sensation for the vertically moving wires tended to be smaller than those for the horizontally moving wires, but not zero for wires having a larger interval. Since it was reported that vertically moving wires induced an illusory flat surface, not a velvety sensation [2], our participants might have evaluated the intensity of the illusory flat sensation instead of the velvety sensation in the vertical-movement conditions. Another possibility for the non-zero intensity ratings for the vertically moving wires is that our vertical-movement condition also had a tiny horizontal-movement component and induced the illusory sensation. Indeed, one researcher shared a valuable experience stating that the VHI is relatively clearly caused by even very tiny horizontal movements of wires (personal communication). Also, it is difficult to completely remove the effect of the horizontal-movement component even under the vertical-movement condition due to the difficulty of maintaining a steady hand position. Therefore, to disentangle the effect of the tiny horizontal-movement component on the illusory sensation from that of the vertical-movement component (e.g., an illusory flat surface) would be an interesting challenge in future studies.

Second, we computed the correlation of the intensity ratings of the illusory sensation with the tactile adjective ratings. To this end, we systematically controlled the intensity of the illusory sensation by modulating the intervals between the wires and movement directions. We found that the sensation during wire movement was evaluated as softer, warmer, and wetter when participants reported stronger intensities of the illusory sensation. However, the intensity ratings did not have very strong correlations with "rough/smooth" and "sticky/slippery."

We also found that the evaluated favorableness tended to be larger when participants reported a stronger illusory sensation. Although a previous study showed the possibility that evaluated pleasantness ratings for the VHI sensation were comparable to those for real velvet [7], our result showed, for the first time, the correlation between evaluated favorableness and the illusory sensation. There are a couple of possible explanations for this correlation. One explanation would be that the softer, warmer, and/or wetter sensations arising during a stronger illusion were evaluated as more favorable. Since it was known that the participants tended to like higher compliance surfaces [18], [19] and dislike wet ones [20], the favorableness evaluation in our study might reflect an increase in the softness sensation more than an increase in the wetness sensation. Another explanation might be that the tactile sensation of fabrics, which was close to the sensation during the stronger illusion (Fig. 5), was more favorable than that of the original material (i.e., metallic wire). In our previous study, we found that preference ratings for fabrics tended to be higher than other materials [16], which is consistent with

[2] The saddle leather we used in this article was cow hide tanned using tannin.

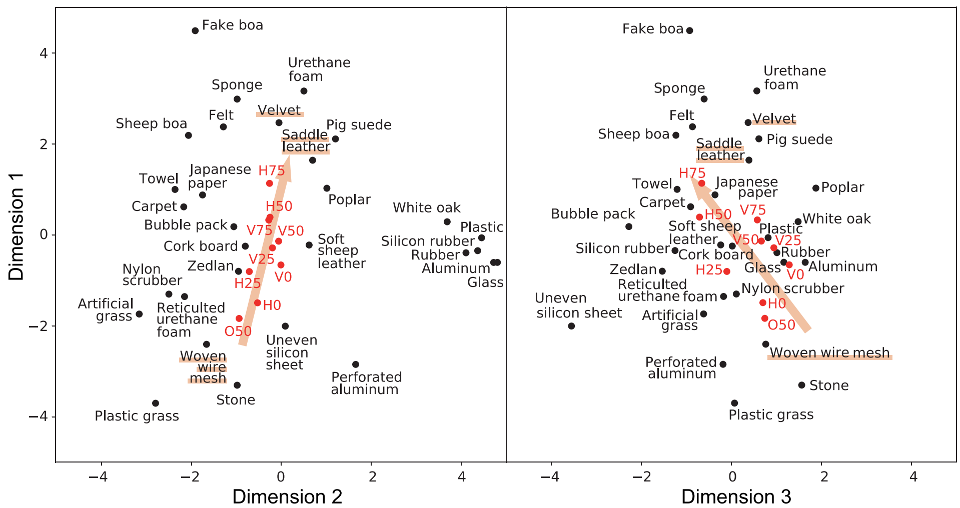

Fig. 5. Results of multidimensional scaling. Red dots denote stimuli of wire condition. Direction of arrow indicates direction inducing stronger illusion. "H," "V," and "O" mean horizontally-moving condition, vertically-moving condition, and one-hand condition, respectively. Number after "H," "V," and "O" denote intervals between wires. Each rating was averaged across repetitions for each participant. Then, since bootstrap analysis showed similarity among participants' ratings was statistically significant (see Fig. S6), ratings were averaged across participants. Correlation coefficients between each dimension and tactile ratings are shown in Fig.S7.

the explanation. Note that this explanation may overlap with the first explanation since it is also known that the physical properties of fabrics that make participants feel pleasant are softness, smoothness, and warmth [21]. Another explanation might be that participants evaluated the VHI experience itself as more interesting and therefore preferred it due to the gap between expected and perceived sensations.

We also assessed whether the illusory sensation induced by the horizontally moving wires was different from that induced by the vertically moving wires and did not find evidence when the intensity of the illusory sensation was matched. Our conjecture here is that the illusory sensation for vertically moving wires might be qualitatively similar (though quantitatively different) to that for horizontally moving wires, at least in terms of the tactile adjectives we used in this experiment.

Finally, we visualized the quality and content of the illusory sensation felt during VHI by comparing the tactile adjective ratings for the stimuli of the wire condition with those for the common material stimuli. We found that the tactile ratings for the moving wires in the one-hand condition, for which the intensity ratings of the illusory sensation were almost zero, were the most similar to those for the wire mesh, which seems to be reasonable since both the wire mesh and moving wires were made of metallic wire. The tactile ratings for the moving wires having a 75-mm interval in the horizontal moving condition (H75) that induced the strongest illusory sensation were the most similar to those for the saddle leather. We also found that all of the stimuli of the wire condition were lined up according to the order of intensity of the illusory sensation in the MDS space even though we did not use the intensity ratings in this analysis. Importantly, our MDS analysis showed that the sensations of the wire stimuli in the MDS space spread across different material categories. This is consistent with the idea that VHI can modulate tactile sensation beyond material categories rather than within a category.

As mentioned in Introduction, Komura and Ohka (2019) recently reported a related experiment [12]. They asked the participants to make a variety of tactile adjective ratings for one-wire conditions (expected to induce no VHI) and two-wire conditions (expected to induce strong VHI), together with 21 materials. The experimental design of this study was similar to ours, although we were more careful in that we conducted a statistical correlation analysis between the intensity ratings and tactile ratings by systematically modulating the intensities of the illusory sensation, rather than only comparing the two end points (i.e., with and without inducing the illusory sensation). We also took special care not to use the term "velvet" at all in the instructions given to the participants prior to the experiments, but how Komura and Ohka gave instructions was not clear. As for the results, Komura and Ohka found that the sensations for the two-wire conditions were warm-softer, smoother, and more slippery than those for the one-wire conditions, in general agreement with our results. Although we did not find significant correlations between the smoothness/slipperiness and the intensity ratings of the illusory sensation, this apparent discrepancy was reconciled when we analyzed our data in the same manner as their study. Indeed, we found a significant change in rough-smoothness when we directly compared the minimum and maximum conditions of the illusory sensation (Fig. S1). Komura and Ohka also reported that the VHI was similar in feeling not only to velvet but also to such materials as sheepskin (in the dimensions of warmth-softness and smoothness). This is also consistent with our results. As a whole, the results of Komura and Ohka support the robustness of our findings.

Our results provide insights into the mechanism of VHI and into tactile texture perception in general. Several hypotheses have been proposed to explain the mechanism, such as the filling-in [2], tactile masking [6], and integration [7], [10] hypotheses. Filling-in is a function that is thought to complement missing information. In the case of VHI, the illusory sensation can be the product of our brains filling in the empty region between wires with the tactile sensation for wires. If filling-in occurs, the sensation of wires (source of inputs) becomes evident through an intense illusory perception (e.g., a harder and/or colder sensation is evoked). Clearly this is not the case we observed. Tactile masking is a phenomenon in which tactile sensitivity is suppressed or degraded by another tactile stimulus. In the tactile masking hypothesis, it is assumed that a tactile sensation felt on the hands is masked by the moving wires and interpreted as frictionless. If tactile sensitivity on the hands were degraded by the moving wires, that variations in the tactile ratings would become large when a strong illusion was induced. Our results do not fully fit this assumption since the variations of all tactile ratings did not change (Fig. S8). In the integration hypothesis, the VHI sensation is explained as an outcome of the integration of sensation felt by the hand with wires and that with the palm of the other hand. We found that the sensation for the almost-zero VHI condition was similar to a wire mesh and those for a stronger VHI condition were evaluated as softer, wetter, and warmer. This could be interpreted as the sensation for the wires being shifted towards that for hand skin as wire movement induces the optimal illusion. Synchronized wire movement may trigger the integration of the sensation from the wires, leading to difficulty in isolating each tactile input detected between wires (i.e., the tactile inputs are integrated). The difference between vertically and horizontally moving wires seems to be explained by the matching of inputs' attributes [22]. It can be speculated that separating of the tactile input of the wires from that of the opposing hand's skin became difficult under the horizontal movement condition due to an overlap in the location between these two. The integration hypothesis explaining VHI suggests that our tactile texture perception has the nature of forming holistic and integrated estimation of multiple inputs. This nature has been supported by other lines of tactile studies, revealing that the frequency/texture perception of an input is integrated with that of another input synchronously presented at a different location on the skin [23]–[25]. Although the nature would be useful for brains to efficiently compute tactile sensation across different skin areas making contact with the same object, different inputs that are presented at different skin locations could be sometimes integrated erroneously.

Our results showed that moving wires with different spacing could induce not only velvet but also a variety of tactile sensations across material categories (from a wire mesh-like sensation to saddle leather-like sensation). This finding could be applicable for the design of haptics devices that induce rich material sensations.

V. Conclusion

In this study, we investigated the quality and magnitude of the illusory sensation felt during VHI. To this end, we asked participants to give tactile adjective ratings for the tactile sensation felt when touching moving metallic wires that induce VHI. To carefully assess the relationships between the tactile adjective ratings and the illusory sensation, we systematically varied the intensities of the illusory sensation. As a result, we found that VHI is the illusion of softness, warmth, and wetness. We also asked participants to give tactile adjective ratings for the tactile sensation for common materials and mapped the sensation for the moving wires and materials into tactile perceptual space, and we found that the metallic wires felt like a different material when a strong illusory sensation was induced. Our findings provide a better characterization of the sensation felt during VHI and a better understanding of tactile texture perception.

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