HUMAN COGNITIONAL ABILITY FOR ELECTRIC STIMULATION SIGNALS

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Summary

Human cognition of signals due to electric stimulation was quantitatively determined in an attempt to collect fundamental data on transmitting information to the human body.

To begin with, the requirements of electric stimulation were clearly defined and on the basis of such findings signal cognition tests were conducted. With respect to varied information regarding amplitude, frequency, amplitude-frequency, and space, the tests, were concerned with the finding of particular levels at which the signals could be recognized with an accuracy over 80 percent. The transmission capacity was between 4.5 and 4.8 bits/second.

It is found possible to utilize the sensory feedback system for the myoelectric hand prosthesis based on electric stimulation by using PAM for the feedback signals of the information on angles of finger opening and PIM for the feedback signals of pressure sensory information.

Introduction

With the recent progress of bionics, mechanical models simulating human sensory functions are being made, benefiting persons with their sensory functions damaged or lost. One of the problems related to this development, which presently requires further investigation, is the method of feeding back sensory signals to the human body.

As a conventional means of feedback signals to the human body, stimulation by mechanical vibration has been employed. But this is not without troubles involved in the sensory variation of the human body under the adaptation and the influence of environment.

The present paper deals with a study of electric stimulation as a feedback means for returning signals to the human body. In the first stage, optimal stimulative conditions for the human being and the factors affecting sensory stimulation were examined. Secondly, with the human being regarded as a receiving set of a communication system, man's cognitive capability of signals was estimated in terms of the amount of information transmitted. As for the components of stimulation, different types of information on amplitude, frequency, and space were considered.

It was ascertained that electric stimulus was free from adaptation which is a controversial problem regarding mechanical stimulus, and that the amount of information that could be transmitted to the human body was about 2.8 bits/symbol in the form of the amplitude-frequency information. Thus it is now certain that electric stimulation is effective for the pressure sensory feedback system in myoelectric hand prostheses.

Electric Stimulation to Human Body

Determination of appropriate stimulative conditions for transmitting signals to a human being and the factors producing effects on stimulation sensation will de discussed.

Determination of Conditions for Electric Stimulation

Because electric stimulus is given to human beings, the stimulation must not impart discomfort or danger to the human body. It is also desirable that the human being, who is to receive the signals, should perceive them easily, and that the stimulus used should contain a great deal of information.

Experimental Method

The following factors were appraised: stimulation wave-form, stimulation electrode, pulse width, stimulated region, and pressure of electrode on the body. Incidentally, the stimulation conditions were determined on the basis of the results of preliminary tests.

1) Stimulation Wave-form

Stimulation wave-form may be studied from various angles, and if we go into all details, there will arise a lot of ramifications. Discussion here will be concerned only with the generalities of the wave-form, which is basically of the following three kinds: sine wave, rectangular wave, and triangular wave. Stimulating conditions were as follows:

Stimulation electrode:	Semiconductive rubber electrode
Stimulated region:	Brachial biceps
State of arm:	Natural
Subjects:	Two normal, healthy men in their twenties

2) Stimulation Electrode

Normally, the electrode used for this purpose is shaped either like a needle or a plate. The needle-shaped electrode is the most dependable when it is fixed to the human body, but it causes various technical obstacles from the engineering viewpoint, so that the plate-shaped electrode alone was employed in this experiment. The electrode may be made of silver, platinum, or stainless steel. When a metal electrode is used, the internal impedance is nearly zero. For comparison, it is considered necessary to try some other material having internal impedance. So we selected, for the material of the electrode, brass as a metal sample and semiconductive rubber as an example possessing internal impedance. Various sizes were tested. Table 2.1 illustrates the varieties of the test electrodes. The following were stimulating conditions:

Stimulation wave-form.	Rectangular wave
Pulse width:	0.5 ms
Subjects:	Nine males in their twenties

3) Pulse Width

With the rectangular wave used as stimulation wave-form, it is impossible to ignore the effect of pulse width on the sensation subject to electric stimulation. In Experiment (2), the pulse width was set at 0.5 ms on the basis of the results of preliminary tests, but here a more accurate study was made of pulse width. Stimulating conditions were as follows:

Stimulation electrode: B_9

4) Stimulated Region

As for the region to be stimulated, selection was made from among such regions as are out of frequent use in daily life, where stimulation sensibility is not much affected by routine behavior, and where it is relatively easy to install the stimulation electrode, for such regions, involving relatively scanty muscular motion, are likely to give better results. Promising regions were as follows:

Cucullar muscle (at the root of the neck)

Deltoid muscle (at the edge of the shoulder)

Brachial biceps

Brachial triceps

For the above four regions, the stimulating conditions were determined as below:

Stimulation wave-from:	Rectangular wave (pulse width: 0.1 ms)
Stimulation electrode:	B_9

5) Pressure of Electrode to Body

It has been reported that in the case of stimulus caused by mechanical vibration, the contact pressure between the vibrator and the skin largely varies vibratory sensation. If similar fluctuations of stimulated sensation should occur in electric stimulation by reason of the contact pressure between the electrode and the skin, there would be the need of devising a proper method of fixing the electrode. Our experiments were tested roughly on the following three values:

Approximately	500 g/cm^2
"	200 g/cm^2
"	0 g/cm^2

Determination of Wave-form

As for stimulation wave-form, the three types, sine, rectangular, and triangular, were studied. Sine and triangular waves showed the following drawbacks:

i) They are apt to produce more discomfort than rectangular wave.

ii) They yield thresholds so unstable that precise measuring was prevented. In the case of electric stimulation, the effect of the stimulus is found to depend upon the intensity of stimulation, requiring higher levels than the threshold. However, the stimulative effect is determined not only by the absolute intensity of stimulation, but also in a large measure by the rate of variation of the intensity. Accordingly, it is anticipated that even if the stimulative intensity of the sine wave or the triangular wave is over the threshold, it may happen that the rate of variation of the intensity is so small that the threshold tends to loose stability or discomfort will be experienced. The use of a rectangular wave by way of stimulation wave-form will most likely produce much better results, because the rate of variation of intensity can be increased infinitely.

Determination of Electrode

The following facts were derived from testing four different electrodes (Table I) on nine subjects.

1) Frequency Characteristics

In any type of electrode tested, the threshold was within the range of 15—20 V, giving a nearly constant value between 1 and 400 Hz. Noticeable was the phenomenon that the upper limit (which denotes here the highest level in which electric stimulation signals can be transmitted without giving discomfort to the receiver) declined as the frequency rose.

Table 1. Stimulation Electrodes

	Material	Size mm	Resistance kΩ
A_9	brass	9∅	0
B_9	semiconductive rubber	9∅×2	80
A_6	brass	6∅	0
B_6	semiconductive rubber	6∅×2	16

2) Comparison of Electrodes (Fig. 1)

Figure 1 illustrates the mean value of each subject for all frequencies tested. Here is observed the lowest threshold for A_9 centering around 15 V, whereas the other electrodes give from 18

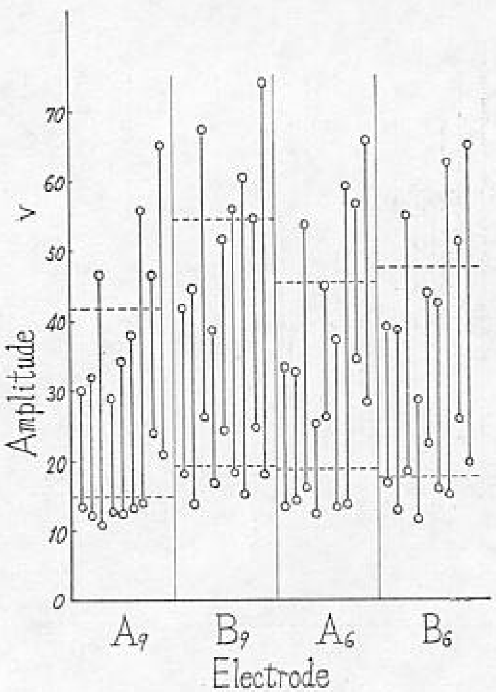

Fig. 1. Stimulation Electrode
(individual range between the threshold and the upper limit)

to 20 V. But a comparison of ranges between the threshold and the upper limit indicates different results: the top-ranking B_9 has a breadth of about 35 V, whereas the others show between 25 and 30 V. With respect to the size of the electrode, either the metal or semiconductive rubber electrode gives every subject smaller variation and higher stabilization in larger sizes. Conversely, the smaller electrodes produce higher variation in each subject. For the same size, the semiconductive rubber electrode has a wider range between the threshold and the upper limit than the metal electrode. In summary, B_9 appears a best choice for transmitting electric stimulation signals to human beings.

Determination of Pulse Width

Average values for each subject in all frequencies are given in Figure 2. The illustration discloses the following:

i) The range between the threshold and the upper limit is maximum (about 40 V) for a pulse width of 0.1 ms, but the range narrows as the pulse width increases. In some subjects, the range between the threshold and the upper limit was as small as 2—5 V for pulse widths of 5 and 10 ms.

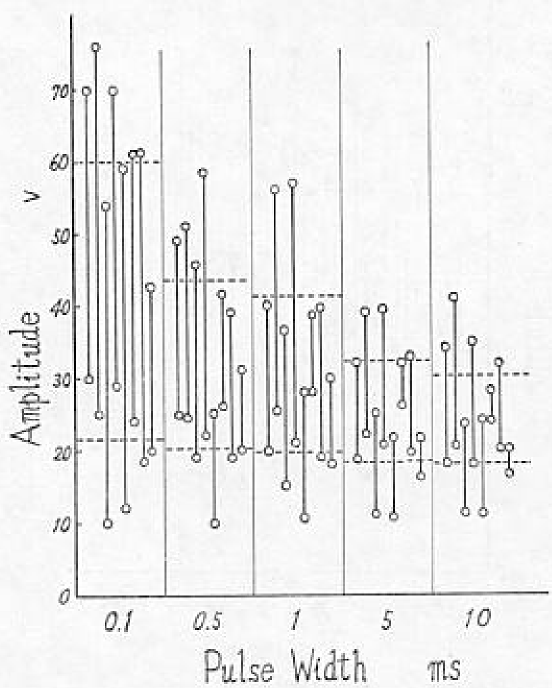

Fig. 2. Pulse Width
(individual range between the threshold and the upper limit)

ii) For pulse widths other than 0.1 ms, the range is not stable as it varies with individual subjects.

iii) Variation of the threshold is not very significant at a pulse width of 10 ms. There is a tendency observed that discomfort occurs more frequently in larger pulse widths despite the smaller amplitude.

Concluding from the above, 0.1 ms is the most appropriate pulse width for electric stimulation. Incidentally, pulse widths smaller than 0.1 ms could not be examined due to the limitations of the equipment, but it is apparent that this should be studied further.

Determination of Stimulated Region

The results are following:

i) A similar tendency is seen in cucullar and deltoid muscles.

In these muscles, the threshold is about 10—15 V higher than that of brachial biceps and triceps.

ii) Individual fluctuations are wild in clavicular and deltoid muscles.

iii) By contrast, the threshold-upper limit range is considerably large for brachial biceps and triceps, with no marked difference seen among individuals.

In consideration of the above results, brachial biceps and triceps appear appropriate as regions to be stimulated.

Determination of Electrode Pressure

The experiments showed that pressure between that electrode and the skin had no effect on sensation produced by electrical stimulation.

i) The threshold does not change with the pressure of the electrode.

ii) The range between the threshold and the upper limit is all but invariable.

iii) Variations of the threshold with the frequency are insignificant.

Accordingly, as far as our studies could go, the contact pressure between the electrode and the skin is not held an important factor at least in connection with electric stimulation.

Varied Effects on Sensation under Electric Stimulation

Effect of Preceding Stimulation

With the stimulation caused by mechanical vibration, sustained application of vibratory stimulus eventually leads to adaptation on the part of the human body, when vibration sensibility is reduced. The following test was conducted to ascertain whether the same phenomenon would occur in electric stimulation.

1) Experiment

After measuring the original threshold, preceding stimulation varying the contents of electric stimulation was applied, and then the resultant threshold was measured. Measurement was made on 27 varieties of preceding stimulation prepared by combining three stages each of stimulation time, frequency and amplitude. The stimulating conditions were as follows:

Preceding stimulation:	Duration — 1, 3 and 10 ms Frequency — 1, 10 and 100 Hz Amplitude — 20, 40 and 60 V
Stimulation electrode:	Semiconductive rubber electrode (B_8)
Stimulated region:	Brachial biceps
Stimulation wave-form :	Rectangular wave (pulse width: 0.1 ms)

2) Results

The rate of variation(in absolute value) of the threshold prior to the preceding stimulation to the threshold thereafter was sought, with the following findings:

i) The rate of variation is larger with the increase in amplitude of the proceding stimulation, but

ii) Such correlation is not observed with respect to the duration and frequency of the preceding stimulation.

Hence the correlation coefficients of the rate of variation with time, frequency and amplitude are found to be

$r_t=0.23$

$r_f=0.04$ and

$r_a=0.41$

It is thus clear that the rate of variation is not correlated either with time or with frequency, but there is observed a slight correlation between amplitude and the rate of variation.

In any case, however, the rate of variation is in the vicinity of 10 percent, so that if measuring error is taken into account, the effect of the preceding stimulation does not appear very remarkable.

Other Effects

Some other factors affecting the sensation exposed to electric stimulation will be considered.

Concerning posture, neither the threshold nor the range between the threshold and the upper limit is affected by any posture assumed. However, when the brachial biceps was chosen as a stimulated region, it was noted that higher sensitivity occurred if the elbow joint was slightly bent. As for sensory changes when strength is put forth in the arm, the threshold remained unchanged but the upper limit tended to rise a little. However, there was no sign of a sharp rise in the range between the threshold and the upper limit.

We also found that the mode of contact between the stimulation electrode and the skin produced not a little influence on sensitivity against electric stimulation. This is because the contact impedance of the electrode comes into play. When electric stimulus is applied with nothing interposed between the electrode and the skin, if perspiration takes place because of a large pulse width or the arrival of a pulse beyond the upper limit, the subsequent threshold drops and the range between the threshold and the upper limit will narrow down abruptly. This effect is conceivably attributed to the decrease of the contact impedance between the electrode and the skin because of sweat produced. When some conductive past was applied between the electrode and the skin as a preventive, the phenomenon disappeared.

Measurement of Human Cognizance of Signals

The objective of this study is to feed back sensory information via the skin to the body of persons deprived of sensory functions, so that it is desirable to obtain a quantitative estimate of man's capability of recognizing signals. It is assumed that human cognizance of signals can be estimated in terms of the quantity of information transmitted according to the communication theory by regarding a human being as a receiving unit of a communication system. As for the components of stimulation, amplitude information, frequency information, and spatial information were taken up for our purpose. And the amounts of various information transmitted to human beings were experimentally measured, and the amount of transmitted information resulting in over 80 percent of correct recognition of each set of information was designated the "information capacity of man", which was used as the norm for estimating man's signal cognizance.

The source of information is a table of signals made up in such a manner that a tally (a stimulus forming a signal) occurs 50 times in one experiment, with the occurrence and sequence of all tallies given an identical probability.

Experimental Conditions

1. Subjects:	Normal males in their twenties
2. Stimulation wave-form:	Pulses with a width of 0.1 ms
3. Working electrode:	Semiconductive rubber electrode B_4
4. Stimulated region:	Brachial biceps
5. Stimulation frequency range:	3—100 Hz
6. Stimulation amplitude range:	20—60 V
7. Number of stimulated regions:	1—4
8. Number of stimuli:	50 per stimulation
9. Learning time:	2—5 minutes

Experiment

Cognizance of Amplitude

In order to examine human ability to recognize amplitude, the following two experiments were carried out.

1) With the stimulation time Td=1,2 sec. assumed as parameter, the stimulation frequency was set at a constant f=10 Hz. The amplitude between the threshold and the upper limit was equally divided into 2. 3, 4, and 5 steps, and the proportion of correct cognition and the amount of transmitted information were plotted as in Figure 3.

Besides, the longer the subject is exposed to stimulation, the more time is allowed for recognition of the stimulation, so that

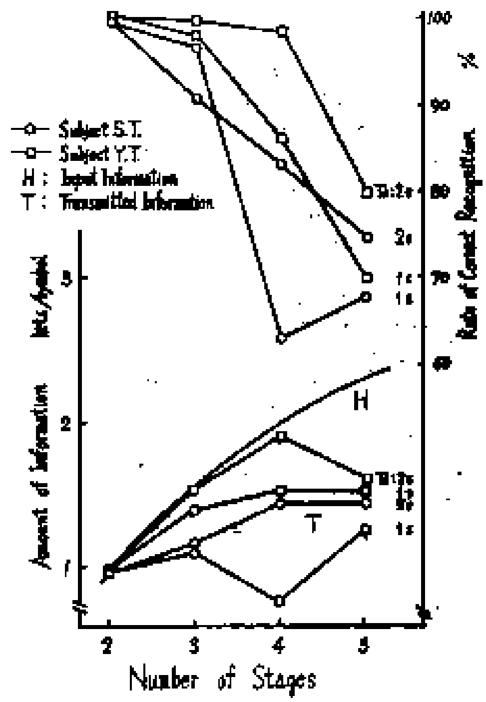

Fig. 3. Amplitude Information (parameter: stimulation time)

the proportion of correct recognition is higher (about 10 percent) when Td=2 seconds, with the number of input stages being 5. However, there is no great difference regarding the amout of information transmitted. As for the amount of information transmitted in a unit time, better results were gained with 1 second than with 2 seconds. Although this experiment was performed without preparatory learning, it seems likely that stimulation time can be shorter if the subject is allowed to engage in sufficient learning, getting himself accustomed to the stimulation. The foregoing suggests that one second would be enough for stimulation time. In Subject Y. T., the transmitted information amount is nearly the same with 1.56 and 1.54 bits/symbol for 4 and 5 input stages, respectively. In other words, the quantitative increase of input information is accompanied with the corresponding decrease of the rate of correct recognition, resulting in no increase of the amount of information transmitted. Seeing that the rate of correct recognition is about 80 percent, the proper number of input stages would be 4 for sending information via amplitude.

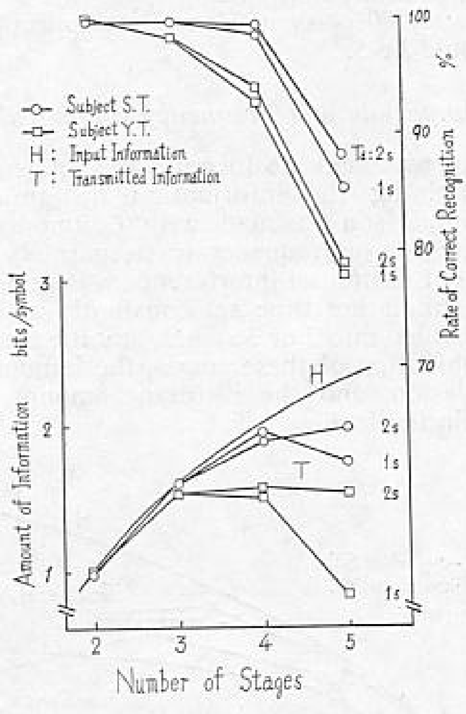

Fig. 4. Frequency Information
(parameter: stimulation time)

2) Asuming the stimulation frequency $f=5.50$ Hz as parameter, with the stimulation time $Td=1$ sec., the rate of correct recognition and the amount of information transmitted have been measured.

The chances are that there is very little variation in the rate of correct recognition with respect to the amount of transmitted information according to the stimulation frequency.

Cognizance of Frequency

For measuring human cognizance of frequency, stimulation time Td=1,2 sec, was taken as parameter, with stimulation amplitude A=30 V. Frequency f=3 to 100 Hz was equally divided, on a logarihmic scale, into 2, 3, 4, and 5 stages, when the rate of correct recognition and the amount of transmitted information were measured as shown in Figure 4. In both subjects S. T. and Y. T,- the rate of correct recognition fluctuates very little with the duration of stimulation, so that one second appears enough for stimulation time as against the recognition of frequency. In the case of Subject Y. T., transmitted information amounts to 1. 94 and 1. 74 bits/symbol for 4 and 5 input stages respectively, showing no big difference. Even with the number of input stages being 5, the rate of correct recognition is aproximately 80 percent. Hence the appropriate number of input stages Would be 5.

Cognizance of Amplitude and Frequency Combined

An attempt was made to increase the total amount of information by combining the information on amplitude and on frequeny, and comparison was made with the amount of information when either amplitude or frequency was separately transmitted. In addition, the extent of mutual interference was examined.

With the stimulation time set constantly at Td= 1 sec., the amplitude was divided into 2 or 3 stages, and the frequency into 2 to 5 stages. In combination of these stages, the human body was subjected to stimulation, and the resultant amount of transmitted information is plotted in Figure 5.

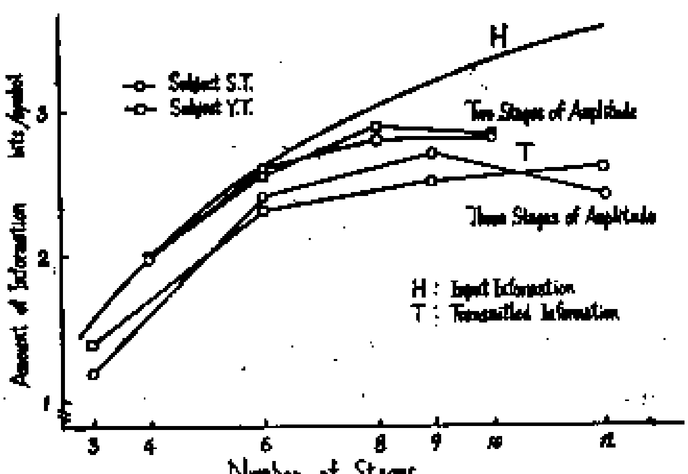

Fig. 5. Amplitude-Frequency Information

The following information was found:

1) When transmission information is quantitatively tantamount to input information, it is better to combine the two types of information than to transmit information by amplitude or frequency separately. The maximum amount of information transmitted by amplitude and frequency combined is about 2.8 bits/symbol for an input information of 3 bits/symbol.

2) When input information is in excess of 3.0 bits/symbol, the increase of input information raises rather than lowers the amount of transmitted information.

3) With the same amount of input information, a larger amount of transmitted information is obtained through two stages than three stages of amplitude.

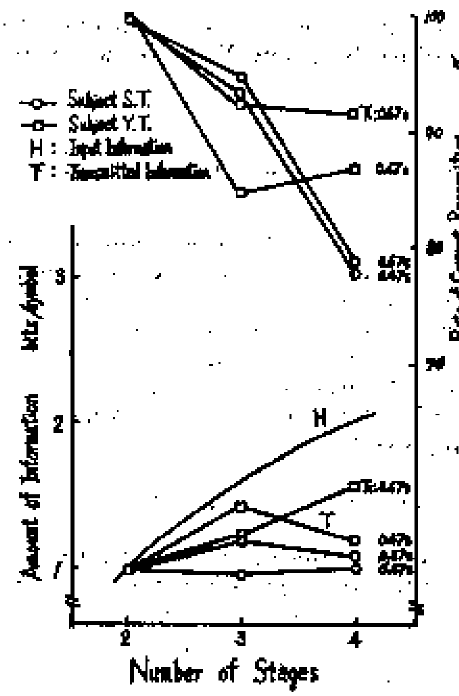

Fig. 6. Spatial Information
(parameter: stimulation interval)

Cognizance of Space

In order to cope with the information having spatial extension and to increase the amount of transmittable information, the capacity of recognizing spatial information was measured.

It has been clear that facile cognizance is provided by arranging the electrodes, one on the upper arm and the other on the lower arm, with the elbow joint serving as a demarcation line. The electrodes were positioned with an intervening distance about 1.5 times two-point discrimination from the upper arm to the upper arm and from the lower arm to the lower arm. With the stimulation interval Ti used as the parameter, and pulses 0.1 ms wide for stimulation, the rate of correct recognition and the amount of transmitted information were sought as in Figure 6.

The findings were:

1) The effect of stimulation interval Ti varied from individual to individual, being insignificant in the case of Subject S. T. with a small difference of 2 to 3 percent in terms of the rate of correct recognition, while in the case of Subject Y. T., the difference was a larger 7 to 8 percent.

2) The maximum amount of transmitted information was 1.2 and 1.6 bits/symbol for S. T. and Y. T., respectively.

Discussion

Comparison between Amplitude Information and Frequency Information

With reference made to Figures 3 and 4, comparison is made between the cognizance of amplitude information and that of frequency information. It is then known that there is no big difference in the maximum amount of transmitted information, but frequency information yields a higher rate of correct recognition for 5 input stages. Consequently, frequency information is more useful for sending information of a wide range if one type of stimulation is to be employed.

Cognizance of Amplitude and Frequency Combined

The amount of information transmitted in case frequency and amplitude are combined is greater when the number of stage for amplitude is smaller, if input information remains the same. Accordingly,if it is desired to transmit a lot of information, it appears advisable to increase the number of stages for frequency rather than amplitude. In this case, moreover, providing the subject is allowed to do sufficient learning, it is possible to transmit information up to about 12 stages of input by combining 3 amplitude stages with 4 frequency stages.

Mutual Interference

We compare the sum of the amounts of information transmitted through amplitude and frequency, assuming that they are independent of each other, with the amplitude-frequency information. The amount of transmitted information is 0.5 — 0.9 bits/symbol lower through the amplitude-frequency information than when either information is used independently. This effect may be attributed not so much to mutual interference as to the prolongation of the experimenting period with the increase of the number of input stages, specifically for the following major reasons:

1) The concordance with the stimulation learned initially becomes blurred.

2) Mental concentration is disturbed.

Therefore, if the subject is made to carry out sufficient learning beforehand so that he is enabled to recognize the stimulus almost through reflex action, it is very likely that the amount of transmitted amplitude-frequency information can be equal to the sum of the amounts of information transmitted through amplitude and frequency assumed to act separately.

Conclusions

Conditions of Electric Stimulation

Admittedly electric stimulation has so far not been used frequently as a way of signal feedback stimulation for the human body because of the relatively narrow range between the threshold and the upper limit in relation to the amplitude. However, if we use the results given above as the stimulation conditions, we can achieve the following results, as evidenced by experiments:

1) The threshold-upper limit range can be extended until it is useful for feeding back such sensory signals as those of pressure sensation on the fingers of an artifical hand.

2) Thanks to less variation in the sensory level with frequency, the frequency information can be incorporated as one of the components of stimulation. Thus it is possible to follow all factors contained in expernal information, such as strength, frequency, and spatial elements.

3) The previous complaints of burns and discomforts involved in the use of electric stimulation can be avoided.

Human Capability to Cognize Signals

When the signal cognizing ability of man was estimated in terms of the amount of information transmitted to the human body, with the amplitude, space, and frequency information adopted as the factors constituting stimulation, the following facts were confirmed.

1) At a certain level of input information, the amount of transmitted information reaches its maximum. If that level is exceeded, the information drops quantitatively.

2) The maximum amount of transmitted information is approximately 1.6, 1.9, and 1.5 bits/symbol for amplitude information, frequency information and spatial information, respectively.

Application to Hand Prosthesis

In this application, the pressure of fingers and the angles of opened hand may be among feasible pieces of information. In this case, if it is arranged that the finger pressure corresponds to frequency and hand opening to amplitude, feedback to one spatial position would be enough. In addition, if it is desired to send more accurate information discriminately, it is possible to secure as wide a range of information as in the human body by utilizing the amplitude-frequency information, namely, dividing a given set of information into several kinds which are made to correspond to varying amplitude, and then subdividing the classified information so as to make the subdivided intensities of information correspond to frequency.

REFERENCES

1. Pfeiffer, E. A., *Digest of the 7th International Conference on Medical and Biological Engineering.*
2. Sueda, T., et al., 7th Convention of Japan ME Society, preprint, 1969.
3. Donaldson, R. W., *IEEE, TIT*, 1967.
4. Ohno, T., *J. Jap. Acoust. Soc.*, 11—3, 1955.
5. Watanabe, R., et al., Data of Elec. Acoust. Res. Foc., Elec. Comm. Soc., 1967.
6. Tanaka, Y., Psychological Measurements, Univ. of Tokyo.
7. Kato, I., Yamakawa, S., Ichikawa, K., and Sano, M., "Multifunctional Myoelectric Hand Prosthesis with Pressure Sensory Feedback System-WASEDA HAND 4p", 3rd ETAN Symposium, Dubrovnik 1969.