Effect of Normal Force Intensity on Tactile Motion Speed Perception Based on Spatiotemporal Cue

Yusuke Ujitoko, Yuko Takenaka, and Koichi Hirota

***Abstract*—While the relative motion between the skin and objects in contact with it is essential to everyday tactile experiences, our understanding of how tactile motion is perceived via human tactile function is limited. Previous studies have explored the effect of normal force on speed perception under conditions where multiple motion cues on the skin (spatiotemporal cue, tangential skin deformation cue, and slip-induced vibration cue) were integrated. However, the effect of the normal force on speed perception in terms of each motion cue remains unclear since the multiple motion cues have not been adequately separated in the previously reported experiments. In this article, we aim to elucidate the effect of normal force in situations where the speed perception of tactile motion is based solely on a spatiotemporal cue. We developed a pin-array display which allowed us to vary the intensity of the normal force without causing tangential forces or slip-induced vibrations. Using the display, we conducted two psychophysical experiments. In Experiment 1, we found that the speed of the object was perceived to be 1.12-1.14 times faster when the intensity of the normal force was doubled. In Experiment 2, we did not observe significant differences in the discriminability of tactile speed caused by differences in normal force intensity. Our experimental results are of scientific significance and offer insights for engineering applications when using haptic displays that can only provide spatiotemporal cues represented by normal forces.**

***Index Terms*—Speed perception, tactile motion, normal force, pin-array display, spatiotemporal cue, haptic, tactile.**

I. Introduction

The relative motion between our skin and objects in contact with it is fundamental to our tactile experience. When we actively explore and manipulate objects, our hands inevitably move across their surfaces, generating a relative motion between our hands and the objects. This relative motion allows us to perceive the haptic properties of the objects, including their shape, material, and texture [1], [2], [3]. Furthermore, relative motion itself plays a crucial role in our everyday interactions with the environment, as evidenced by our ability to grasp and manipulate objects effectively. For instance, when initially grasping an object, our ability to detect unexpected tactile motion on the object's surface triggers an automatic reinforcement of the grip [4]. Furthermore, it is known that we have the ability to perceive the speed of such motion through touch [5].

Despite the importance of tactile motion in our daily lives, our understanding of motion perception in human tactile function is limited. Tactile motion perception involves multiple motion cues (spatiotemporal cues, slip-induced vibration cues, and tangential skin deformation cues), which add to its complexity [6]. Most previous studies have investigated perceptual characteristics of tactile motion in the particular situation of a real object sliding across the skin [7], [8], [9]. In this scenario, the multiple motion cues are integrated into tactile motion perception. However, since these studies have not isolated motion cues in their experiments, the role of individual cues on speed perception remains unclear. For example, a previous study showed that the discriminability of tactile motion speed was improved under conditions where a larger normal force was applied [8]. While this was attributed in that study to the suppression of slip-induced vibration, the role of other motion cues, such as spatiotemporal cues, is unclear for conditions where a larger normal force is applied.

This study focuses on the role of the normal force in a situation where humans perceive tactile motion speed based only on spatiotemporal cues. We anticipated that the intensity of the normal force would have an effect on speed perception based on the following conjecture. It is assumed that motion is computed based on the sequential activation of nerve fibers with spatially displaced receptive fields [10]. The mean firing rates of nerve fibers tend to increase as stimuli move faster across the skin, implying that motion speed information is encoded in these firing rates [11]. The mean firing rates can account for the perceived speed [12]. It is also known that mean firing rates are modulated when stroking the skin with a stiffer and less stiff brush, indicating that the intensity of the normal force may modulate mean firing rates [11]. Thus, we speculated that the intensity of the normal force may be related to speed perception in situations where that speed perception is based solely on spatiotemporal cues.

We developed a pin-array display for our experiments. Our pin-array display was capable of varying the intensity of normal

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the ethics committee of the University of Electro-communications under Application No. 23007, and performed in line with the Helsinki Declaration.

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force without altering shear force or slip-induced vibration when representing object motion on the skin. We conducted two psychophysical experiments in which we systematically manipulated the intensity of normal force using the pin-array display. In Experiment 1, we investigated the effect of normal force intensity on the magnitude of perceived speed. In Experiment 2, we investigated the effect of normal force intensity on the discriminability of perceived speed.

Our experimental findings hold both scientific significance and offer valuable insights for engineering applications. In virtual reality (VR), tactile motion perception is crucial for users to discern the haptic properties of virtual objects (e.g., shape and texture), dexterously manipulate them, and communicate with others through affective touch [13]. In the context of representing motion on the skin for VR applications, one of the more common methods involves the use of a haptic presentation device (e.g., pin-arrays [14]) capable of exerting forces in the normal direction. For such devices, determining the intensity of the presented normal force is a key design consideration. Improved knowledge about the role of normal force intensity on tactile speed perception will be valuable for determining optimal levels of the force to be applied to users' skin through such haptic displays.

II. Related Work

In order to characterize motion speed perception based on tactile information, comparisons have been made with motion speed perception based on other types of cue. In [15], participants estimated the speed of a moving object either solely from tactile cues (i.e., motion across the skin) while keeping their hand stationary or solely from kinesthetic cues by tracking the object with a guided arm movement. Participants tended to overestimate motion speed when relying on tactile cues compared to kinesthetic cues. Other studies have compared visual and tactile motion speed perception [16], and explored the specific influence of visual motion on tactile motion speed perception [17], [18]. There has been a report of visual pursuit eye movements introducing bias to the perception of speed [19].

Previous studies have aimed to identify the specific tactile cues that impact the perception of motion speed. It has been shown that spatiotemporal cues originating from an object's surface (e.g., the spatial distance between surface dots and the periodicity of the dots) influence the perception of motion speed [7], [20]. The material types of the surfaces also influenced speed perception [12]. The material-dependent effects seemed to be related to the intensity of slip-induced vibrations. Vibrations originating from relative motion have been shown to influence the discrimination of motion speed perception [21]. This may be related to the fact that motion speed influences the intensity and frequency composition of slip-induced vibrations [22]. The effect of slip-induced vibration on speed perception has been suppressed by the presentation of masking vibrations. Application of a substantial normal force has been shown to mitigate the influence of masking vibrations [8]. While various cues influencing tactile motion speed perception have been studied, the specific impact of the normal force in isolation, without alterations in shear force or slip-induced vibrations, remains unexplored, and constitutes the central focus of this study.

Previous research investigating the perception of tactile motion speed using real objects, has focused on two stimulus scenarios in which (1) the contact area moves on the skin (e.g., [5]), and (2) the contact area remains fixed while the spatiotemporal pattern of the stimulus presented on the skin is varied (e.g., [7]). For example, in the former scenario, the hand is stroked with a brush while in the latter scenario, a relatively moving surface continuously stimulates the same skin area. This study employed the former stimulus type in our experiments since it represents one of the most basic stimuli that can be presented with a pin-array display. A pin-array display can also replicate the stimulus in the latter scenario by spatially reproducing the stimulus presented in the former scenario.

III. Apparatus

A. System Overview

We developed an experimental system consisting of a pin-array display, an air pressure controller, and a PC (see Fig. 1(a)). The system architecture was the same as that in our previous study [14].

B. Pin-Array Display

Fig. 1(b) shows the pin-array display. Participants were instructed to place their right hand on an ABS resin base which had on its surface a hand-shaped dent and a series of pin holes with a 2 mm diameter (see Fig. 1(c)). The pin holes and hand-shaped dent in the resin base were created using CNC machining (Original Mind, Qt100). The hand-shaped dent was designed to ensure that the participant's hand and the pins would make good contact without any gaps between them, and it was modeled on the surface shape of a hand model obtained from BodyParts3D [23]. To prevent the participants' fingers, particularly the thicker ones, from becoming lodged in the dent of the display, we scaled down the thickness of the hand model by half during the modeling of the dent. The maximum depth of the dent was 3.9 mm.

Cylindrical pins were created using Clear Resin with a 3D printer (FormLab, Form3). Pins with a 1.9 mm diameter were arranged in a grid pattern with a 3 mm spacing between their centers. Our experiments utilized only the pins enclosed by the blue line in Fig. 1(b). The air pressure applied to each pin was independently controlled. Calibration was performed for each pin to ensure the accurate delivery of the target pressure stimulation within a pressure range up to 0.06 MPa.

To evaluate the temporal resolution of the display, we manipulated the stimulus onset asynchrony (SOA) of adjacent pins with 3 mm spacing and measured it using high-speed camera (SONY, RX0M2). The evaluation result showed that pin control was achievable in the millisecond order. Please see details in Supplementary Note 1 and Supplementary Fig. 1.

C. Other Components

The experimental software running on the PC transmitted control values to the FPGA (Xilinx, XC7S50) in the air pressure

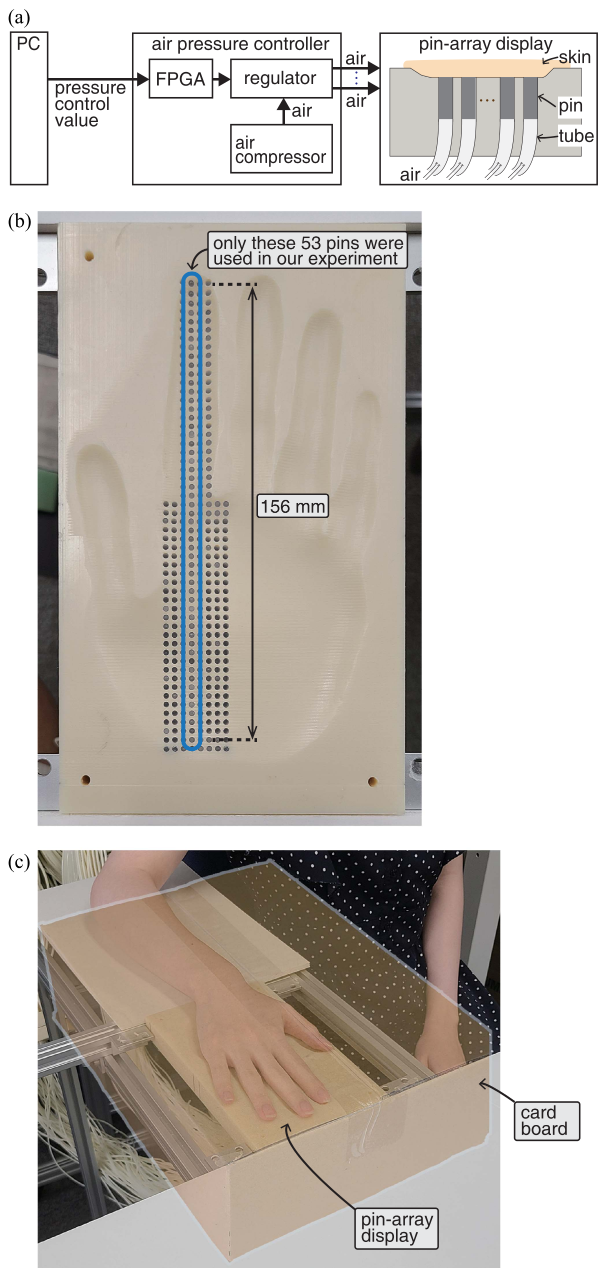

Fig. 1. (a) Components of experimental system and data flow. (b) Pin-array display. In total, a straight line of 53 pins was used in our experiment. (c) The participant's right hand that was located on the pin-array display. A cardboard barrier was positioned to prevent participants from seeing their right hand.

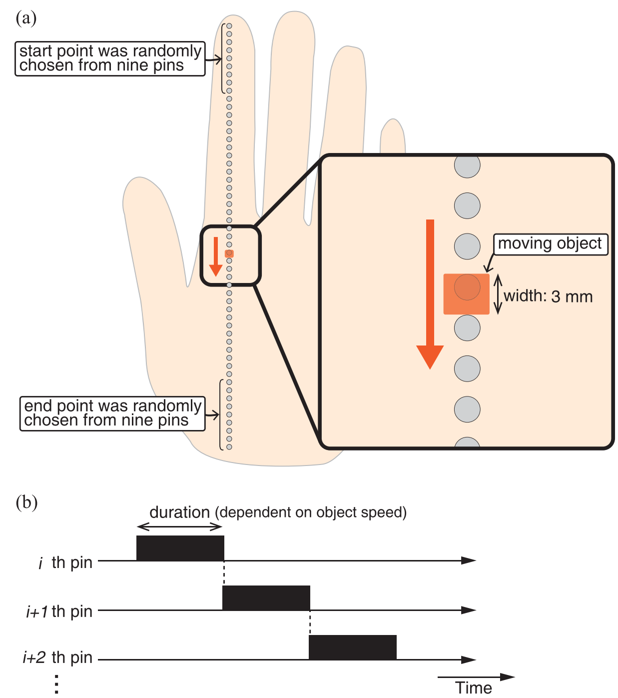

Fig. 2. (a) Virtual moving object (colored in orange). The moving object was represented by the pin-array display in the experiment. Start and End points were randomly chosen. (b) Timing when pins were pressured to push out. Pins were sequentially pressured.

controller through USB serial communication. The air pressure controller's internal regulator (SMC, VY1B00) controlled the valves. To efficiently generate the air needed for the system, two air compressors (RYOBI, ACP-50 and ACP-60) were employed as air sources for the regulator. The regulator operated at a response time of 30 ms.

IV. Experiment 1: Effect of Normal Force Intensity on Perceived Speed of Tactile Motion

In this experiment, we investigated the effect of normal force intensity on the magnitude of perceived speed of tactile motion. The experiment followed a within-participants design.

A. Participants

Ten male participants took part in the experiment; all were right-handed and had a mean age of 23.3 (SD: 1.3) years. All participants were naive to the purpose of the study and reported no sensorimotor disorders. The experiment lasted approximately 45 minutes, and the participants were paid about 1,200 Japanese yen (equivalent to about 8 USD) for their participation. Ethical approval for this study was obtained from the ethics committee of the University of Electro-communications (approval number: 23007). The experiments were conducted following principles that have their origin in the Helsinki Declaration.

Participants were comfortably seated in chairs. They wore earplugs and noise-canceling headphones that played white noise to block out external sounds. The participants rested their right arms on the armrests, with their right hands placed on the pin-array display. A cardboard barrier was positioned over the right hand to prevent participants from seeing the pin-array display (Fig. 1(c)). We measured the size of the participants' hands along a straight line following the pin layout and found that the average was 175.5 (SD: 5.0) mm.

B. Stimulus

The pin-array display simulated a virtual moving object with a constant speed, spanning a width of 3 mm in a line from the fingertip to the wrist, as illustrated in Fig. 2(a). Pressure was applied to push out the pin when any part of the virtual object overlapped with the center positions of the pins. The rationale for setting the object's width to 3 mm was to ensure a consistent normal force as the object moved along the pin-array with its 3 mm spacing between the pins (see Fig. 2(b)). Setting the width over 3 mm would result in a momentary simultaneous actuation of two adjacent pins. Setting the width below 3 mm would result in a brief period of time during which no actuation of any pins would occur. In both scenarios, unintended variations in normal force intensity would occur, which would be clearly unsuitable for a study investigating the effects of normal force intensity.

To prevent participants from judging speed based on either the global distance of movement or the duration, for each stimulus we randomly selected one of the nine pins near the fingertip to be the starting point for the object's movement. Likewise, we randomly selected one of the nine pins near the wrist to be the endpoint of the object's movement. Consequently, the shortest movement distance covered 108 mm (37 pins), while the longest movement distance spanned 156 mm (53 pins).

This implementation, involving the random assignment of starting and ending points for the movement stimulus, was related to the definition of the stimulation area we wanted to adopt in this experiment. Unlike previous studies that focused solely on stimulating the fingertip area (e.g., [7]), we wanted to conduct stimulation across both the finger and palm areas. By activating a series of pins over this extended area, we increased the pool of pins available for random selection as starting and ending points, thereby enhancing the randomization of the movement distance.

To clarify the effect of normal force intensity, we configured two conditions of intensity per pin: 0.015 MPa (0.0425 N) and 0.03 MPa (0.085 N). The rationale for this configuration is as follows. We aimed to explore the impact across a wide range of normal force intensities. However, when we represented relatively high motion speeds (e.g., 0.12 m/s) with the developed display, we found that intensities exceeding 0.03 MPa per pin caused pain for the human subject. To prevent a perception of pain from influencing the results, we capped the maximum pressure condition at 0.03 MPa. Also, we found that intensities below 0.015 MPa were sometimes too weak to be perceived clearly. Therefore, we selected a range of 0.015 MPa and 0.03 MPa for pin intensity in this experiment.

C. Procedure

At the beginning of the experiment, participants were provided with written instructions explaining the details of the experiment and were asked to provide informed consent in writing. Then, they moved on to the practice and main sessions.

In each trial during the practice and main sessions, participants were sequentially presented with two stimuli: a reference stimulus (0.015 MPa for each pin) and a comparison stimulus (0.015 MPa or 0.03 MPa for each pin). Participants were asked to judge whether the second stimulus (the comparison stimulus) was faster than the first stimulus (the reference stimulus) and were required to make a two-alternative forced choice by pressing a foot button. We informed participants in advance that the global distance of the object's movement was randomized and instructed them not to base their judgment of motion speed on the global distance of movement or duration. Once they had made their choice, they could proceed to the next trial.

We employed a randomly interleaved staircase method with two staircases. One of the reference stimuli (0.04 m/s, 0.08 m/s, and 0.12 m/s) was assigned to the two staircases. The presentation order of the two staircases was randomized: in one staircase, the initial speed of the comparison stimulus was 0.025 m/s faster than that of the reference stimulus, while in the other staircase, the initial speed was 0.025 m/s slower than that of the reference stimulus. We increased or decreased the speed of the comparison stimulus by 0.005 m/s in the next step of the staircase in response to participants' "slow" or "fast" responses, respectively. The experiment was terminated when the responses in both staircases had been reversed six times.

The range of speeds for the reference stimuli (ranging from 0.04 m/s to 0.12 m/s) was selected based on prior studies [7], [12]. The main session comprised six blocks, each corresponding to one of the three reference stimulus speeds and one of the two comparison stimulus intensities. The order of the six blocks was randomized. Before each block started, a practice session was conducted, during which the participants performed only five trials. The speed of the reference stimulus and the intensity of the comparison stimulus in the practice session were the same as those in the subsequent block. The procedure was the same for the practice as it was for the main sessions.

D. Data Analysis

For each block and participant, we fitted the responses with psychometric functions of the form,

$$\Phi^{-1}[P(Y=1)] = \beta_0 + \beta_1 v_{comp} \tag{1}$$

where Φ^{-1} is the probit link function and P is the probability of $Y = 1$. The response variable Y takes the value 1 if the participant reported that the object was moving faster in the comparison stimulus than in the reference and 0 otherwise. On the right side of the equation, v_{comp} is the speed of the comparison stimulus, and β_0 and β_1 are the intercept and the slope of the linearized equation, respectively. We analyzed the data for each participant using a generalized linear model (GLM).

We evaluated the accuracy of the responses to address our research question: whether the intensity of normal force affected the perceived motion speed. To this end, we computed the point of subjective equality (PSE $= -\beta_0/\beta_1$) corresponding to the stimulus value yielding a response probability of 0.5.

To determine whether the PSE changed with two factors (speed of reference stimulus and force intensity of comparison stimulus), we conducted a two-way repeated measures ANOVA using the two factors. If there was a violation of normality as determined by the Shapiro-Wilk test, we conducted an ART [24] on the data and then conducted the ANOVA on the aligned ranks. Since other conventional nonparametric statistical tests (e.g., Kruskal–Wallis test and Mann-Whitney U test) cannot test the effect of multiple factors and their interaction, we adopted the ART procedure.

While we could also calculate just noticeable difference (JND) from the psychometric function, the analysis of the JND value in this experiment would not provide any insights relevant to our purpose and thus, we did not use it.

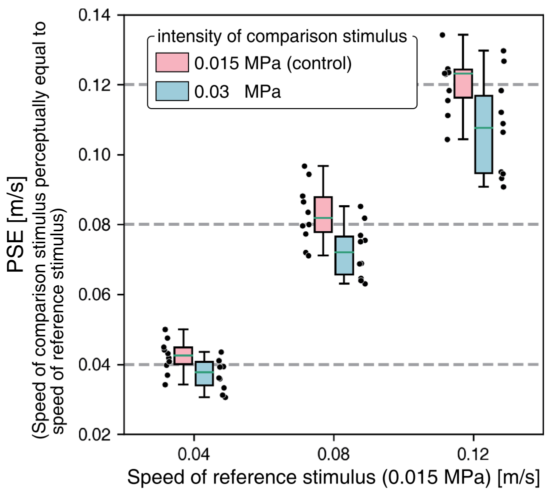

Fig. 3. Result of Experiment 1 (N=10). Box plots indicate PSEs for each speed of reference stimulus and each intensity of comparison stimulus. The black point denotes the PSE for each participant.

E. Result

Fig. 3 shows the distribution of PSE estimates for each combination of reference speed and comparison stimulus intensity. We conducted a two-way ANOVA on the PSE data. There were significant main effects of reference stimulus speed [$df = 2$, $F = 277.6$, $p < 0.001$, $\eta_p^2 = 0.91$] and comparison stimulus force intensity [$df = 1$, $F = 16.5$, $p < 0.001$, $\eta_p^2 = 0.23$]. There was no significant interaction effect between them [$df = 2$, $F = 1.5$, $p = 0.23$, $\eta_p^2 = 0.05$]. See post-hoc multiple comparisons between conditions of reference stimulus speeds in Supplementary Note 2 (this analysis does not fall within the main scope of our study).

The result shows that the perceived speed was faster when a larger normal force was presented than when a smaller one was presented. Specifically, when the intensity of normal force doubled, the median perceived speed increased by 1.12 times at a reference stimulus speed of 0.04 m/s, and by 1.14 times at reference stimulus speeds of 0.08 m/s and 0.12 m/s. The difference in PSE values due to normal force intensity were 0.0047 m/s at a reference stimulus speed of 0.04 m/s, 0.0098 m/s at a reference stimulus speed of 0.08 m/s, and 0.0155 m/s at a reference stimulus speed of 0.12 m/s.

V. Experiment 2: Effect of Normal Force on Discriminability of Tactile Motion Speed

In this experiment, we investigated the effect of normal force intensity on the discriminability of tactile motion speed. We regarded the JND in speed for tactile motion at a certain force intensity as the discriminability. We compared the JND at a small normal force intensity and also at a larger normal force intensity. This experiment was conducted in a within-participants design.

Ten male participants took part in this experiment; all were right-handed and had a mean age of 23.6 (SD: 1.2) years. The length of the participants' hands on a straight line along the pin layout was 175.1 (SD: 8.6) mm. All participants were naive to the purpose of the study and reported no sensorimotor disorders. The experiment lasted approximately 45 minutes, and the participants were paid about 1,200 Japanese yen (approximately 8 USD).

A. Procedure

The procedure was basically the same as in Experiment 1 and here we describe only the differences. In Experiment 2, the intensities of the normal force for both the reference stimulus and the comparison stimulus were the same. This is because we aimed to estimate the discriminability of tactile motion speeds at constant force levels, and to determine whether the discriminability was dependent on the force level. There were two conditions for the intensity of the normal force: 0.015 MPa and 0.03 MPa. There were three conditions for the speed of the reference stimulus (0.04 m/s, 0.08 m/s, and 0.12 m/s), which was the same as in Experiment 1. In total, there were six blocks. The order of the blocks was random. Before the first block started, a practice session was conducted, during which the participants performed only ten trials. The speed of the reference stimulus and the intensity of the normal force of stimuli in the practice session were randomly assigned. The procedure was the same for the practice as it was for the main sessions.

B. Data Analysis

For each block and participant, we fitted the responses with psychometric functions as shown in the expression (1). We determined whether the intensity of normal force affected the discriminability of perceived tactile motion speed. To this end, we computed the JND from the psychometric functions (JND $= 0.675/\beta_1$, where 0.675 is the 75th percentile of a standard normal distribution).

To determine whether JND changed with two factors (speed of reference stimulus and intensity of stimulus), we conducted a two-way repeated measures ANOVA using the two factors. If there was a violation of normality as determined by the Shapiro-Wilk test, we conducted an ART on the data and then conducted the ANOVA on the aligned ranks.

While we could also have calculated the PSE from the psychometric functions, the analysis of the PSE values in this experiment would not provide any insights relevant to our purpose since the force levels of the reference and comparison stimuli were the same.

C. Result

Fig. 4 shows the distribution of JND estimates. We conducted an ART on the data and then a two-way ANOVA using the two factors on the aligned ranks. There was a significant main effect of reference stimulus speed [$df = 2$, $F = 7.6$, $p = 0.001$, $\eta_p^2 = 0.22$]. There was no significant main effect of stimulus force intensity [$df = 1$, $F = 0.1$, $p = 0.92$, $\eta_p^2 = 0.0002$] and interaction effect [$df = 2$, $F = 1.0$, $p = 0.38$, $\eta_p^2 = 0.036$]. See post-hoc multiple comparisons between conditions of reference stimulus speeds in Supplementary Note 3 (this analysis does not fall within the main scope of our study). The results suggest that the discriminability of the motion speed did not change due to the intensity of normal force.

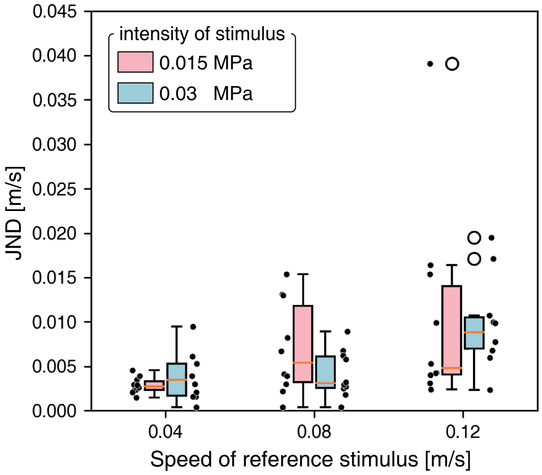

Fig. 4. Result of Experiment 2 (N=10). Box plots indicate JNDs for each speed of reference stimulus and each intensity of normal force. The black point denotes JND for each participant.

The median JND values for normal force intensity of 0.015 MPa were 0.0027 m/s at a reference stimulus speed of 0.04 m/s, 0.0054 m/s at a reference stimulus speed of 0.08 m/s, and 0.0048 m/s at a reference stimulus speed of 0.12 m/s. These JND values were smaller than the difference in quantified speeds due to stimulus intensity at each reference speed in Experiment 1. This indicates that the difference in perceived speed due to the doubled stimulus intensity in Experiment 1 is perceptible to humans.

VI. Discussion

A. Interpretation of the Main Results

In this study, we developed a pin-array display that could systematically manipulate normal force intensity without causing slip-induced vibrations or tangential forces. The display enabled us to investigate the effect of normal force intensity on the perception of tactile motion speed in a situation where participants perceive tactile motion based solely on spatiotemporal cues. We made several previously undiscovered findings.

Our first finding was a significant effect of normal force intensity on the magnitude of perceived speed. Within our stimulus range, when the intensity of normal force was doubled, the motion speed was perceived to be 1.12-1.14 times faster. The difference in perceived speed due to the difference in normal force intensity was below the JND, and thus is perceptible to humans. Our results may be due to the inability of humans to completely separate signals related to speed and normal force at the level of mechanoreceptor firing rates, although this is only a conjecture. It is known that information about motion speed is encoded in nerve firing rates [11]. It is also known that a large normal force increases the firing rate of mechanoreceptor nerve fibers. This leads us to speculate that when speed perception relies on spatiotemporal cues, there is a possibility that signals based on intensive normal force may be incorrectly attributed to a higher speed.

Another conjecture relating to our first finding is that a larger normal force could have increased the skin's deformation area per pin, potentially resulting in an increased estimate of the local distance traveled by the virtual object within a given time period (see Fig. 5). There exists a potential scenario where speed computation may be performed via the estimated local distance, which increased due to larger deformation. It should be noted, however, that it is unclear whether local distance perception would be changed by this. It is also unclear whether speed would be computed based on local distance perception.

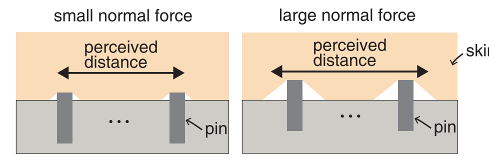

Fig. 5. Deformation area of the skin is enlarged when a larger normal force is applied by a pin. This might make participants perceive a longer travel distance, leading to a larger perceived speed.

This finding apparently contradicts the results of a previous study, which suggested that speed magnitude remained unaffected by contact force when a finger is pressed against a textured surface with varying contact forces [7]. In this previous study, the tangential force and slip-induced vibrations changed concomitantly with variations in contact force. It is conceivable that participants in the previous study were better able to accurately estimate motion speed by utilizing these multiple cues, which were not available in our experiment. Another factor to consider is that differences in how motion is presented to participants may influence the results. In our experiment, the stimulus moved across the skin, whereas in the previous study, the skin area being stimulated remained fixed.

Our second finding was that there was no significant difference in the discriminability of speed when the intensities of normal force differed. This result also apparently contradicts the findings of previous work, which suggested that discriminability increased with greater normal force when a finger was pressed against a textured surface on a moving substrate with varying normal force [8]. The two factors mentioned in the previous paragraph are also possible reasons for this inconsistency. For example, the tangential force and slip-induced vibrations may have contributed to discriminability, but normal force may not have.

B. Implications for Future Research and Application Scenarios

It is crucial to determine whether the effect of stimulus intensity on speed perception is specific to spatiotemporal cues represented by normal pushing force or whether it is common to spatiotemporal cues represented by other types of stimuli. Stimuli representing spatiotemporal cues include vibrations [25] and electrical stimuli [26] in addition to normal force. Investigating whether similar results can be obtained when the intensity of such other stimuli increases would allow us to understand the underlying mechanisms. For instance, if the phenomenon of faster speed perception were not observed when applying electrical skin stimulation with higher intensity, our explanations attributing the increased speed perception to larger skin deformation in this paper (see Fig. 5) could be seen as more plausible.

Future experiments that more deeply investigate tactile motion speed perception based on spatiotemporal cues should take into account the intensity of normal force. Specifically, when comparing multiple conditions based on a specific factor (e.g., differences in spatiotemporal cues originating from the pin layout), the intensity of normal force should be pre-adjusted across the conditions. Otherwise, the effect of the normal force intensity cannot be eliminated.

Finally, let us consider application scenarios involving the representation of tactile motion in VR space. In such scenarios, it is common to use haptic displays that can only present forces in the normal direction [14]. The perception of tactile motion may influence various aspects, including the perception of haptic properties of virtual objects in relative motion, dexterity in grasping, and the pleasantness of affective touch. Our results suggest that, depending on the normal force intensity setting, the perception of speed may vary, potentially impacting the phenomena mentioned above. It should be noted that the question of whether the normal force intensity setting does indeed affect such phenomena requires further investigation.

References

[1] J. J. Gibson, "Observations on active touch," *Psychol. Rev.*, vol. 69, no. 6, pp. 477–491, 1962.

[2] D. Katz, *The World of Touch*. England, U.K.: Psychology Press, 2013.

[3] S. J. Lederman, "Tactual roughness perception: Spatial and temporal determinants," *Can. J. Psychol.*, vol. 37, no. 4, pp. 498–511, 1983.

[4] R. S. Johansson, "Sensory input and control of grip," in *Proc. Novartis Found. Symp. 218-Sensory Guid. Movement: Sensory Guid. Movement: Novartis Foundat. Symp. 218*. 2007, pp. 45–63.

[5] G. Essick, O. Franzen, and B. Whitsel, "Discrimination and scaling of velocity of stimulus motion across the skin," *Somatosensory Motor Res.*, vol. 6, no. 1, pp. 21–40, 1988.

[6] T. Seizova-Cajić, X. Fuchs, and J. Brooks, "Creating tactile motion," in *Somatosensory Research Methods*. Berlin, Germany: Springer, 2023, pp. 71–94.

[7] A. Dépeault, E.-M. Meftah, and C. E. Chapman, "Tactile speed scaling: Contributions of time and space," *J. Neuriophysiol.*, vol. 99, no. 3, pp. 1422–1434, 2008.

[8] C. P. Ryan, S. Ciotti, L. Cosentino, M. O. Ernst, F. Lacquaniti, and A. Moscatelli, "Masking vibrations and contact force affect the discrimination of slip motion speed in touch," *IEEE Trans. Haptics*, vol. 15, no. 4, pp. 693–704, Oct.-Dec. 2022.

[9] G. C. Bettelani, A. Moscatelli, and M. Bianchi, "On the role of lateral force in texture-induced motion bias during reaching tasks," *IEEE Trans. Haptics*, vol. 13, no. 1, pp. 233–238, Jan.-Mar. 2020.

[10] E. P. Gardner and R. M. Costanzo, "Neuronal mechanisms underlying direction sensitivity of somatosensory cortical neurons in awake monkeys," *J. Neuriophysiol.*, vol. 43, no. 5, pp. 1342–1354, 1980.

[11] G. K. Essick and B. B. Edin, "Receptor encoding of moving tactile stimuli in humans. II. the mean response of individual low-threshold mechanoreceptors to motion across the receptive field," *J. Neurosci.*, vol. 15, no. 1, pp. 848–864, 1995.

[12] B. P. Delhaye, M. K. O'Donnell, J. D. Lieber, K. R. McLellan, and S. J. Bensmaia, "Feeling fooled: Texture contaminates the neural code for tactile speed," *PLoS Biol.*, vol. 17, no. 8, 2019, Art. no. e3000431.

[13] G. K. Essick, A. James, and F. P. McGlone, "Psychophysical assessment of the affective components of non-painful touch," *Neuroreport*, vol. 10, no. 10, pp. 2083–2087, 1999.

[14] Y. Ujitoko, T. Taniguchi, S. Sakurai, and K. Hirota, "Development of finger-mounted high-density pin-array haptic display," *IEEE Access*, vol. 8, pp. 145107–145114, 2020.

[15] A. Moscatelli, C. R. Scotto, and M. O. Ernst, "Illusory changes in the perceived speed of motion derived from proprioception and touch," *J. Neuriophysiol.*, vol. 122, no. 4, pp. 1555–1565, 2019.

[16] A. Tomassini, M. Gori, D. Burr, G. Sandini, and M. C. Morrone, "Perceived duration of visual and tactile stimuli depends on perceived speed," *Front. Integrative Neurosci.*, vol. 5, 2011, Art. no. 51.

[17] S. J. Bensmaia, J. H. Killebrew, and J. Craig, "Influence of visual motion on tactile motion perception," *J. Neuriophysiol.*, vol. 96, no. 3, pp. 1625–1637, 2006.

[18] A. Lécuyer, M. Congedo, E. Gentaz, O. Joly, and S. Coquillart, "Influence of visual feedback on passive tactile perception of speed and spacing of rotating gratings," in *Proc. Haptics: Generating Perceiving Tangible Sensations: Int. Conf.*, 2010, pp. 73–78.

[19] C. R. Scotto, A. Moscatelli, T. Pfeiffer, and M. O. Ernst, "Visual pursuit biases tactile velocity perception," *J. Neuriophysiol.*, vol. 126, no. 2, pp. 540–549, 2021.

[20] J. Yang et al., "Brain networks involved in tactile speed classification of moving dot patterns: The effects of speed and dot periodicity," *Sci. Rep.*, vol. 7, no. 1, 2017, Art. no. 40931.

[21] C. J. Dallmann, M. O. Ernst, and A. Moscatelli, "The role of vibration in tactile speed perception," *J. Neuriophysiol.*, vol. 114, no. 6, pp. 3131–3139, 2015.

[22] C. M. Greenspon, K. R. McLellan, J. D. Lieber, and S. J. Bensmaia, "Effect of scanning speed on texture-elicited vibrations," *J. Roy. Soc. Interface*, vol. 17, no. 167, 2020, Art. no. 20190892.

[23] N. Mitsuhashi, K. Fujieda, T. Tamura, S. Kawamoto, T. Takagi, and K. Okubo, "Bodyparts3D: 3D structure database for anatomical concepts," *Nucleic Acids Res.*, vol. 37, no. suppl_1, pp. D782–D785, 2008.

[24] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, "The aligned rank transform for nonparametric factorial analyses using only anova procedures," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2011, pp. 143–146.

[25] I. R. Summers, C. M. Chanter, A. L. Southall, and A. C. Brady, "Results from a tactile array on the fingertip," in *Proc. Eurohaptics*, 2001, pp. 26–28.

[26] H. Kajimoto, "Design of cylindrical whole-hand haptic interface using electrocutaneous display," in *Proc. Haptics: Percep., Devices, Mobility, Commun.: Int. Conf.*, 2012. pp. 67–72.

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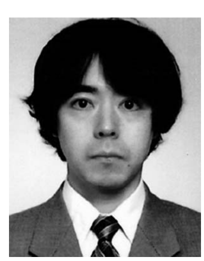

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