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Relationship between Interoceptive Accuracy and Tactile Exploration Behavior

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ABSTRACT This paper presents a novel finding suggesting that tactile exploration behaviors, with a focus on finger scanning motion, are influenced by interoception. Initially, we investigated finger motion for surface scanning across various precisely controlled surface patterns using microfabrication techniques. Participants were then categorized into two distinct groups based on whether their finger scanning speed depended on surface patterns. Subsequently, we assessed participants' interoception through a heart rate counting task. The identified groups correlated with levels of interoceptive accuracy, indicating a significant relationship between interoception and tactile-related behaviors. This discovery could have a profound impact on tactile research, as it suggests the need to consider interoception properties alongside conventional participant demographics such as age and gender in experimental design.

INDEX TERMS Finger Scanning, Tactile Exploration, Interoception, Interoceptive accuracy, Exteroception, Surface Texture,

I. INTRODUCTION

The tactile receptors, responsible for sensing a variety of surfaces, possess their own sensitivity characteristics [1]-[5]. Merkel discs, also known as slow-adapting type I (SAI) receptors, are sensitive to stimuli at low frequencies ranging from 1 to 100 Hz, with an amplitude threshold of 100 μm. Pacinian Corpuscles, classified as fast-adapting type II (FAII) receptors, can detect stimuli with an amplitude of 1 μm at 200 Hz. As we investigate surfaces, we scan them with our fingers, converting the spatial information of the surface into temporal information [6].

Since the vibration frequency generated on the skin is determined by the scanning speed and surface roughness, the finger scanning speed has been previously reported to correlate with surface roughness [7]-[11]. Although it was reported that the tactile perception of texture does not depend on scanning speed [12], it is reasonable to assume that scanning speed is consciously or unconsciously controlled to maximize tactile perception capacity, which is expected to depend on the characteristics of tactile receptors.

One challenge in such studies is the difficulty in independently controlling the physical properties of textures. For instance, in our previous study [13], [14], we utilized 18 test samples composed of various materials such as wood, polystyrene forms A and B, urethane, lumpy rubber, and flat rubber. Each sample exhibited different surface properties including geometry, roughness, stiffness, friction coefficient, surface energy, and thermal conductivity. To establish correlations between tactile perception or behaviors and individual physical properties, the test samples ideally should possess identical properties except for the specific property under investigation. However, precisely controlling each parameter of such samples proves challenging.

Micromanufactured tactile samples have emerged as a potential solution to this issue. Techniques such as photolithography or machining can be employed to create surfaces with textures ranging from micrometer to millimeter scales for various materials. The dimensions of these textures, such as the widths and depths of stripe or dot patterns, can be accurately specified. Examples include metal samples patterned with picosecond laser pulses [15], photolithographically micromanufactured silicon [16] and polymer samples [17], and stretchable tactile samples with variable micropatterned features [18]. Tactile perception has been quantitatively characterized using microfabricated tactile samples, particularly in terms of roughness and dryness [19].

In this study, we conducted experiments using tactile samples with microfabricated features that could be quantitatively characterized [19]. The tactile samples are photosensitive and are patterned with striped patterns using photolithography. We experimentally measured the scanning speed of participants' fingers when they were requested to investigate surfaces that have the stripe patterns with designated widths. Eight types of samples were tested in a random order.

We had expected that the finger scanning speed would increase with surface roughness or the widths of the striped patterns, aligning the tactile stimuli with the frequencies to which the receptors are most sensitive. Remarkably, the participants were clearly divided into two groups. Participants in one group (Group A) exhibited a clear correlation between scanning speed and surface roughness; scanning speed monotonously increased with surface roughness. On the other hand, in the case of the other group (Group B), participants' scanning speed did not vary with surface roughness. 19 out of 43 participants belonged to Group A while 24 to Group B.

Participants in Group A were considered to have stronger feedback from tactile perception compared to those in Group B. While tactile sense is one of the exteroception, in this study, we explored the interoception of the participants, referring to the ability to sense and perceive internal physiological states, particularly focusing on the interoceptive accuracy among several interoceptive measures [20]-[25]. The hypothesis posits that participants with better interoceptive accuracy exhibit stronger feedback, influencing behavior, such as finger scanning in this case. The heart rate measurement task is a well-established experiment for assessing the accuracy of interoception [26]. In this paper, we empirically investigate the relationship between interoception accuracy and finger scanning speed as a tactile behavior. The discovery that interoception relates to sensory behavior and that participants can be categorized into two groups could have a significant impact on tactile research. The experiments might involve participants with completely different characteristics. While participants are conventionally labeled by their age and gender, consideration of interoception properties is necessary in tactile experiments.

II. METHOD

A. TACTILE SAMPLES

Roughness perception is categorized into macroroughness and microroughness perception [27], based on the responsible tactile receptors. Macroroughness, characterized by surface patterns exceeding several hundred micrometers, is perceived through Merkel's disks [28]-[30]. Microroughness, with corresponding surface patterns smaller than 100 µm, is sensed via Meissner corpuscles and Pacinian corpuscles [31]-[33]. Surface-texture patterns ranging from 0.1 to 1 mm are considered to exhibit properties of both macro- and microroughness. Consequently, they are of significant interest in studies investigating roughness perception.

In previous studies on roughness perception, various materials such as paper, textiles, rubber, etc., were tested. However, the samples not only differed in surface roughness but also in other material properties like stiffness and thermal conductivity [34]-[38]. Our group has introduced micro-manufactured tactile samples, ensuring identical material properties except for surface roughness [18],[19]. This enables a focused examination of the effects of surface roughness on tactile perception. In this study, we tested micro-manufactured tactile samples with surface features ranging from 0 to 1.5 mm.

To prepare our samples, a negative photoresist (SU-8 3050, Kayaku Advanced Materials, Westborough, MA, USA) was patterned onto a glass substrate. The fabrication process is described in Figure 1 and the photo of the sample is shown in Figure 2. The thickness of the SU-8, denoted as h, was 50 µm, which was experimentally proved to be sufficient for perception. Stripe patterns with a ridge width w and a groove width p were created using photolithography (see Figure 1). In this study, we designed w and p to be identical and investigated the effects of w and p on roughness perception using tactile samples with w and p values of 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.5 mm.

B. TACTILE EXPERIMENTS

All the experiments were approved by the Research Ethics Committee of Faculty of Science and Technology, Keio University (2023-055).

In this study, we emphasize finger scanning motion as the primary tactile exploration behavior, focusing specifically on scanning speeds. Participants conducted experiments while seated and wearing an eye mask to eliminate visual information. They were instructed to scan the surface back-and-forth eight times perpendicular to the stripes using one of their fingers to assess surface roughness. The finger's motion was optically captured at a frame rate of 60 fps, which was confirmed to be sufficiently high to measure the finger scanning speed. The scanning speed was determined by measuring finger positions at each frame and dividing them by the frame length. Image analysis was performed using OpenCV, where the finger outline was extracted from the video. The analysis comprised three steps: 1) Grayscale conversion of the video, 2) Binarization of the video (extracting only skin-colored parts), and 3) Utilizing the center of the x-coordinate and y-coordinate of the contour extracted in step 2 as the finger's center (indicated by the star in Fig. 3), tracking the center point of the finger.

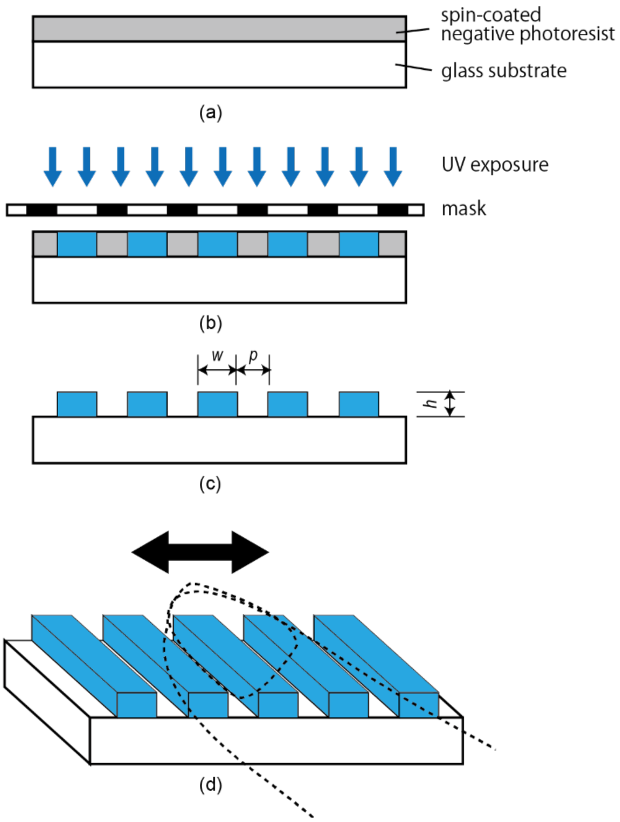

FIGURE 1. **Tactile samples fabricated from photosensitive polymer. The patterns are easily and precisely controlled through the photolithography process. (a) Negative photoresist (SU-8) is spin-coated onto a glass substrate, with thickness adjustable via spinning speed. (b) UV-light exposure to define the patterns. (c) Following the development process, the exposed areas remain on the surface. In this study, striped patterns with ridge width w, groove width p, and height h were employed. During experiments, w and p were intentionally set to be identical but varied to investigate the effect of surface roughness on tactile behavior, while the height h was fixed at 50 μm. (d) Participants scanned the surface of the tactile sample with their index finger.**

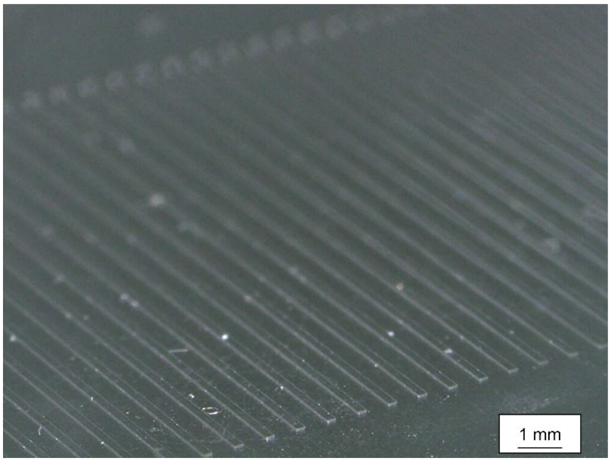

FIGURE 2. **Photo of the manufactured tactile sample created from photosensitive polymer. The stripe patterns are precisely formed using photolithography. Participants scan the surface of the sample perpendicular to the stripe patterns.**

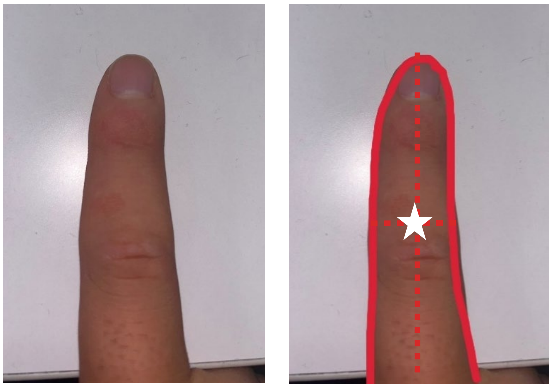

FIGURE 3. **The point tracked to deduce finger movement. Finger motion was optically captured at a frame rate of 60 fps, and scanning speed was determined using image processing with OpenCV.**

We considered that the finger scanning motion would converge over successive back-and-forth motions to align with the frequency of the tactile stimuli from the stripe patterns, corresponding to when the tactile receptors are most sensitive. As illustrated in Figure 5, the discrepancies among participants remained consistent in Group B and decreased in Group A as the number of back-and-forth motions increased. While we could increase the number of motions, we believe that 8 repetitions are sufficient. We investigated the average finger speed during the 8th scan and examined the change in scanning speed across the repeated back-and-forth motions.

Participants randomly traced eight tactile samples, and three trials were conducted for each tactile sample. This resulted in a total of 24 trials for each participant.

C. HEART RATE COUNTING TASK

The heart rate counting task is a frequently used method to assess the accuracy of interoception [20]-[25]. Participants, while seated and wearing an eye mask, were instructed to count the number of their heartbeats without relying on external cues and verbally report it. Participants counted their heart rate during nine trials with three trials per each of three time intervals varying in length (15, 30, 45 s). The intervals were not disclosed to participants in advance, and the order of counting intervals was randomized for each participant. This variation in the intervals prevents the participants from memorizing the number of heartbeats [22, 23].

The correct number of heartbeats was recorded using a wearable device (Fitbit Inspire2, Fitbit Inc., Delaware, US). The accuracy score was derived as:

$$(1 - |n_{correct} - n_{reported}|/n_{correct}) \times 100[\%],$$

where $n_{correct}$ and $n_{reported}$ are the correct number and the reported number of heartbeats. Resulting accuracy scores were averaged over the nine trials, yielding an average value for each participant. A more accurate interoception yields a value closer to 1.

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III. RESULTS AND DISCUSSION

A. TACTILE EXPERIMENTS

The experiments involved 43 participants (7 females and 36 males, aged between 21 and 55 years). Figure 4 illustrates the finger scanning speeds of all participants relative to the width of the tactile samples. Each trial is represented by the finger scanning speed of the 8th back-and-forth scan, and the speeds depicted in Figure 4 represent the average of three trials for each tactile sample.

As evident in the figure, the participants displayed two distinct trends: for participants in Group A (shown in orange, 19 participants), the scanning speed increased with the feature size, while the speed remained consistent regardless of the feature size for those in Group B (depicted in blue, 24 participants). Note that we did not aim to recruit participants to match the numbers in each group. Interestingly, not only the trend but also the absolute value of the finger scanning speeds were almost the same in each group. In the case of Group A, the average scanning speed for the flat surface was found to be 2.1 cm/s, with a standard deviation of 0.5 cm/s. The minimum and maximum values were 1.3 and 3.1 cm/s, respectively. The speeds increased monotonically with the width of the tactile samples, reaching an average speed of 5.1 cm/s at a width of 1.5 mm, with a standard deviation of 0.5 cm/s. The minimum and maximum values were 4.5 and 5.6 cm/s, respectively. In the case of Group B, the finger scanning speeds ranged approximately from 4.0 to 5.9 cm/s in all experiments and did not vary based on the tactile samples.

To further investigate our initial hypothesis regarding whether participants unconsciously adjust their scanning speed based on roughness, we analyzed the changes in standard deviation of speed throughout the scanning motion. The results are summarized for Group A and Group B. As depicted in Figure 5, the standard deviation in the group exhibiting a correlation (Group A) decreases with each scan, whereas it remains constant for Group B. These findings suggest that in Group A, participants initially set their scanning speed somewhat randomly during the first scan, and then gradually adjusted the speed as they iterated the scanning motion, eventually converging to a certain value. Conversely, participants in Group B maintained a consistent scanning speed throughout the 8 back-and-forth motions.

B. INTROCEPTION

Figure 6 shows the histogram describing the accuracy of the heart rate count, i.e., interoception. The average accuracy of the heartbeat counting task was 38%, with the maximum being 80% and the minimum being 17%. Interestingly, as illustrated in Figure 6, the participants are largely divided into two groups around the 50% mark; Group I with high interoception, having the heart rate counting accuracy above 50%, and Group II with low interoception, having the accuracy below 50%.

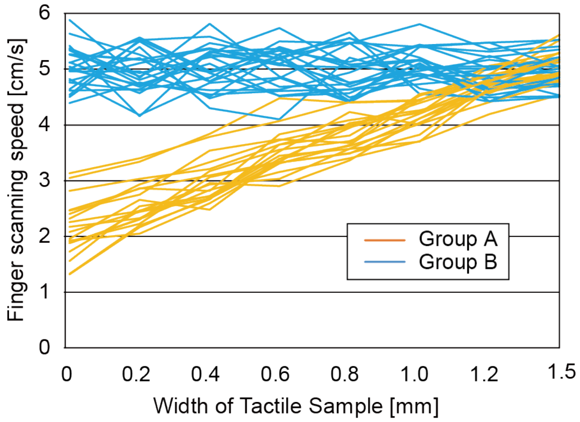

FIGURE 4. Finger scanning speeds of all participants relative to sample widths. The average of the three trials at the 8th back-and-forth scan was used. Participants were classified into two distinct groups: for Group A participants (shown in orange, 19 participants), scanning speed increased with feature size, while for Group B participants (depicted in blue, 24 participants), speed remained consistent regardless of feature size.

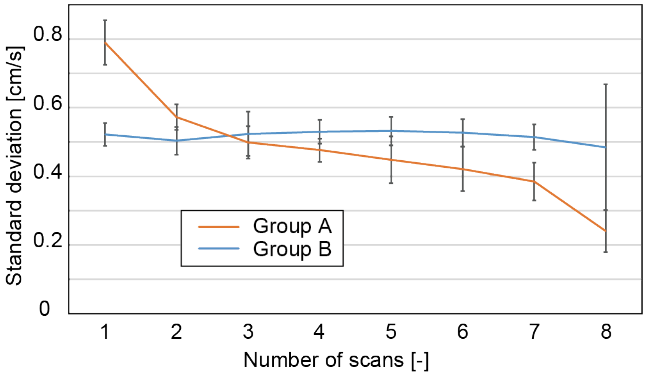

FIGURE 5. Standard deviation of finger speed for each scanning motion in the three trials. The data shown in this figure represent the average across participants in Group A and Group B. Error bars represent the standard deviation.

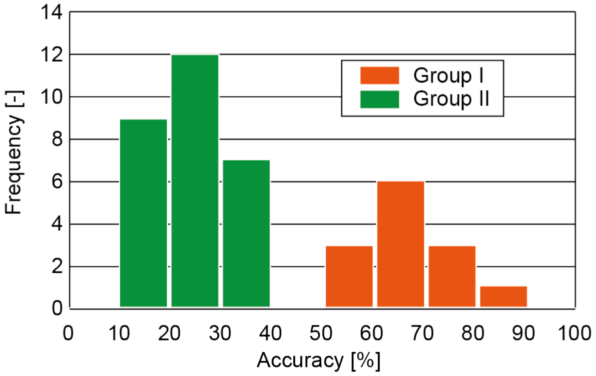

FIGURE 6. Histogram of interoception accuracy, based on the accuracy of the heart rate count. Participants were divided into two groups at the 50% mark.

TABLE I
FINGER SCANNING SPEED AND INTEROCEPTION

	Group I	Group II
Group A	13	6
Group B	2	22

C. DISCUSSION

We investigated the association between finger scanning speed and interoception, denoted as the correspondence between Group A/B and Group I/II, as summarized in TABLE I. A Chi-Square test was conducted to assess the relationship between finger scanning speed and interoception. The null hypothesis assumes independence between them. If the null hypothesis is rejected, it can be concluded that finger scanning speed is associated with interoceptive accuracy. The degrees of freedom are 1. With a significance level of 0.01, the chi-square value required to reject the null hypothesis is 6.64. The chi-square value computed from the data presented in Table I is 17.47, which exceeds 6.64. Hence, we conclude that there is a strong relationship between finger scanning speed and interoception.

It has been reported that exteroception, which includes tactile perception, and interoception, can influence each other. For instance, seeing or smelling food when hungry can increase the desire for that food [39]. People experiencing stress become more sensitive to tactile stimuli when their interoception is affected by stress [40]. Emotions, which are regulated by interoception, are known to affect tactile experiences [41].

In this experiment, finger scanning speed, a representative measure of tactile behavior, was found to relate to interoceptive accuracy. This relationship is unlikely to be caused by participants' emotions or external stressors, as the tactile tasks and heart rate counting tasks were conducted separately. It is implied that exteroception and interoception are directly related to each other. Particularly, this relationship is assumed to have a direction from interoception to exteroception, as discussed below.

The sensitivity of tactile receptors depends on input frequency, or finger scanning speed. Participants with high interoceptive accuracy were able to discern differences in tactile receptor responses, prompting them to vary their scanning speed.

The variation in scanning speed and the accuracy of heart rate counting were quantitatively compared for all participants. The variation in scanning speed is defined as the difference between the finger scanning speeds at widths of 1.5 mm and 0 mm, as shown in Figure 4. As depicted in Figure 7, clear correspondence between Groups A, B, I, and II is observed. Note that the participants with high interoceptive accuracy exhibited large variation in the scanning speed while they are not quantitatively related to each other.

One of the most significant contributions of this paper to the tactile research field is the discovery that participants can be categorized into two groups, exhibiting different tactile behaviors. Conventionally, tactile experiments involve selecting healthy participants labeled with their age and gender, and collecting and analyzing data collectively. However, this research suggests that assessing the interoception of participants and analyzing the data separately may yield better results. This approach could potentially alter the discussions and conclusions drawn in previous research.

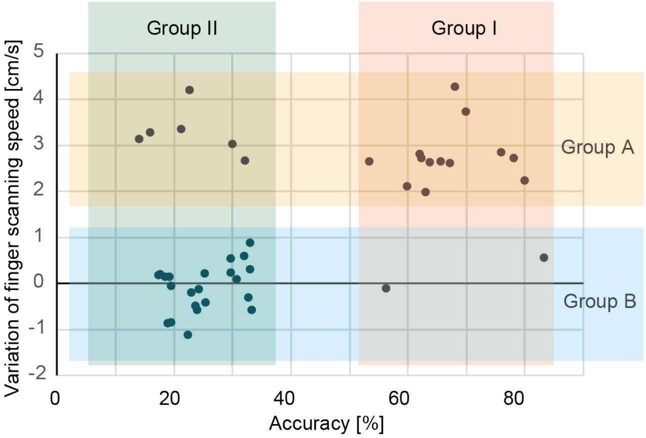

FIGURE 7. **Variation of scanning speed relative to interoception accuracy, depicted for Groups A, B, I, and II. Chi-Square test results indicate a significant relationship between scanning speed variation and interoception accuracy.**

IV. CONCLUSIONS

In this study, we quantitatively examined the relationship between finger surface scanning speed and surface roughness using tactile samples. The results revealed two distinct trends: finger scanning speed increased with roughness in one group but remained constant in the other. Participants were divided into two groups based on their finger scanning speeds: Group A, showing a correlation between scanning speed and roughness, and Group B, showing no such correlation. The decrease in standard deviation of scanning speeds for each trial in Group A suggests that participants unconsciously adjusted their scanning speed in response to surface roughness. Interoception levels of participants were experimentally assessed through a heart rate counting task, leading to their classification into two groups: Group I, with high interoceptive accuracy (above 50% in the heart rate count task), and Group II, with low interoceptive accuracy. Interestingly, Groups A and I corresponded, as did Groups B and II, with a significance level of 0.01. Because the sensitive tactile receptors are likely to be subserved by accurate interoception, the results suggest that tactile behavior, specifically finger scanning speed in this study, is influenced by interoception. These findings underscore the importance of classifying participants based on interoception levels in tactile experiments.

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