Analysis of Spatiotemporal Memory Using Air-Jets as Tactile Stimuli for Development of Noncontact Tactile Displays

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Abstract. The effects of delay and distance of a pair of tactile stimuli on the memory of the two locations were analyzed. Tactile stimuli were induced at the palm with seven levels of interstimulus distances and seven levels of interstimulus intervals. The results showed that the smallest two-point differential threshold was when the delay time was around 0.5–2.0 s. The fundamental characteristics associated with spatiotemporal tactile memory that were obtained in the present study can lead to the design of a noncontact tactile display.

1 Introduction

Many studies have recently focused on the development of tactile displays, which have the potential to effectively present information to users in situations where other sensory modalities cannot be used [1]. Various types of stimulus modalities have been proposed for the tactile display; these have been discussed as a key issue for effectively presenting stimuli [2][3][4]. Most studies have used vibrotactile and electrocutaneous stimuli, where pins and electrodes are directly attached to the surface of the human body to generate stimuli. However, this type of tactile display is plagued by unstable stimulus presentation owing to poor contact between the skin and actuators and discomfort with prolonged dwell times [2]. In this study, we used air-jet stimuli to develop a noncontact tactile display that avoids such problems induced by physical contact between the body and display.

For developing such a display, it was important to clarify the information transmission characteristics of the noncontact tactile display because the stimulus transmission medium was air jets, which have significantly different physical properties compared to stimuli using mechanical pins and electrodes.

To clarify the characteristics of tactile perception, Murray et al. [5] investigated the tactile differential threshold at 12 body sites by using an aesthesiometer. They evaluated not only the conventional two-point differential threshold, where two stimuli are given at the same time, but also obtained the differential threshold for the delayed stimulus condition, where the second stimulus is given after a certain delay. In their results, they obtained a two-point threshold of 7.8 mm at the palm with simultaneous stimulus presentation, whereas the threshold dropped to 2.5 mm when a 1.0-s delay was given for the second stimulus presentation. When the second stimulus was delayed by 8.0 s, the threshold was reduced to 5.0 mm. They reasoned that the change in thresholds was because lateral inhibition was generated for simultaneous stimulus presentation and suppressed when there was a delay between two stimuli.

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Our tactile display that uses air-jet stimuli has a structure consisting of a matrix of 1.0-mm-diameter nozzles; hence, the tactile perception characteristics may differ from the experimental results reported by Murray et al. in terms of fluid-based stimulation and stimulation size. The aim of the present study was to investigate the spatiotemporal characteristics of tactile perception induced by an air-jet-based tactile display. In particular, the effects of stimulus delay and different palm areas on the change in tactile differential thresholds were empirically identified.

2 Methods

2.1 Tactile Display Using Air-Jet Stimuli

Figure 1 shows the schematic diagram of the apparatus. The air-jet stimuli are presented by means of a 12 × 12 air-jet array controlled by a precision pressure regulator. The pressure level and airflow duration are controlled by an electro-pneumatic regulator (CKD EVD-1900-P08 SN), and the location selector used for determining the location to generate stimuli is controlled by an electromagnetic valve (KOGANEI 025E1-2).

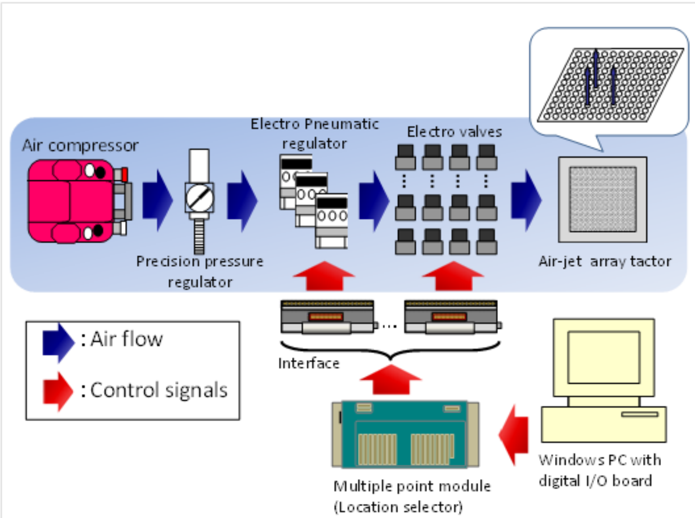

Fig. 1. Structure of the tactile display used in this study

2.2 Participants and Experimental Procedure

Eight male participants volunteered for this study. All were university students and reported normal tactile perception. The sets in the experiment took two days to complete. As shown in Figure 2, each participant placed the palm of his non-dominant hand on top of the tactile display surface. The location of the hand was then marked and fixed throughout the experiment. Each participant wore earplugs and headphones to completely eliminate the airflow noise generated from the tactile display. In each trial, two tactile stimuli with a certain interstimulus interval (ISI) were presented to the participant. The participant responded as to whether the two stimuli were presented at the same location. Each set consisted of 49 trials with seven levels of delay time and seven levels of interstimulus distance. Nine sets of three replicates and three palm locations (proximal area of the proximal phalanx and distal and middle parts of the palm) were tested. Short breaks were given to the subjects between sets. The experimental conditions are summarized in Table 1.

Fig. 2. Posture of the participant perceiving the stimuli from the tactile display

Table 1. Experimental conditions

Participant	Eight male university students
Pressure for stimulus presentation	100kPa
Duration	0.5s
Areas to be tested	Three sections at the palm area (The proximal area of the proximal phalanx, the distal and middle part of the palm)
Time interval	0, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0 [s]
Interstimulus distance	0, 4, 8, 12, 16, 20, 24 [mm]

2.3 Data Analysis

The percentage of correct answers was calculated for each condition, and the differential threshold for the condition was extrapolated as the distance such that the percentage of correct answers would be 50%. The following formula was used to determine the differential threshold:

$$d_{threshold} = d_L + \left\{\frac{50 - E(d_H)}{E(d_H) - E(d_L)}\right\} \times (d_H - d_L)$$

where $d_{threshold}$: estimated differential threshold [mm]
d_L: minimum interstimulus distance, which was set to 4 mm
d_H: minimum interstimulus distance at which the percentage of correct responses significantly changed [mm]
$E(d)$: percentage of correct responses at the interstimulus distance d [%]

Figure 3 shows the relationship between the differential threshold and percentage of correct responses.

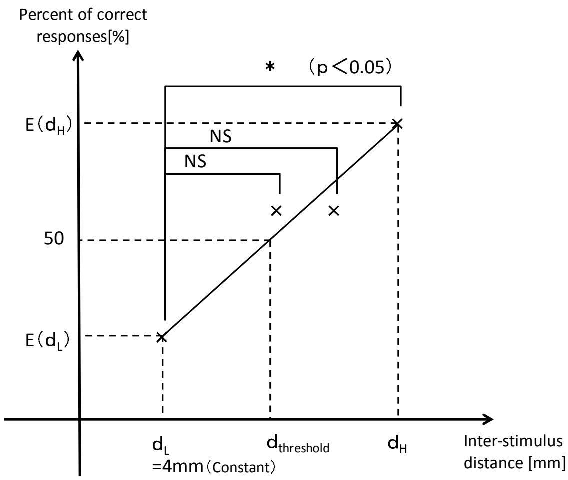

Fig. 3. Relationship between the differential threshold and percentage of correct responses

3 Results

Table 2 shows the percentage of correct responses by interstimulus distance and ISI. As shown in the table, the percentage of incorrect responses was low when the interstimulus distance was 4–8 mm for all sections of the tested hand sites. The percentage of correct responses significantly decreased as the applied stimulus locations approached the middle of the palm from the proximal part of the proximal phalanx ($p < 0.01$). Figure 4 shows the relationship between the interstimulus distance and percentage of correct responses. The percentage of correct responses gradually increased as the interstimulus distance became wider. A 100% correct response rate was obtained when an interstimulus distance of more than 20 mm was given. Table 3 summarizes the estimated tactile differential thresholds by section and ISI. The estimated tactile differential threshold was about 9.0 mm for the simultaneous stimulus presentation.

The threshold fluctuated between 7.4 and 8.3 mm for the delayed stimulus presentation. For all tested hand sites, the smallest threshold was obtained when an ISI of 0.5 s was given. When stimuli were presented simultaneously, the differential threshold was significantly higher than the thresholds for the delayed stimuli.

Table 2. Percentage of correct responses by the interstimulus distance and ISI

(a)

		Time interval [s]						
		0.0	0.5	1.0	2.0	4.0	8.0	16.0
Interstimulus distance [mm]	0	–	17%	4%	4%	0%	8%	33%
	4	75%	67%	83%	83%	75%	79%	67%
	8	63%	42%	38%	38%	42%	38%	58%
	12	25%	4%	13%	25%	21%	13%	13%
	16	0%	8%	13%	4%	8%	13%	8%
	20	4%	4%	0%	8%	0%	0%	4%
	24	0%	0%	0%	0%	4%	0%	0%

(b)

		Time interval [s]						
		0.0	0.5	1.0	2.0	4.0	8.0	16.0
Interstimulus distance [mm]	0	–	0%	8%	13%	4%	21%	17%
	4	79%	83%	96%	83%	83%	71%	67%
	8	71%	54%	46%	63%	50%	42%	42%
	12	29%	21%	4%	8%	21%	8%	29%
	16	4%	4%	8%	4%	4%	13%	4%
	20	4%	0%	0%	4%	0%	0%	8%
	24	0%	0%	0%	0%	4%	0%	4%

(c)

		Time interval [s]						
		0.0	0.5	1.0	2.0	4.0	8.0	16.0
Interstimulus distance [mm]	0	–	4%	0%	4%	8%	25%	29%
	4	92%	92%	75%	79%	79%	67%	71%
	8	75%	50%	54%	71%	46%	46%	50%
	12	25%	8%	42%	25%	33%	46%	29%
	16	17%	17%	21%	21%	4%	21%	8%
	20	0%	0%	0%	0%	4%	0%	0%
	24	4%	0%	4%	0%	13%	0%	8%

Table 3. Estimated tactile differential thresholds by different hand sites and ISIs

Time	0.0s	0.5s	1.0s	2.0s	4.0s	8.0s	16.0s	
Proximal phalanges	8.0	6.2	7.7	6.9	7.7	7.5	6.5	
Distal palm	8.6	8.2	8.0	7.5	8.2	6.7	7.6	
Middle palm	11.3	8.0	9.5	8.3	9.1	8.5	8.0	
Average	9.3	7.5	8.4	7.6	8.3	7.5	7.4	[mm]

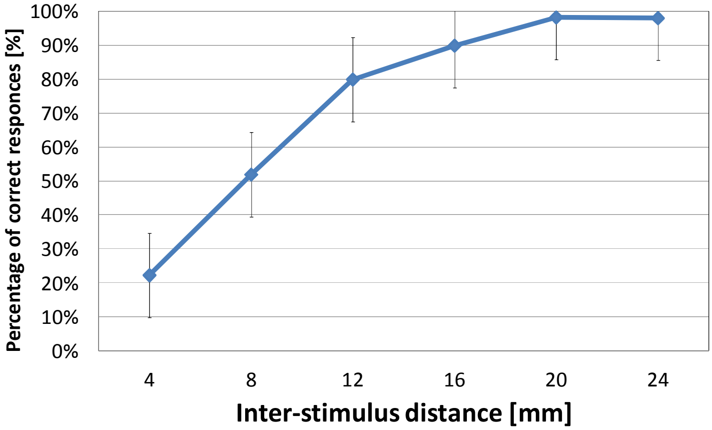

Fig. 4. Relationship between the interstimulus distance and percentage of correct responses

Figure 5 shows the relationship between the delay time and differential thresholds at different hand sites. There was a significant difference in differential thresholds among the hand sites. The differential threshold was shortest at the proximal part of the proximal phalanges followed by the distal part of the palm and middle part of the palm.

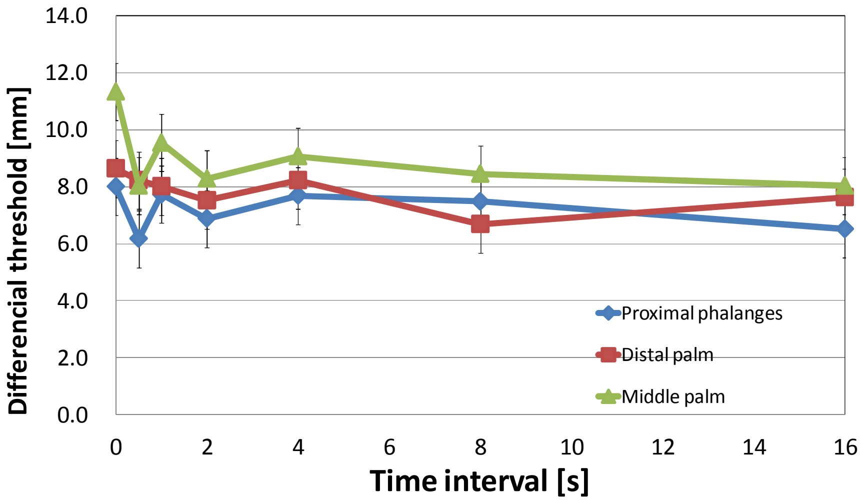

Fig. 5. Relationship between the delayed time and differential thresholds at different hand sites

4 Discussion

As shown in Table 2 and Figure 5, the tactile sensitivity decreased from the proximal part of the proximal phalanges to the middle part of the palm. This tendency was consistent with the findings of Shimawaki et al. [6], who observed static differential thresholds at the palm area using mechanical pins as stimuli. The sensitivity obtained by the size of tactile differential thresholds is thought to have a good correlation with the density of subcutaneous mechanoreceptors [6]. Because air-jet-based stimuli give a rather dull perception that covers large skin areas relative to pin-based stimuli, the present results imply that the area of stimulus presentation may not be a factor that violates the relationship between the mechanoreceptor density and tactile sensitivity.

At our experimental settings for the tactile display—that is, nozzle diameter of 1.0 mm and distance of 5.0 mm between the palm and nozzle—the participants were apparently able to identify that two stimuli were present when an interstimulus distance of at least 20 mm was given. However, the interstimulus distance should be easily adjustable by changing the distance between the nozzle and palm because the nozzle–palm distance affects the size of the area being presented with the stimuli owing to the dynamic properties of fluids.

Murray et al. [5] examined two-point differential thresholds by using an aethesiometer. A comparison of their study with the present results showed that the differential threshold in the present study was 1.5 mm wider for simultaneous stimulus presentation and 2.5–5.0 mm wider for delayed stimulus presentation. The results of the comparison imply the effect of stimulus modality, especially the size of the area the stimulus is applied to. In other words, Murray et al. used an aesthesiometer, which consists of fine mechanical pins, whereas we used stimuli from air-jets sprayed from a 1-mm-diameter nozzle; this may have appeared to give rather blurred sensations to the participants.

As shown in Figure 5, the differential threshold decreased when a certain ISI was given between two consecutive stimuli. This tendency was consistent with the results of the previous study [5]. Murray et al. reasoned that such tendencies may be observed because the lateral inhibition built up around the perceived location and the subsequent stimuli are perceived to be further apart than they really are. Although the medium for the stimulus presentation was different, our findings can presumably be explained by Murray et al.'s reasoning.

With regard to the relationship between the ISI and differential threshold, Figure 5 does not show that the differential threshold became less sensitive based on the power function; the previous study reported a negatively accelerated curve [5]. The difference can be attributed to the physical properties of the air-jet-based stimulus. When the air-jet stimuli were presented intermittently, interference was generated between the airflows; thus, mixed airflows may cover the areas nearby, or the air pressure may cover not only the area being stimulated but also induce pressure indirectly to adjacent areas, which lowers or masks the tactile sensitivity of the area.

5 Conclusion

In this study, two-point differential thresholds were investigated on human palms to obtain characteristics for the development of a noncontact tactile display. The following results were found. The tactile differential threshold was approximately 9 mm and became more sensitive when the presentation of subsequent stimuli was delayed. The most sensitive value was 7.5 mm when a 0.5-s ISI was given. The differential threshold was blurred after 0.5 s of the ISI, which differed from the previous study where a power function for forgetting the rate of tactile sensation was observed. In this study, the memory characteristics for a tactile display using air-jet stimuli was obtained. Further study is needed, especially on the clarification of the relationship between the pressure level and spatiotemporal memory characteristics, for the design of a noncontact tactile display that can transmit information effectively.

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