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Identification of Cutaneous Detection Thresholds against Time-delay Stimuli for Tactile Displays

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Abstract— **Tactile display is a technology that gives an artificial sense of touch to operators of information terminals or master-slave systems. The generation of tactile stimuli in response to the hand movements of the operators is associated with active touch and is considered to be one of the effective display methods, however which inevitably causes delayed tactile feedbacks from tactile displays. The knowledge of the detection threshold of system latency between the hand movements and the stimuli is helpful in designing the tactile displays. In this study, the identification of the thresholds through psychophysical experiments of 13 participants revealed two types of thresholds. One was the time-delay at which the participants observed the existence of latency. The other was the minimal time-delay that could affect the subjective feelings of the operators while they were not conscious of the latency. The means of the thresholds were 41 ms and 59 ms, respectively. The participants reported that the time-delay stimuli caused various changes in their subjective feelings. The empirical results suggest that the two types of thresholds depend on different sensory processes. This paper also proposes a design policy for tactile display systems in terms of system latency.**

I. INTRODUCTION

For tactile displays, a display method that produces appropriate tactile stimuli in response to the hand motions of operators is effective to induce the natural sense of touch. The method is compatible with active touch, because the operators move their hands and experience cutaneous sensations as well as when they touch real objects.

However, in this method, there is an inevitable time-delay between the hand movements and the stimuli presented by the tactile displays. When the delay is significant, the operators do not consider that the stimuli are causal effects of their motions, or they feel that virtual objects move unnaturally by themselves. The identification of cutaneous detection thresholds against the system latency is helpful in designing the tactile display systems in which hand movements are inputs and tactile stimuli are outputs.

The aim of this study is to investigate two types of detection thresholds. It is possible that the following two types of the thresholds exist. One is a minimal time-delay at which the operators can notice its presence. When the system latency exceeds this threshold, the operators notice that the tactile feedback is delayed. The other threshold is a minimal time-delay that affects the tactile feelings of the operators, while they are not conscious of the existence of delay. In touching processes, spatio-temporal information such as temporal variations in the firing rates of the tactile mechanoreceptors, hand motions, and physical characteristics of target objects are mutually interlinked. A temporal disparity in the information possibly changes the tactile feelings of the operators. If this disparity changes the feelings, it prevents the operators from experiencing the sensations as the developer of the display systems intended.

The following tactile display systems must consider the permissible system latency. The authors have proposed a method that synthesizes tactile stimuli from the hand position, velocity, acceleration of the operators and the physical properties of target objects [1]. Other tactile display systems also present tactile stimuli based on the measured hand motions [2-4]. These systems must be designed such that their response time does not exceed the thresholds. A tactile telepresence system is another example. The authors have also proposed a tactile telepresence system that enables the operators to touch remote objects in master-slave systems [5]. In remote environments, the tactile feedback from the tactile sensor includes the communication time-delay. It is necessary to design tactile telepresence systems by taking the permissible time-delay into account.

To the best of our knowledge, no studies on cutaneous detection thresholds against the time-delay between input actions and tactile stimuli have been reported. As a related study, for designing virtual reality systems, detection thresholds of time-delays in other sensory channels have been identified; - as summarized in table I. For auditory displays with head movement trackers, detection thresholds of the time-delay between the head movements and the presented virtual sound sources were reported (45–80 ms) [6][7]. The following thresholds also have been reported; the threshold between the play motions of the operator and sound generation for virtual musical instruments (70–80 ms, calculated from their report) [8], the threshold between typing motions or mouse actions and graphical responses for graphical user interfaces (100–200 ms) [9], the threshold between

TABLE I

DETECTION THRESHOLDS OF TIME-DELAY FOR VARIOUS SENSORY CHANNELS AND INPUT ACTIONS

Sensory Channel	Input action	Threshold [ms]
Auditory	Head movement	45–80 [6][7]
Auditory	Hand movement	70–80 [8]
Visual	Key type, mouse	100–200 [9]
Visual	Eye movement	100 [10]
Visual and haptic	Hand movement	30–35 [11]

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eye movement and image presentation for eye-movement-tracking-type image displays (100 ms) [10] and the threshold between visual and force feedbacks in presenting soft sphere (30–35 ms) [11]. They cannot be compared directly because some of the related studies employ different definitions for the detection thresholds.

For force displays that are thought to be similar to cutaneous sense displays in terms of time-delay effects on the sensations, several studies have reported that the delay impairs the task performances of the operators. The permissible time-delay that does not disturb tasks for remote training or teaching with haptic interfaces [12][13] ,and the time-delay that decreases the quality of service in collaboratively grasping and lifting objects in remote environments have been identified [14]. The system latency of force display against a hand movement possibly affects the softness discrimination[15]. These studies have investigated how the delay influences task performances and have not focused on the just noticeable time-delay for the operators.

The thresholds depend on the sensory channels and tasks. The cutaneous detection thresholds against the time-delay with hand motions as inputs and tactile stimuli as outputs need to be identified by a specific method.

The disposition of the paper is as follows. Experimental equipment and methods for identifying the two types of detection thresholds are described in section II. The experimental results are summarized in section III, and discussions are presented in section IV. The conclusions are given in the end of this paper.

II. Experiment for Identifying The Detection Thresholds of Time-delay

A. Tactile Stimuli

This study addresses the presentation of virtual textures as a task. The texture presentation is one of the typical applications for the tactile displays. The users explore and recognize the textures through tactile displays.

The tactile stimuli are vibrations, which are fundamental frequencies of the vibrations that occur to finger skins in touching the roughness scales whose spatial wavelength is λ at velocity v. The vibratory stimuli are produced according to the hand velocity. The voltage y supplied to the vibrator was defined as

$$y = A\sin(2\pi t\frac{v(t-D)}{\lambda}) + A \quad (1)$$

where A is the amplitude of the voltages and it was 75 V. D is the time-delay. The stimuli were produced using the buffered velocity to simulate the system latency. In this study, λ was 1 mm.

B. Experimental System

Figs. 1 and 2 show the experimental equipment. Fig. 3 shows the block diagram of the entire system. The vibrator was installed on a linear slider. Its position on the slider was measured by a linear encoder whose spatial resolution was 1.6 μm. A control computer received the encoder

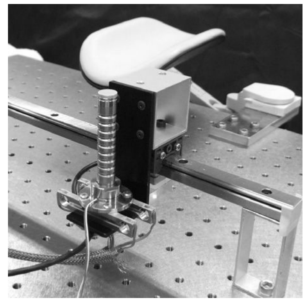

Fig. 1. Experimental apparatus and an elbow rest for participants

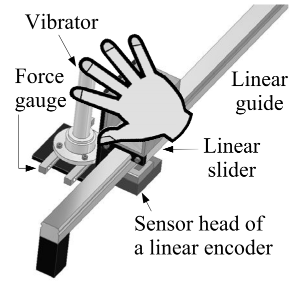

Fig. 2. Schematic representation of the experimental apparatus

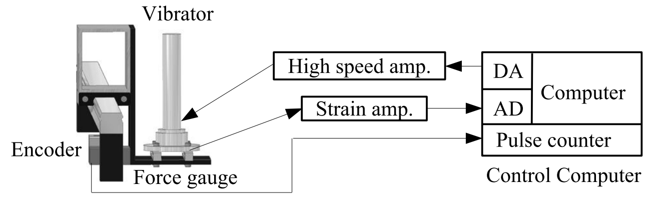

Fig. 3. Block diagram of the entire system

pulses and supplied voltages to the vibrator. The control frequency of the computer was 5 kHz. As a tactile vibrator, a piezo-stack-type actuator (NEC/TOKIN ASB510C801P0) was adopted. The maximum indentation of the vibrator was approximately 60 μm for 150 V, and it was confirmed that the vibrator produced sufficient vibrations up to 300 Hz for good perception.

The inherent time-delay of the system was measured 10 times; the maximum and median were 160 μs and 140 μs, respectively. The inherent time-delay was the minimum delay of the system. It was defined as the period from the onset of the encoder pulses to the resulting voltage changes in the vibrator.

C. Experimental Methods and Procedures

The participants were 13 males in their 20–30s. Each participant touched the vibrator with his right middle finger as shown in fig. 4. The participants were instructed not to touch any parts of their hands except their middle finger to the vibrator and slider. The participants were blindfolded and heard pink noise through a headphone. All the cues during the experiment were beep sounds. Each participant scanned the virtual object for 5 s after the first beep until the second beep. With an interval of 3 s, the participant scanned it again for another 5 s after the third beep until the fourth beep. During the first 5 s, a stimuli with no time-delay was displayed, as a reference stimulus. During the next 5 s, a stimulus whose time-delay was controlled was displayed, as a test stimulus. During the experiments, no true-false feedback was given to the participants. Fig. 5 shows the reference and test stimuli and an example of the hand velocity of the participant during one trial. Prior to each trial, the participants removed their finger from the vibrator once and then placed it on again in order to prevent it from paralysis. Within each trial, they tried to maintain contact

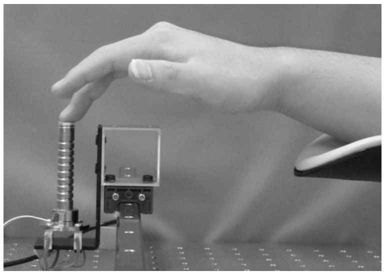

Fig. 4. Experiment: Participant touched the vibrator with their right middle finger

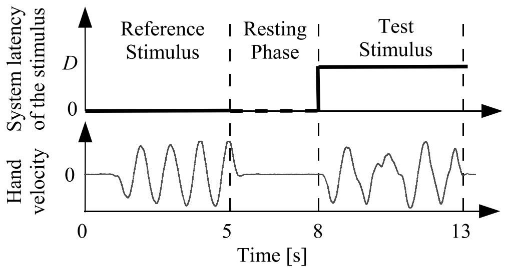

Fig. 5. Example of the hand motion and simulated latency of the stimuli in the trial

between their finger and the vibrator. The pressing force on the vibrator was measured, and if it exceeded 2 N in the trial, the trial was regarded as invalid and it was tested at the end of the experiment again. The participants practiced touching and moving the vibrator with a force smaller than 2 N for minutes. The encoder counts were recorded.

Two types of experiments (experiment A and B) were conducted.

Experiment A aimed to identify the threshold for delay detection. In experiment A, an experimenter explained to the participants that delayed tactile stimuli would be presented, and the aim of the experiment was to identify the detection threshold against the time-delay. The participants were required to judge whether the test stimuli were delayed or not.

Experiment B aimed to identify the threshold for detecting the subjective changes caused by the time-delay. In experiment B, the experimenter explained to the participants that some parameters in the test stimuli might be changed slightly, and the aim of the experiment was to investigate whether the participants notice the changes. The experimenter did not give them information regarding the types of parameters that were changed. The participants were required to determine whether the test stimuli were the same as the reference stimuli or were different.

The objectives and the questions posed to the participants in the two types of experiments are summarized in table II. Except for the prior explanations and questions described above, all the procedures were the same in experiments A and B. All 13 participants were subjected to both the types of the experiments with an interval of at least one day. Seven subjects conducted experiment A at first, then experiment B

TABLE II
OBJECTIVES AND QUESTIONS POSED TO THE PARTICIPANTS IN EXPERIMENTS A AND B

	Experiment A	Experiment B
Objectives	Identifying the thresholds for delay detection	Identifying the thresholds to notice the tactile changes caused by time-delay stimuli
Questions	Delayed or not	Same or different

on different days. The remaining 6 participants conducted them in reverse order. In order to prevent the preceding experiment from affecting the subsequent one, experiment A and B were conducted on different days for every participant.

Before each main experiment, a preliminary experiment was conducted in order to estimate the time-delay D_{max} which the individual participant could always notice, by a limitation method. D_{max} was in the range of 70–110 ms, in 26 experiments.

The main experiments were performed by a constant method; the standard stimulus was $D = 0$. D_{max} was equally divided into 6 stimuli between 0 ms, and one of the 6 stimuli was assigned to D as the test stimulus. Each D value was tested 10 times; the display order was random. One experiment comprised 60 trials and it took approximately 40 min including the instructions, practices and preliminary experiments.

In this study, both the reference stimuli (stimuli with no time-delay) and the test ones (controlled time-delay) were presented to the participants in each trial. When both the stimuli were coupled, the participants became more sensitive toward the changes in the signals than when the test stimuli were presented individually; Brungart et al. reported this observation in their auditory tests[7]. The experiments were planned so that the participants remained sensitive; this is because the identification of the maximum permissible system latency is necessary for designing tactile display systems.

III. EXPERIMENTAL RESULTS

A. Method for calculation of detection thresholds

Fig. 6 outlines a method for calculating the thresholds in this study. The vertical axis in the figure shows the ratio of the positive answers. The horizontal axis shows the time-delay of the test stimuli. Examples of the positive answer rates of the participant and a fitted curve $f(D)$ are shown in the figure. The fitting function is a logistic function defined as

$$f(D) = \frac{1}{1 + \exp(-a - bD)} \tag{2}$$

where a and b are characteristic parameters of the curve. The detection threshold is defined as D at which $f(D) = 0.5$. DT_A and DT_B denote the detection thresholds of the participant in experiment A and B, respectively.

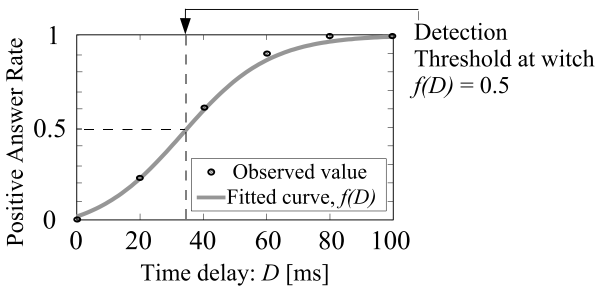

Fig. 6. Calculation method and the definition of the detection threshold: an example of the positive answer rates of the participant as a function of the time-delay of the test stimuli

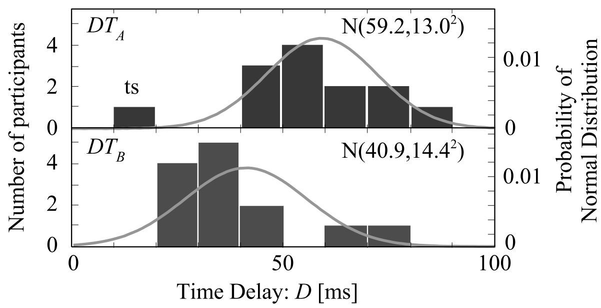

Fig. 7. Histogram of DT_As (thresholds identified through experiment A) and DT_Bs (thresholds identified through experiment B)

B. Detection Thresholds of Participants

The histograms of the calculated thresholds of 13 participants in experiment A and B are shown in fig. 7. The normal distribution curves of the threshold populations are also shown in the figure.

Among 13 participants, DT_A of participant ts might be an outlier (Grubb's test, $G = 2.393 > G(0.05, 13) = 2.331$). Moreover, the false alarm rates of ts in both experiment A and B were 0.3, higher than those of the other participants. The authors considered the results of ts as outliers and excluded them from any statistics. The means and the standard deviations of the thresholds excluding ts were $DT_A = 59.2 \pm 13.0$ ms and $DT_B = 40.9 \pm 14.4$ ms. When ts was included, they were $DT_A = 55.6 \pm 17.8$ ms and $DT_B = 39.4 \pm 14.9$ ms.

In the case of 12 participants, DT_A of each participant was larger than his DT_B. The mean DT_A was larger than mean DT_B with significant levels of 0.01 with or without the outliers. Table III shows the results of paired t-test.

Fig. 8 is a scatter plot of DT_As and DT_Bs. There was no significant correlation between DT_As and DT_Bs. ($r = 0.342$, t-test, $n = 12$, two-tailed, $p > 0.05$, $p = 0.273$).

Two-way ANOVA was applied to the results. The factors were the types of the experiments and the experimental order. Fig. 9 shows the mean values of DT_As and DT_Bs with their standard deviations; they are grouped on the basis of the experimental order. The circles in the figure indicate mean DT_As and DT_Bs of 6 participants who conducted experiment A first. The rhombuses indicate the means of the

TABLE III

TEST RESULTS, COMPARING MEAN DT_A AND DT_B: TEST STATISTICS AND p VALUES

t_0 (p)	
Whole samples (n=13)	Exclude outliers (n=12)
3.494 (0.00222)**	4.013 (0.00102)**

** significant at level 0.01

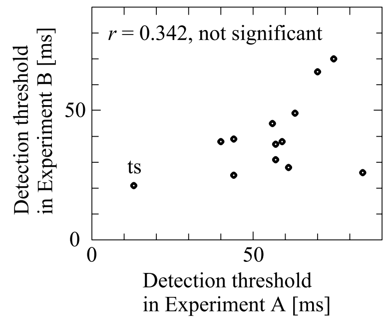

Fig. 8. Scatter plot of DT_As vs. DT_Bs: There was no significant correlation between DT_As and DT_Bs.

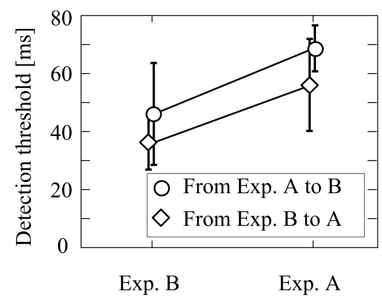

Fig. 9. Mean DT_As, DT_Bs and their standard deviations by the experimental order

other 6 participants who conducted experiment B first. Table IV summarizes the analysis results. The type of experiment is the only significant factor that affects the thresholds. The experimental order did not affect the thresholds.

C. Correlation between Detection Thresholds and Touch Motions

Pearson's correlation coefficients between the thresholds and the feature quantities of the touch motions of the participants were calculated. Three types of feature quantities were used. The first one was the frequency of the reciprocating hand velocity. The power spectrum density of the hand velocity of each participant was computed and the frequency at which the power spectrum was the maximum

TABLE IV

TWO-WAY ANOVA SUMMARY OF THE DETECTION THRESHOLDS

Factor	df	Mean Square Sum	F	p
Type of experiments	1	1998.4	10.87	0.0036**
Experimental orders	1	442.0	2.404	0.14
Type × Order	1	15.0	0.082	0.78
Error	20	183.9		

was considered the representative frequency of the touch motions of the participant. The second one was the average of the peak speed in each half cycle of motions. The maximum speeds of every half cycle of the reciprocating motions were collected and their average was considered as the feature quantity of the hand speeds of each participant. The third feature quantity was the average of the peak acceleration in each half cycle of the hand motions. From the results of the test, it was observed that the frequencies and the average peak speeds exhibited weak correlations between the detection thresholds.

Fig. 10 shows a plot of the relationship between the frequencies and the thresholds. The thresholds are normalized in the figure, by dividing them by the mean thresholds in experiment A or B. There was a negative correlation between the 24 pairs of the thresholds and the frequencies ($r = -0.541$, t-test, $n = 24$, one-tailed, $p < 0.01$, $p = 0.0032$). DT_Bs correlated with the frequencies ($r = -0.661$, t-test, $n = 12$, one-tailed, $p < 0.01$, $p = 0.0096$), while DT_As did not.

Fig. 11 shows a plot of the relationship between the hand speeds and the normalized thresholds. There was a positive correlation between the 24 pairs of the thresholds and the corresponding speeds ($r = 0.509$, t-test, $n = 24$, one-tailed, $p < 0.01$, $p = 0.0056$). DT_Bs correlated with the hand speeds ($r = 0.561$, t-test, $n = 12$, $p < 0.05$, one-tailed, $p = 0.029$), while DT_As did not as in the case of the relationship between the frequencies and the thresholds.

DT_Bs showed a negative correlation between the hand frequencies and a positive correlation between the hand speeds. From these correlations, DT_Bs tended to be lower when the participants moved their hands with higher frequencies and smaller strokes.

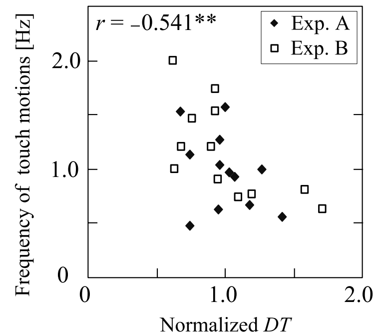

Fig. 10. Frequency of the reciprocating touch motions vs. the detection thresholds

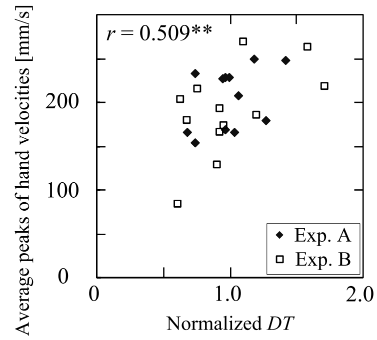

Fig. 11. Average peak velocities of the reciprocating touch motions vs. the detection thresholds

D. Subjective Tactile Feelings during the Trials

After the experiments, the participants were asked about the subjective feelings. This section summarizes their major opinions.

After experiment A, the experimenter asked the participants about how they detected the time-delay in the stimuli. Their major answers were as follows; they recognized the existence of the delay when they found no tactile feedback at the onset of their motions, when the stimuli were still even after they stopped the motions, or when they felt the virtual object unnaturally moved. They also reported that they felt that something was moving beneath their hands.

After experiment B, the participants were asked about the changes in their tactile feelings caused by the time-delay stimuli (actually they were not given information about the types of parameters that were changed). Their answers were as follows; they felt that the strength of the stimuli increased (rougher) or decreased (smoother), the weight of the slider increased or decreased, or they felt frictional and viscous resistance in their moving directions. It was observed that a simple time-delay tactile stimuli caused various changes in the subjective feelings under the experimental conditions of this study. Interestingly, contradictory opinions such as rougher and smoother were reported even from the same participant.

IV. Discussion

A. Design Policy of System Latency according to the Objectives of Display Systems

The design policy of tactile display systems in terms of system latency is derived from the fact that there are two types of cutaneous detection thresholds against time-delay. The permissible system latency varies according to the objectives of the systems.

In the system that aims to present the textures of objects, a threshold as small as 41 ms is a permissible delay. If the delay is above this threshold, the perceived texture is most likely altered. The users may not receive the tactile sensations as the designer had intended to present.

In the system that aims to inform the users of the completion of their inputs to the system, a large threshold (59 ms) is a permissible delay. For example, a display panel that presents vibrotactile stimuli to show that a user presses a virtual button on the panel, requires a time-delay that is smaller than 60 ms. This is because the stimuli in this application must be recognized as causal effects of the inputs and the texture does not matter.

B. Difference between the Sensory Information Processes of Two Types of Thresholds

There is a possibility that sensory information for latency detection and the detection of tactile changes are processed in different ways. The following two points suggest that the difference of the sensory information processes in the two experiments of this study.

First, from the observations of the participants in experiment A to detect the presence of latency, the authors find that they took a longer time to answer the questions. On the other hand, in experiment B where the changes in their tactile sensations are detected, they often answered immediately even during the trial. From the differences between the necessary times to answer the questions, in experiment A and B the thresholds may be generated from different information processes.

Second, as shown in section III-C, the thresholds for delay detection were not correlated with the feature quantities of the hand motions, whereas the thresholds for detecting the tactile changes correlated between the two feature quantities of the hand motions. This fact also suggests that the two types of thresholds are influenced by different processes.

C. Relationships between Hand Motions and Thresholds for Detecting the Tactile Changes Caused by Time-delay

As the hand speeds were small and the strokes were small, the participants were more sensitive to the changes in their tactile feelings caused by the time-delay. These relationships are interpreted as follows.

Because the tactile stimuli are produced based on (1), when the participant scans the object at a constant speed, there is no change in the stimuli and the participant can not notice the time-delay. As the participant's hand speed is varied, the time-delay produces the stimuli that are different from the ones with no delay. With higher frequencies of the reciprocating hand motions, the stimuli are varied further and the participants could more easily notice the tactile changes caused by the time-delay.

Existing studies are consistent with the tendency that the participants were more sensible to the tactile changes when the hand speeds were slow. Lederman has reported that slower scanning slightly enhanced the perceived roughness [16]. Gamzu et al. have reported that the performances of roughness discrimination tasks increased by training a certain group of people to slowly scan roughness samples [17]. It is possible that slower scanning improved the sensitivity of the participants toward the tactile changes caused by the time-delay.

V. Conclusion

This study identified the two types of cutaneous detection thresholds against the time-delay tactile stimuli through the psychophysical experiments. In one threshold, the subjects could notice the existence of system latency in the tactile displays. This threshold was 41 ms. In the other threshold, the participants experienced changes in their tactile feelings while they were not conscious of the time-delay. This threshold was 59 ms. It was observed that the simple time-delay stimuli caused various changes in their tactile feelings. This study resulted in the development of a design policy for the tactile display systems in terms of system latency. The permissible system latency should vary according to the objectives of the systems.

Acknowledgments

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