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Study on Two-Variable Electrocutaneous Communication

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Abstract

This paper deals with the information transmission characteristics of a two-variable electrocutaneous communication method using magnitude and frequency simultaneously. Firstly, the channel capacity of a two-variable electrocutaneous communication system is discussed. Secondly, the maximum information transmission rate is estimated from a category discrimination test. Finally, the reaction time, the time between the presentation of a two-variable stimulus and a detectable response to it is measured and the maximum information transmission rate per second is calculated.

1. Introduction

To establish a tactile input channel to human is essential to construct an effective sensory substitution system for the sensory handicapped. Several methods of tactile stimulation has been known. Electrocutaneous stimulation is one of the most excellent tactile displays.

Basic investigations concerning the electrocutaneous stimulation have been performed by several investigators. Relevant stimulus parameters and information transmission characteristics of the electrocutaneous stimulation were investigated by Kato et al.[1], Prior[2], Ichikawa et al.[3], Solomonow et al.[4], Anani et al.[5], Tachi et al.[6] and Tanie[7]. An electrocutaneous sensory feedback systems for hand prostheses were proposed by Beeker et al.[8], Kato et al.[9], Shannon[10], Reswick et al.[11] and Prior et al.[12].

Pulse stimulation is usually chosen for electrocutaneous communication. As in the case of hearing, magnitude, pitch and location of the perceived stimulus can be used as carriers of information. It has been found that the information rate associated with the magnitude or the pitch of an electrocutaneous stimulus lies about 4.0 bits/symbol when it is estimated from just noticeable differences, and about 2.0 bits/symbol when it is estimated from category discrimination test[7]. This information rate is not high enough for practical applications. In order to transmit a large amount of information, it may be effective to use a multi-variable display where more than one stimulus aspect of the stimulation are used simultaneously. In the past, Pollack investigated a two-variable auditory display and suggested that a multi-variable display led to the both increases of information rates and the kind of transmitted information[13]. Multi-variable communications are considered to be one of the most excellent information transmission methods, but few researches have been performed on multi-variable electrocutaneous displays.

This paper deals with the information transmission characteristics of a two-variable electrocutaneous communication method using magnitude and pitch sensations simultaneously. The channel capacity and the maximum information transmission rate in a two-variable electrocutaneous communication system are measured, and the optimum presentation of stimulus categories is experimentally studied.

2. Experimental System

Fig.1 shows the experimental setup used. The experimental system includes a computer(PDP-11/40), multi-channel simultaneous stimulator[14], stimulus energy controller[15] and etc. The output of the stimulator is isolated by the photo-coupling type isolator and is presented on to the skin of a subject via wet electrodes. Three electrodes are located on the skin just above the triceps brachii along the direction of the muscle 20 mm apart from each other. The two outer electrodes are connected and used as a common, and negative pulse is presented the central electrode.

In a previous paper the authers reported the fact that the magnitude sensation of the electrocutaneous stimulation is strongly related to the stimulus pulse energy[6]. In the following experiments, stimulus pulse frequency and pulse energy are used as two variable parameters of the stimulation. Electrocutaneous stimulation is provided by a constant current source and the energy of each pulse is regulated by a stimulus energy controller. Stimulus parameters are able to be versatilely controlled by computer programs.

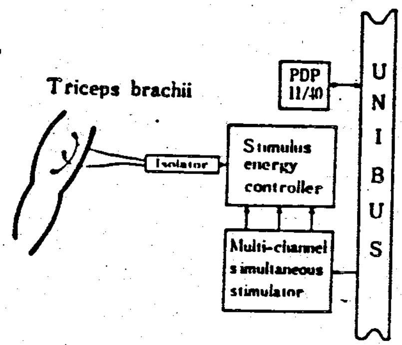


Fig. 1 Experimental Setup.

3. Channel Capacity in a Two-Variable Display

The construction of a two-variable display must be discussed before estimating the channel capacity of it. Fig.2 shows a typical two-variable electrocutaneous information transmission system which transmits two kinds of information. The signals A

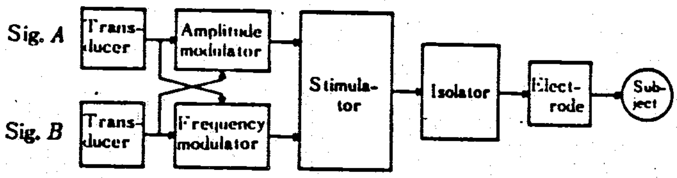


Fig.2 Typical two-variable electrocutaneous information transmission system.

and B detected by transducers are converted into the magnitude of the pulse energy and the frequency of the pulse, respectively, by modulators and are presented to a subject via a stimulator, an isolator and electrodes. In auditory and tactile displays, magnitude and pitch sensations for pulsated stimuli are not generally independent. Magnitude sensation is affected by the change of frequency and vice versa. If pulse energy is changed along the equal magnitude sensation curves and pulse frequency is changed along the equal pitch sensation curves, magnitude and pitch sensations can be independent and the subject will be able to perceive the information seperately. In Fig.2 the crossing arrows from the outputs of the transducers show the signal flows which compensate the modulator outputs. Usually, the variance in pulse energy has little influence on the pitch sensation. In the following two-variable display, only the output of the amplitude modulator is compensated.

Fig.3 shows the equal magnitude sensation curves for electrocutaneous stimulation. Some of these curves were memorized in the mini-computer memory and used. The channel capacity can be estimated from Fig.3.

The channel capacity of a sensory communication system is defined as the logarithm to the base two of the number of just noticeable differences cumulated in a dynamic range of sensation. Both this definition and the above-mentioned construction of a two-variable display suggest that the channel capacity of a two-variable electrocutaneous display can be estimated from the number of the cross points of equal magnitude sensation curves and equal pitch sensation curves which are discriminable from each other curves of the same kind. When the maximum number of the cross points in the pulse energy - pulse frequency plane is N, the channel capacity is finally calculated to be $\mathrm{Log}_2 N$.

Equal magnitude sensation curves and equal pitch sensation curves which are discriminable from each other curves of the same kind, and cross points of them are shown in Fig.3. Each dotted lines in this figure indicates the differential limen from the corresponding equal magnitude sensation curve.

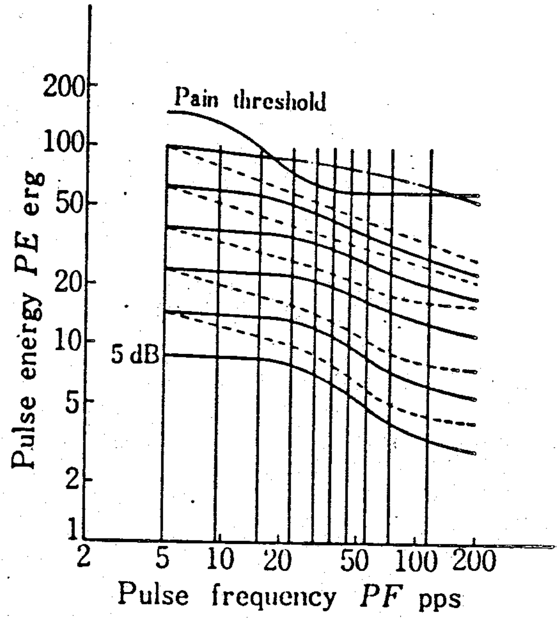


Fig. 3 Channel capacity of two-variable electrocutaneous information transmission system is estimated from the number of cross points of equal magnitude curves and equal pitch sensation lines. Each dotted line in the figure indicates the differential limen from the corresponding equal magnitude curve (subject: K.T.).

In general, the differential liemen of pitch sensation in electrocutaneous stimulation decreases according as the increase of stimulus pulse energy, and that of magnitude of sensation decreases according as the increase of stimulus pulse energy. Equal sensation curves can be usually put in approximately parallel alignment. These facts suggest that the channel capacity of a two-variable electrocutaneous communication system is estimated from the sum of the channel capacity of the magnitude aspect of stimulation in minimum frequency level and the channel capacity of the pitch aspect of stimulation in minimum magnitude level.

The channel capacities for four subjects were calculated using this estimation method. Their values ranged from 5.6 bits/symbol to 6.0 bits/symbol, when the dynamic range in magnitude aspect and that in frequency aspect are assumed to be 5 dB - pain threshold and 5 pps - 150 pps, respectively. They are greater than the channel capacity of an one-variable communication system.

4. Category Discrimination Test and Maximum Information Transmission Rate

4.1 Experimental Procedures

In the experiments N_m equal magnitude sensation curves and N_f equal pitch sensation curves drawn on the pulse energy - pulse frequency plane were firstly chosen. The equal magnitude sensation level was varied in approximately equal pulse energy steps between magnitude level 5 dB and pain threshold level at the frequency level 5pps. The equal pitch sensation level was varied in equal logarithmic steps between 5pps and 150pps. The stimuli corresponding to $N_m x N_f$ cross points of their curves, (E_1,F_1), (E_2,F_2),---,(E_n,F_m), were chosen as the stimuli to be discriminated by subjects. The set of presented stimuli was varied in 2x2, 2x3,3x2,3x3,3x4,4x2,4x3 and 4x4. In each experiment, subjects were randomly presented with a stimulus in a set of stimuli and were asked to report upon both stimulus aspects - its magnitude and its pitch level. The subjects used a switch matrix as shown in Fig.4 to respond the presented stimulus.

Subjects judged 20 times for each set of presented stimuli. The time duration of each stimulus was 2 sec. Three subjects of ages 22, 24, 32 were used in this experiments. One of them is an experienced researcher and the others are students highly interested in the experiments.

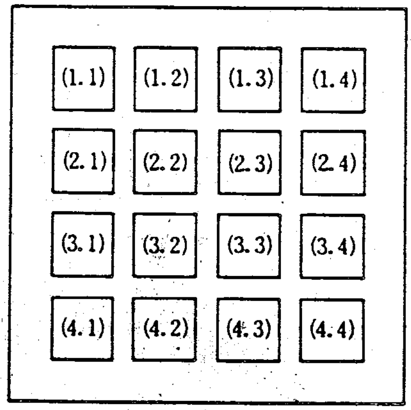


Fig. 4 Switch matrix.

From the results of this category discrimination test, the information transmission rate $H(x,y;z)$ for each set of stimuli was computed. The following formula was used to calculated it.

$$H(x,y;z)=H(x,y)-H_z(x,y) \qquad \text{[bits/symbol]}$$

where,

$$H(x,y)= -\sum_i\sum_j P(x_i,y_j)\,\mathrm{Log}_2 P(x_i,y_j)$$

$$H_z(x,y)= -\sum_i\sum_j\sum_k P(x_i,y_j,z_k)\,\mathrm{Log}_2 P(x_i,y_j/z_k)$$

and x_i denotes ith stimulus category on the magnitude stimulus aspect and y_j does jth stimulus category on the pitch stimulus aspect. z_k denotes kth category of response. $P(x_i,y_j)$ is the joint probability for the events x_i and y_j, and $P(x_i,y_j,z_k)$ is the joint probability for the events x_i,y_j and z_k. $P(x_i,y_j/z_k)$ is the conditional probability of the events x_i and y_j given that the event z_k was observed.

4.2 Experimental Results

The information transmission rates $H(x,y;z)$ associated with a two-variable electrocutaneous display for several sets of presented stimuli are shown in Table 1. In the table, N_m is the number of steps of one stimulus aspect of the electrocutaneous stimulation, that is, stimulus magnitude. N_f is that of pulse frequency. The

Table 1 Two-variable information transmission rate. $H(x,y;z)$: information transmission rate, bits/symbol.

N_f	N_m	H(x,y;z) bits/symbol		
		Subject K.T.	Subject Y.T.	Subject K.K.
2	2	2.0	2.0	2.0
	3	2.5	2.5	2.3
3	2	2.5	2.5	2.4
	3	2.9	2.8	2.7
	4	3.0	2.8	2.6
4	2	3.0	2.7	2.6
	3	3.2	2.9	2.6
	4	3.1	3.0	2.7

Table 2 Maximum information transmission rate(H_{max2D}: two-variable, H_{maxm}: magnitude, H_{maxf}: pitch).

Subjects	H_{max2D}	H_{maxm}	H_{maxf}	$H_{maxm}+ H_{maxf}$
K.T.	3.2	1.8	2.1	3.9
Y.T.	3.0	1.8	2.0	3.8
K.K.	2.7	1.7	1.8	3.5
Data from ref. 1)	2.9	1.9	2.0	3.9

[bits/symbol]

results indicate that the information transmission rates have a tendency to be saturated, when 16 (N_m=4,N_f=4) stimulus categories were employed in the two-variable test. The maximum information transmission rate associated with a two-variable electrocutaneous display is estimated to be 2.7 - 3.2 bits/symbol from those results.

Table 2 shows the maximum information transmission rates associated with one- and two-variable electrocutaneous displays. In one-variable display, only one stimulus aspect of electrocutaneous stimulation - its pulse frequency or its pulse energy - was varied. In the one variable test, the maximum information transmission rates associated with the pulse energy and frequency were about 1.8 bits/symbol and about 2.0 bits/symbol, respectively.

The information transmission rate associated with a two-variable display is superior to that associated with a one variable display, that is, $H_{max2D} > H_{maxm}$, H_{maxf}. On the other hand, H_{max2D} is less than $H_{maxm} + H_{maxf}$. The results indicate that the information transmission rates per one stimulus site can be greater when two-variable display is employed than when one-variable display is employed, though subjects can identify a single stimulus aspect more acculately when only that aspect is varied than when two stimulus aspects are both varied.

The fact that H_{max2D} is less than $H_{maxm} + H_{maxf}$ is considered to result from judgement interactions in two-variable situations as Pollack suggested[13]. The effect of the interactions between the two stimulus aspects on the identification of two-variable stimulus categories becomes smallest when stimulus energy and frequency are manipulated on the equal pitch and the equal magnitude sensation curves, respectively. In the lowest line of the table 2, the maximum information transmission rates associated with one- and two-variable displays without the equal pitch and the equal magnitude compensation by Kato et al. are shown to be compared with the results in this experiments. $H_{max2D}/(H_{maxm} + H_{maxf})$ can be available as a criterion of the judgement interactions. The greater $H_{max2D}/(H_{maxm} + H_{maxf})$, the less the effect of the interaction between the two stimulus aspects. $H_{max2D}/(H_{maxm} + H_{maxf})$ are 0.77 -0.82 in this experiments and 0.74 by Kato et al.. It is noted that the former is a little larger than the latter. The fact suggests that the equal magnitude and the equal pitch compensation in a two-variable electrocutaneous display is effective to reduce the judgement interactions.

To estimate the interaction between the two stimulus aspects, the two-variable response pattern was artificially broken into its one-variable parts. Information transmission rates associated with one stimulus aspect in a two-variable display were obtained as functions of the number of categories on the other stimulus aspect. These are shown in Fig.5 and 6. The figures indicate that the information transmission rates associated with the magnitude sensation have a tendency to decrease clearly according as the increase of the number of categories on the frequency aspect of stimuli, while that associated with the pitch sensation has a tendency to decrease a little according as the increase of the number of categories on the magnitude aspect. This is due to the fact that subjects can discriminate the frequency aspect of stimulus more acculately and absolutely than the magnitude aspect of stimulus. The results suggest that more steps should be employed for the frequency aspect of stimulus than for the magnitude aspect when some two-variable categories are presented to subjects.

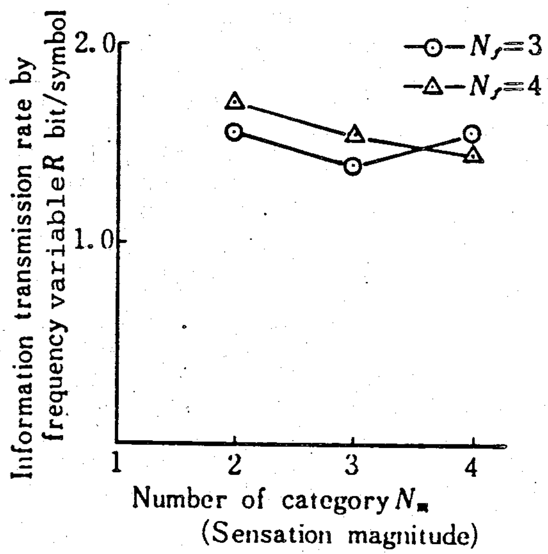


Fig. 5 Information transmission rate as a function of number of category N_m (subject: Y.T.).

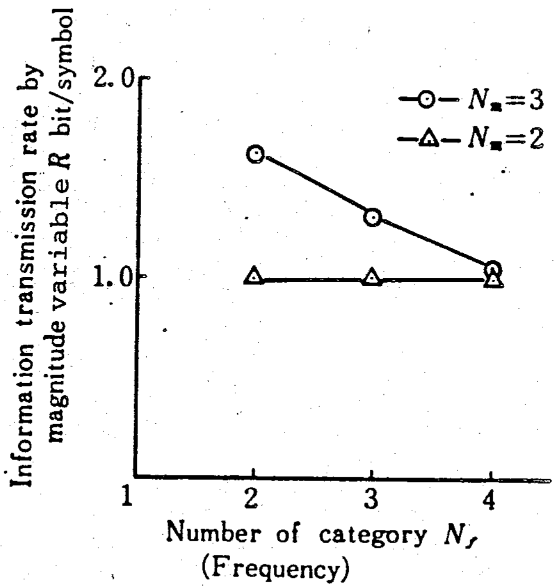


Fig. 6 Information transmission rate as a function of number of category N_f (subject: Y.T.).

5. Reaction Times and the Optimum Number of the Stimulus Categories

The time between the presentation of a stimulus and a detectable response to it is called the reaction time. Usually, the average reaction time RT for a presented stimulus set in H(x) required to specify a member of the presented stimulus set, namely, input information rate, then,

$$RT = a + bH(x)$$

The reaction time in a two-variable display is inferred to be dependent on the input information as is the case in an one-variable display. The less input information a set of presented stimuli has, the faster subjects can respond to it. The excessive input information presented may lead to the decrease of the information transmission rates per a unit time. A two-variable electrocutaneous display is advantageous, only if the average reaction time T_{2D} of the two-variable display is evidently less than the sum of individual average reaction times for the sequential presentation where the subject responds to the two variables one after the other.

In this section, the relations between the reaction times for the simultaneous presentation of two-variable stimuli and the sequential presentation of them are discussed.

5.1 Experimental Procedures

The experiment consists of three sessions. In this experiment three subjects were used. The experimental setup employed was identical to Fig. 1.

Session I : In general, reaction times are broken into two parts; simple reaction time T_d and choice time T_s[16]. In this session, T_d is measured. Only one kind of stimuli were presented 20 times at random intervals. Subjects were asked to press a specified key on the switch matrix as soon as they accepted a stimulus. Each stimulus was presented until a subject responded to it. The duration times of the presented stimuli, which are the reaction times in the case of this session, were measured by the real time clock in the mini-computer PDP-11/40. T_d was estimated from the average of 20 reaction times obtained in this experiment. The pulse frequencies of the stimuli employed were 10, 20, 50, 100 pps. The pulse energy of the stimuli was kept in the middle of the minimum threshold and the pain threshold of magnitude sensation.

Session II : Several sets of two-variable stimuli were presented to subjects as mentioned in section 4. Subjects were asked to identify a stimulus by pressing the correct key on the switch matrix. They were told to respond as quickly as possible. The sets of two-variable stimulus categories employed were (N_m, N_f)= (2,2), (2,3),(3,2),(3,3),(3,4),(4,3) and (4,4). The trials for each set of two-variable stimuli were continued until 20 correct responses were obtained for each category of the presented stimuli. Error trials were discarded. The number of the actual trials was about

10% greater than 20 times the number of the presented stimuli for each set of the two-variable stimuli. The presentation of each stimulus was stopped by a detectable response as in session I. The reaction times for the presented stimuli were finally memorized. The measuring procedure of them were identical to that of session I.

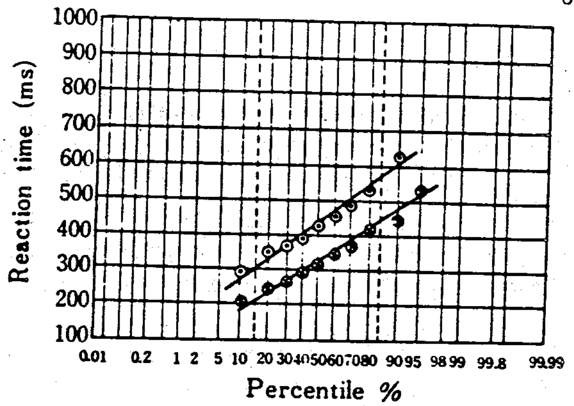
Session III : Several sets of two-variable stimuli were presented. Subjects were required to identify only one stimulus aspect of a presented stimulus by pressing the correct key on the switch matrix. The trials were performed for either of the two stimulus aspects of the presented stimuli -their magnitude and frequency level- individualy. The sets of two-variable stimulus categories which were employed here were the same as in session II. The reaction times for each trial were memorized into the mini-computer.

5.2 Experimental Results

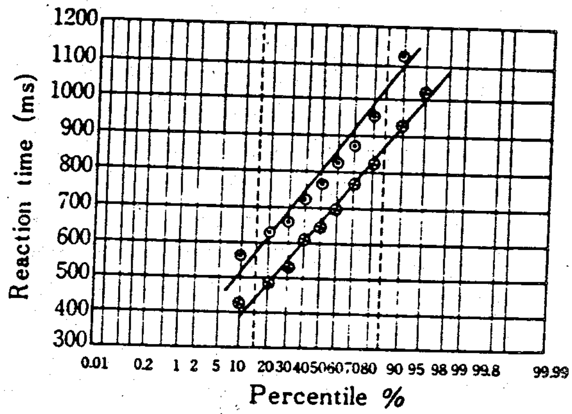
As the results of session I, the average T_d across frequencis for three subjects was 183, 202 and 214 ms. In session II and III, a reaction time measured for each subject, which is usually called a disjunctive reaction time[16], was subtracted by the T_d corresponding to the same subject. A disjunctive reaction time minus T_d, choice time, is called the reaction time in the following discussions.

The results obtained in session II and III were summerized on cumulative probabilistic functions. From the results in session II, the reaction times T_{2D} for various percentiles for each set of stimulus categories were computed. These values were then averaged across subjects. To analyze the results in session III, combinations of T_m and T_f, reaction times for the magnitude and the frequency identifications, respectively, were considered. These two kinds of reaction times, T_m and T_f, were added in consideration of their probability to give the compound reaction times T_m+T_f as functions of percentiles for each set of stimulus categories. All compound reaction times obtained were averaged across subjects as in session II. T_{2D} can be considered to be the reaction time of simultaneous presentation of the two-variable stimuli and T_m+T_f can be considered to be that of sequential presentation of the two-variable stimuli

Reaction times as functions of percentile plotted on normal-probability paper for the simultaneous presentation of two-variable stimuli and the sequential presentation of them are shown in Fig. 7. In the figure, only three cases, that is, $(N_m, N_f) = (2,2), (3,3), (4,4)$ were plotted. Other cases were similar, though they were not shown. In Fig.7 (a), (b) and (c), it is noted that the reaction time T_{2D} for the simultaneous presentation of stimuli is different from the reaction time T_m+T_f for the sequential presentation of stimuli. When the number of categories of the presented stimuli is small, T_{2D} is smaller than T_m+T_f. The difference of T_{2D} and T_m+T_f decreases according as the increase of the number of categories of the presented stimuli. Especially for the set of presented stimuli $(N_m, N_f) = (4,4)$, T_{2D} is even greater than T_m+T_f except for the range of percentile 0-30%. These results suggest that subjects can

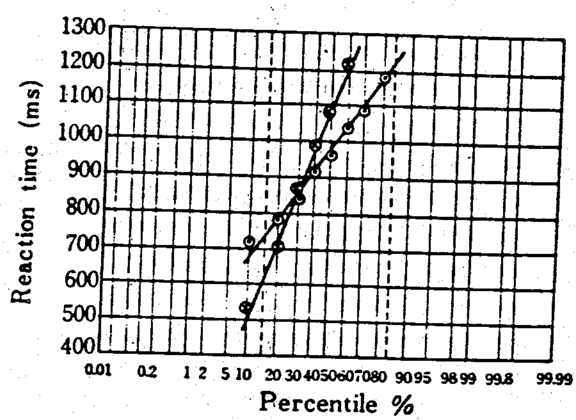


(a)



(b)

Fig. 7 Reaction times as a function of percentile plotted on normal probability paper for the simultaneous presentation of two-variable stimuli (—⊗—) and the sequential presentation of them (—⊙—).
(a) $N_f=2, N_m=2$ (b) $N_f=3, N_m=3$ (c) $N_f=4, N_f=4$.



(c)

identify two stimulus aspects of two-variable stimuli as a whole rather than seperatly, when the number of categories of the presented stimuli is relatively small. The averaged reaction times obtained from the experiments of session II and III are shown in Table 3. Also shown in this table are paired t-test values for testing the significance of the difference between the averaged reaction times T_{2D} and T_m+T_f for each set of presented stimuli.

Table 3 Average reaction times for the simultaneous presentation of two-variable stimuli and the sequential presentation of them and associated t-tests(N_f: number of category of frequency aspect, N_m: number of category of magnitude aspect, T_{2D}: average reaction time of the simultaneous presentation, T_m+T_f: average reaction time of the sequential presentation).

N_f	N_m	T_{2D} ms	T_m+T_f ms	t*	Freedom
2	2	317	437	-2.14	38
	3	487	583	-2.18	38
3	2	506	629	-2.53	38
	3	643	774	-2.56	38
	4	770	874	-1.15	38
4	3	773	886	-1.15	38
	4	1079	965	0.82(0-100%)	38
				-0.58(0-50%)	16
				2.52(50-100%)	18

* Critical $t(38)=1.68$, $t(18)=1.73$ and $t(16)=1.75$, $p<0.05$, one-tailed.

Especially for the set of presented stimuli $(N_m, N_f) = (4,4)$, t-test values are shown for the ranges of percentiles 0-100, 0-50 and 50-100%. Inspection of table 3 suggests that the effect of the simultaneous presentation of two-variable stimuli is advantages for $(N_m, N_f) = (2,2), (2,3), (3,2)$ and $(3,3)$. From the results, the practical limit of the number of categories of the two-variable stimuli is $(N_m, N_f) = (3,3)$, which can be more advantageous for the simultaneous presentation of two-variable stimuli from the standpoint of increasing the information transmission rate per second than for the sequential presentation of them. In table 3, information transmission rates per second for $(N_m, N_f) = (2,2)$, $(2,3)$, $(3,2)$ and $(3,3)$ are shown. They were estimated from $H(x,y;z)/T$ (T: the average reaction time). It is found that the two-variable electrocutaneous transmission rates are in the range of 4.5 and 6.4 bits/s, and the maximum information rate per second is obtained for the set of stimulus categories: $(N_m, N_f)=(2,2)$.

Table 4 Two-variable information transmission rates for three subjects (N_f: number of category of frequency aspect, N_m: number of category of magnitude aspect, H(x,y;z): information transmission rate, T: choice time).

N_f	N_m	H(x,y;z)/T bits/s
2	2	6.4
	3	5.1
3	2	5.0
	3	4.5

6. Conclusions

From the data analyzed above, the following conclusions are obtained regarding a two-variable electrocutaneous display.
(1) The channel capacity of the two-variable electrocutaneous communication system is the summation of the channel capacities of both the magnitude aspect of stimulation in a minimum frequency level and the pitch aspect of stimulation in a minimum magnitude level. Its value ranges from 5.6 to 6.0 bits/symbol for four subjects. (2) The maximum information transmission rate estimated from the category discrimination test is 2.7-3.2 bits/symbol for three subjects. It is larger than the individual one-variable information rate, but not more than the sum of the both. Especially, when the pitch and the magnitude aspects of stimulus are presented simultaneously, the information rate associated with the magnitude aspect has a tendency to decrease due to the interaction between the two variables. (3) The reaction times of the two-variable category discrimination tests is 300-970 ms for N_m=2∿3, N_f=2∿4, where N_m and N_f indicate the number of categories of magnitude and pitch aspects, respectively. On the basis of the above results, the practical limit of the presented number of the two-variable categories is a paired N_m=3, N_f=3. For N_m=2∿3, N_f=2∿3 information transmission rate per second is found to be 4.5 bits/symbol to 6.4 bits/symbol.

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