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INFORMATION TRANSMISSION BY TWO-DIMENSIONAL ELECTROCUTANEOUS PHANTOM SENSATION

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1. INTRODUCTION

Attempts to augment or replace human sensory function have led to the investigations of electrocutaneous communication systems and studies of human characteristics to electrocutaneous stimulation [1,2,3,4,5]. As in the case of hearing, loudness, pitch and location of the perceived stimulus can be used as carriers of information. It has been found that electrocutaneous loudness sensation evoked by the pulse train signal corresponds physically to the energy of a pulse of the stimuli [6], and that pitch sensation corresponds to the pulse repetition rate.

With the variation of these parameters alone, however, the information rate lies between 3 and 5 bits per second for each parameter [7,8]. In order to transmit a larger amount of information, it is necessary to include the location or the position of sensation on the skin as another dimension of information. In general it is necessary to place a discrete set of electrodes and an isolator for each position of the skin desired to be stimulated, which leads to the expensive and complex apparatus not suitable for practical use.

A display of particular interest has been suggested which is based on the utilization of the cutaneous phantom sensation [9,10]. Sundstrom [11] and the authors [12] have demonstrated that two equally loud electrocutaneous stimuli simultaneously presented to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two electrodes, just as in the case of binaural sound localization in hearing and the vibration phantom sensation on the skin. This phantom sensation location can be controlled by relative magnitudes of the two stimuli and by the time delay between them [13]. Thus the number of electrodes can be reduced by using this phantom sensation display in comparison to a display requiring a discrete electrode for each position desired.

In the previous reports [13,14], the effects of relative magnitude and time delay on the phantom sensation were experimentally studied, and maximum information transmission rate was calculated from just noticeable difference (jnd) of perceived location and was found to be between 2 to 3 bits. Those studies were, however, restricted to one-dimensional phantom sensation. In order to utilize spatial cues it is necessary to evaluate the two-dimensional electrocutaneous phantom sensation as it has been evaluated by McEntire [15] for the vibrotactile phantom sensation.

In this paper the effect of relative magnitudes on the perceived location of the two-dimensional phantom images and their jnd's are measured, and channel capacity and maximum information transmission rate are experimentally studied.

2. EXPERIMENTAL APPARATUS

Three channels of the previously designed general purpose multi-channel simultaneous stimulator system [16] are used. The stimulator system consists of a digital computer (PDP 11/40), a pulse control unit, and output circuits and is equipped with 256 output channels. Each channel generates an independent pulse signal, parameters of which, namely, height, width, frequency and stimulus duration, can be set arbitrarily by the computer program.

Each output of the stimulator is controlled by the stimulus energy controller (SEC) to ensure the constant current output, keeping the energy of a pulse also constant at the value specified by the program via LPS (laboratory peripheral system) [17]. Since skin impedance changes with time, it is necessary and sufficient to keep the energy of stimulus constant to ensure the subjective loudness sensation constant [6,7].

Each output of SEC is isolated by a photo-coupling type isolator (San-ei Instrument Co. 5361) and is presented to the skin of a subject via a set of electrodes (Fig. 1). The set of electrodes, called a channel, consists of three wet electrodes. Two outer electrodes of each channel are connected and used as a common, and the negative pulse is presented to the center electrode. Sensation therefore occurs at the center electrode when a pulse train is applied to only that channel. Three independent sets of electrodes (ch.0, ch.1 and ch.2) are located in a triangular configuration on the skin just above the biceps brachii. Distance d between the two center electrodes is set to 70 mm. Although previous experiments [14] indicated an optimal d of 100 mm, spatial restrictions forced d to be set to a value near the optimal.

Four subjects of age 22, 25, 27 and 32 were used in the following experiments. Two are researchers of experience, and two others are students with an interest in the experiments.

3. EXPERIMENTAL PURPOSE AND PROCEDURE

Three equally loud electrocutaneous stimuli simultaneously presented to triangularly located electrodes (ch.0, ch.1 and ch.2) on the human skin just above the biceps brachii were not felt separately but rather combine to form a sensation near or at the center of the triangle. The location of this phantom sensation could be controlled by the relative magnitude of the three stimuli.

This study evaluates the information transmission characteristics of the human for the two-dimensional phantom image by measuring the location of the phantom image as a function of energy ratios applied to the three channels and by calculating the channel capacity and maximum information transmission rate associated with the two-dimensional phantom sensation.

To evaluate the localization characteristics of the phantom image, the following experimental method was used: A template shown in Fig. 2 was applied to the skin of a subject together with the electrodes. The overall triangle is subdivied into 169 small triangles with the electrodes enclosed as shown.

Several stimuli, E0, E1 and E2, representing different energy levels (in ergs) are applied to channels 0, 1 and 2, respectively, several times in random order. The subject is asked to identify the location of the stimulus perceived by giving the number associated with the small triangle on the template. The location of the evoked sensation is taken as the mean value of the co-ordinates of the centers of the reported triangles.

The coordinate system is shown in Fig. 3, in which rectangular co-ordinates are represented as (x,y), and oblique co-ordinates are represented as (X,Y). Thus a location (X_o,Y_o) for some energy level of E0, E1 and E2 is evaluated as follows:

$$X_o = \sum_{n=1}^{169} a_n X_n , \quad Y_o = \sum_{n=1}^{169} a_n Y_n \tag{1}$$

where a_n is the frequency ratio of the reported location in the triangle n, and $X_n Y_n$ are the co-ordinates of the center of that triangle.

The discriminability (or the area of the perceived image) is evaluated using the standard deviation of the reported co-ordinates as measured by the rectangular co-ordinates:

$$\bar{\sigma} x_o = \sqrt{\sum_{n=1}^{169} a_n (x_n - x_o)^2} , \quad \bar{\sigma} y_o = \sqrt{\sum_{n=1}^{169} a_n (y_n - y_o)^2} . \tag{2}$$

To maintain these results consistent with the AB method for the one-dimensional case previously reported [14], $2k\,\bar{\sigma}\, x_o$ and $2k\,\bar{\sigma}\, y_o$ are used as a measure of discriminability of the phantom image. A value of 0.8 for k was derived from a least-square comparison of the prior AB data with a one-dimensional version of the matrix electrode arrangement of Fig. 2.

4. LOCATION DISCRIMINATION CHARACTERISTICS AND CHANNEL CAPACITY

4.1. Location of the Two-dimensional Phantom Sensation

First, an increase or decrease of the total energy E0+E1+E2 did not change the perceived position of the phantom image as long as their ratio was constant. Based on this fact we first set the ratio E1/E0 constant, changed E2, and then observed the location of the phantom image as a function of E2.

Six different values of E2 were chosen and six stimuli were presented to the subject 120 times randomly (20 times for each kind of stimuli). The experiments were repeated for several values of E1/E0, while E0+E1 were maintained almost constant of 30 to 50 ergs.

The abscissae of Fig. 4(a) and (b) represent the position of the image obtained as the mean of X and Y co-ordinates for 20 responses. The ordinate represents the energy E2 on a log scale.

From this data the following approximation hold:

$$E2 = 10^{(-\alpha X+\beta)}, \quad E2 = 10^{(-\gamma Y+\delta)} \tag{3}$$

where α, β, γ and δ are constants. From (3)

$$Y = \frac{\alpha}{\gamma} X - \frac{\beta - \delta}{\gamma} \quad . \tag{4}$$

Thus the perceived location of the image moves almost linearly from a location between the ch.0 and ch.1 (determined by the energy ratio E0/E1) toward ch.2 as the energy E2 increases.

Recalling that E0+E1 = constant, from Equation (3) we also get

$$X = k_1 \log \{E2/(E0 + E1)\} + m_1; \; Y = k_2 \log \{E2/(E0 + E1)\} + m_1$$

where

$$k_1 = 1/\alpha; \; k_2 = - 1/\gamma; \; m_1 = \beta/\alpha - k_1 \log (E0 + E1); \; m_2 = \delta/\gamma - k_2 \log(E0 + E1). \tag{5}$$

Thus the position of the perceived phantom image is proportional to log (E2/(E0+E1)) as long as E0 is kept constant. This suggests that the location of the two-dimensional phantom image can be predicted as follows: Stimuli on ch.0 and ch.1 produce one-dimensional imaginary phantom image A with magnitude E0+E1 somewhere between ch.0 and ch.1 determined by E1/E0. The imaginary phantom image A and the stimulus on ch.2 in turn produce the two-dimensional phantom image B somewhere between ch.2 and imaginary image A. The position of image B is determined by log (E2/(E0+E1)).

4.2 Channel Capacity

Figure 5 gives an example of the results of the experiment described in Section 4.1. Crosses indicate the standard deviations $2k\sigma x$ and $2k\sigma y$, and the intersections give the position of the phantom image. The area of image is large around the center of the enclosed triangle and rather small at the periphery.

The channel capacity can be calculated by the following formula:

$$R_{max} = \log_2 \{\int_s \frac{ds}{f(x,y)}\} \qquad \text{[bits]} \tag{6}$$

where s is the triangular area and f(x,y) is the area of discrimination threshold (or area of the image) as a function of the position.

It is assumed that f(x,y) can be represented as

$$f(x,y) = 4k^2 \bar{\sigma}x(x,y) \; \bar{\sigma}y(x,y) \tag{7}$$

where k= 0.8 as was derived in Section 3. It is also assumed that $\bar{\sigma}x(x,y)$ and $\bar{\sigma}y(x,y)$ can be approximated by spherical functions. The dots in Fig. 5 represent the major axes of the spherical approximations.

The channel capacity measured for the three subjects were 4.2, 3.9, and 4.1, averaged as 4.1 bits.

5. MAXIMUM INFORMATION TRANSMISSION RATE

In order to evaluate the maximum information transmission rate, n patterns of phantom sensation perception (n = 3,4, ..., 9) are chosen as shown in Table 1. For each pattern, a forced choice test of location was performed; i.e., one location in a particular pattern was presented to a subject randomly. For each of 20n times, the subject selected the perceived location.

The following formula was used to calculate the information transmission rate associated with each pattern:

$$T(x;y) = H(x) - H(x|y) \qquad (8)$$

where x's are stimuli, y's are responses, H(x) is the information content of input, and H(x|y) is the equivocation of the channel.

Table 1 shows the result of the forced choice tests of three subjects for eight different input patterns. At about 8-9 stimuli locations, the information transmission rate asymptotes. Category 8 pattern with six locations on triangle sides and two locations on the inside is the best arrangement.

Thus the maximum information transmission rate can be estimated as 2.8 bits.

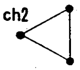
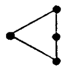
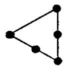
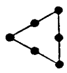
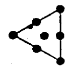
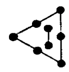
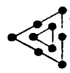
Phantom images	Number of category	Input information (bit)	Information transmission rate (bit/symbol)		
			Subject : K.T.	Subject : K.A.	Subject : Y.T.
	3	1.6	1.6	1.6	1.6
	3	1.6	1.6	1.6	1.6
	4	1.9	1.9	1.9	1.9
	5	2.3	2.3	2.1	2.1
	6	2.6	2.3	2.4	2.3
	7	2.7	2.5	2.6	2.6
	8	3.0	2.7	2.8	2.6
	9	3.1	2.6	2.7	2.8

Table 1. Information Transmission Rate

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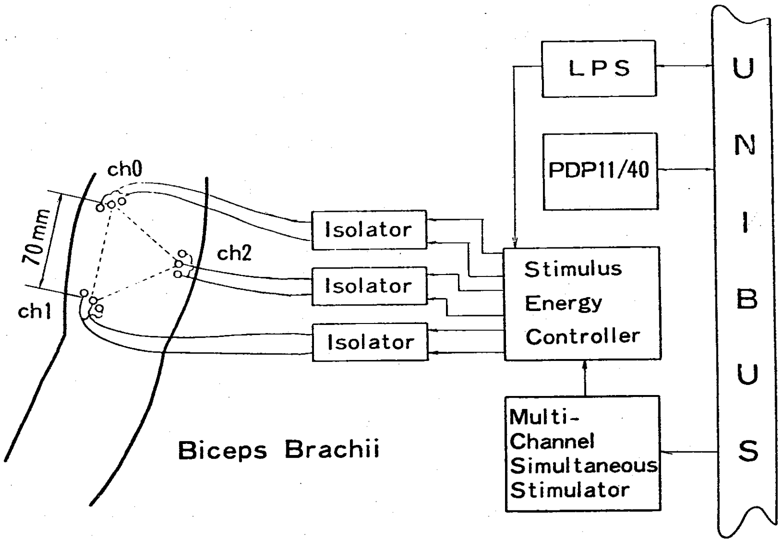

Fig. 1 Experimental Arrangement

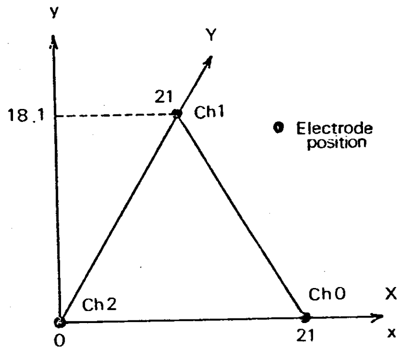

Fig. 2 Template

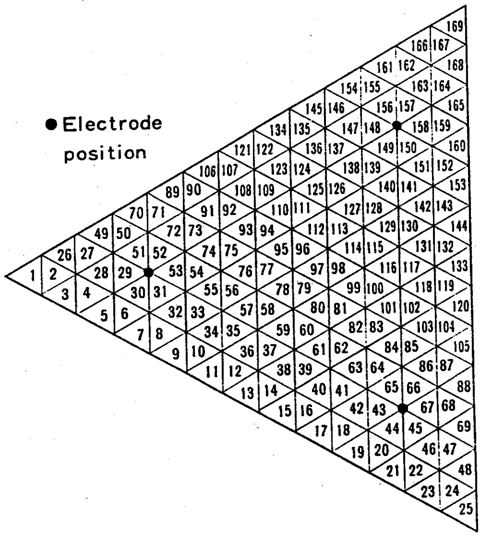

Fig. 3 Co-ordinate System

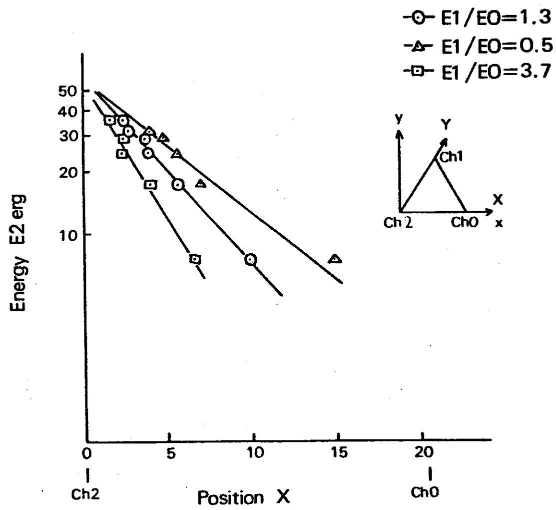

Fig. 4(a) Location of the 2D Phantom Image

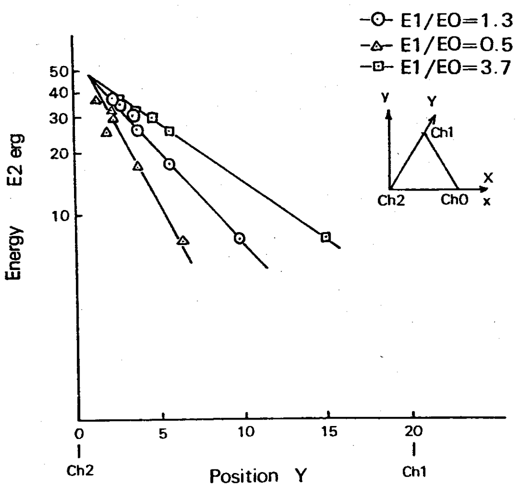

Fig. 4(b)

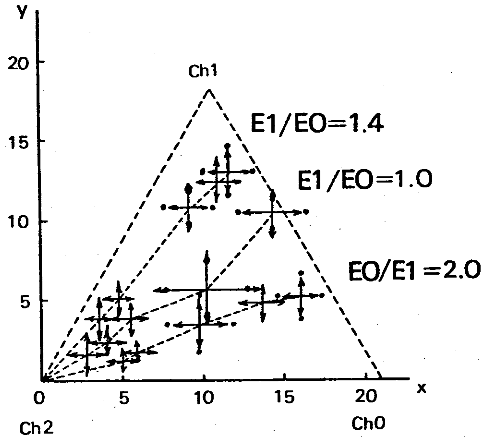

Fig. 5 Standard Deviation of the 2D Phantom Image