On summation: a psychophysical study of the tactual sense

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journal: STL-QPSR
volume: 6
number: 4
year: 1965
pages: 014-025

http://www.speech.kth.se/qpsr
C. ON SUMMATION: A PSYCHOPHYSICAL STUDY OF THE TACTUAL SENSE

0. Franzén

INTRODUCTION

Recoding of speech signals through the tactual sense seems to be one possible solution for real-time communication with the deaf. The signals of importance for perception of speech in the tactile vocoder system are the location and movements of maximum amplitudes roughly corresponding to formant frequencies or other energy maxima. In this system the finger tips are the sensing part of the subject

To find out optimal coding strategies it is necessary to know more about the human observer as a complex information processing system in general and to determine the capacity and limitations of tactile perception in particular.

One of the difficulties in such a system is the considerable amount of masking (or inhibition) that takes place when the fingers are simultaneously stimulated by the vibrators. As a consequence of this kind of neural interaction one receives only a fragmentary pattern of the compound signals. In order to understand the approach to the problem and to get a general frame of reference the concept of another type of neural interaction ought to be introduced, viz. summation.

Sensory information is signalled in two ways: in time and in space. These two general ways are related to two kinds of summation discovered in the nervous system, temporal summation between successive impulses and spatial summation between impulses in adjacent channels defined as a route over which a message is sent from a transducer to the brain. Summation is a well-established fact from experiments in other sense modalities, e.g. binaural summation, temporal auditory summation, and spatial summation within the retina. But summation and inhibition are not mutually exclusive. They can exist at the same time as von Békésy has demonstrated. To describe this phenomenon he has introduced the concept of funneling for the combined effect.
Funneling may occur at one or several levels from the periphery up to the somatosensory cortex, see Fig. II-C-1. Uttal has investigated the inhibitory effects following electrical stimulation of the fingers (7).

However, research into the tactual sense, like studies in other sense modalities, is complicated by the final event in the chain from the receptor to the brain being a psychological experience. This experience can be inferred from the character of the responses.

The main purpose of this paper is to test, on the psychological level, two simple mathematical models intended to give a quantitative description of the summation process. These two models assume different types of neural organization.

**METHODS**

**Experimental conditions**

Three bone conduction telephones (type Oticon 200 k) were used as transducers. Their frequency response curves relating displacement amplitude to applied voltage as determined by means of a capacitive method described by A. Möller (8) were flat in the region of the selected carrier frequency 300 c/s. In addition the linearity of the transducers was tested by means of a Brüel & Kjær accelerometer.

The velocity amplitude and thus also the displacement amplitude were found to be linearly related to input voltage up to 4 V RMS. Accordingly the stimulus variable is specified in voltage relative to 0.05 V RMS being the approximate threshold. Five stimulus levels were used (see Table II-C-1).

<table>
<thead>
<tr>
<th>Table II-C-1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vibrator input voltage re 0.05 V RMS</strong></td>
</tr>
<tr>
<td>linear scale</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>7.1</td>
</tr>
<tr>
<td>12.6</td>
</tr>
<tr>
<td>22.4</td>
</tr>
<tr>
<td>40.0</td>
</tr>
</tbody>
</table>
Fig. II-C-1. Schematic drawing of the somatosensory system indicating the levels at which neural interaction probably may occur.
In order to get a better defined stimulus area a convex button of Plexiglass with an area of about 0.3 cm² was glued on to the vibrator. Verrillo has demonstrated and confirmed that the area of the contactor is a significant parameter of the vibratory signal \(9\).

Two consecutive signals, each lasting 1 sec, were presented with an interval of 1 sec. The time between the pairs was 10 sec. Two dimensions were varied: locus and amplitude. The index, middle, and ring fingers were chosen for stimulation because they are of approximately equal length, so that no neural flux will suffer a delay in relation to the other ones. All combinations of fingers and amplitudes were randomized. The test program was stored on a tape-recorder as a 3 bits 5 position tone code. The tone code was read by an especially built tone code reader that controlled the attenuators and the switch and also gave the on-off times of the two gates, the rise time of which was 10 msec. A block scheme of the arrangements is shown in Fig. II-C-4. The subjects were seated in a soundproofed room. They wore ear cushions so as to prevent auditory interference from the vibrators. The numbers assigned to the variable stimulus were put into a machine. The slip of the paper was hidden behind a screen.

There has been very much debate about the stimulus correlate of intensity of vibratory sensation and also about the process underlying the perception of mechanical vibration. The vibration stimulation has a U-shaped threshold as function of frequency with a minimum in the neighborhood of 250 c/s (see Fig. II-C-2) \(^{10}\). The carrier frequency 300 c/s was chosen on the basis of this information. Sato’s work on Pacinian corpuscles is an interesting contribution to our understanding of neurophysiological and perceptual mechanisms. His measurements show that isolated Pacinian corpuscles also have a minimum at about 250 c/s (see Fig. II-C-3) \(^{11}\). The two threshold curves have striking similarities. But the behavior of the Pacinian corpuscles cannot singly explain the characteristic of the threshold curve. Lindblom \(^{12}\) has found in the distal glabrous skin of the monkey receptors sensitive to vibration exhibiting a sensitivity maximum at 100-200 c/s. These receptors are not identified as Pacinian corpuscles.
Fig. II-C-2. Comparison of threshold data from six investigations. 
(From R.T. Verrillo: "Cutaneous threshold for vibration", J. Acoust. Soc. Am. 34 (1962), Fig. 6, p. 1771.)
Fig. II-C-3. Effect of temperature change on the absolute threshold of an isolated corpuscle for sinusoidal vibration of various frequencies. (From M. Sato: "Response of Pacinian corpuscles to sinusoidal vibration", J. Physiol. 159 (1961), Fig. 7, p. 399.)
Fig. II-C.4. Block diagram of the experimental setup.
Procedure
Introduction

Modern psychophysics offers two classes of methods for the quantification of sensation magnitudes: indirect and direct (13). The indirect technique requires a set of assumptions linking experimental data to the final scale values. With a direct technique, on the other hand, one escapes from these assumptions and the scale construction is, in the simplest case, essentially an averaging of the data delivered by the observer; of course, the direct methods are based on the possibly strong assumption that observers are capable of reporting quantitative perceptual relations adequately.

On the basis of two physiological mechanisms Stevens has made a distinction between two classes of subjective continua called prothetic and metathetic (14). Metathetic continua are qualitative (e.g. pitch) and the prothetic continua refer to quantity or intensity (e.g. loudness). In this investigation the prothetic continuum (15) of perceived vibratory intensity is studied by means of a direct technique, viz. the method of magnitude estimation, based on a predescribed reference standard.

By the above-mentioned method a series of experiments have been performed to determine, (1) the form of the psychophysical function for a vibratory signal applied to the finger tips, and (2) the relationship between the percepts reported when one finger and combinations of two and three fingers are stimulated.

The stimulus intensity 7.1 given to all the three fingers simultaneously was used as the standard. The 450 estimates delivered by each observer were obtained in two sessions, each lasting about one hour.

The following printed instruction was presented to the observer: "This is an experiment to see how you perceive the intensity of vibratory signals applied to the finger tips. Two consecutive stimuli, each lasting 1 sec, will be presented with an interval of 1 sec. The first of each pair is the standard and will be given to all the three fingers (index, middle, and ring fingers) simultaneously. The second in each pair is the variable and will differ from one pair to another in respect to the amplitude and the number of fingers stimulated."
The standard is called 20. Your task will be to estimate the sensation magnitude of the variable. For instance, if the variable seems twice as strong, put 40 into the machine, if it is half as strong, put 10 into the machine etc.

Use whatever numbers seem to you appropriate. Do not worry about what number you have assigned to the previous one. And do not try to identify the stimulus location. Remember that it is the total sensation magnitude you have to estimate."

Observers

Five students of technology, KTH, were employed as observers. They had about four to five months of practice from various discrimination experiments with vibratory signals. The dimension under investigation was well known by the observers and the perceptual learning (16) had attained a high level, as far as discrimination is concerned. They had no previous experience of direct estimation techniques. The results from four of the subjects will be presented in this paper, those from the fifth one will appear in a final report.

RESULTS

The subjective scales of perceived vibratory intensity are shown in Table II-C-2.

The scales obtained by the method of magnitude estimation are usually well described by a generalized form of the power function,

\[ Y = c(\varphi - \alpha)^\beta, \]

where

- \( Y \) is the sensation magnitude
- \( \varphi \) is the physical magnitude
- \( c \) is a constant related to the arbitrary unit of magnitude
- \( \alpha \) is a constant related to the threshold
- \( \beta \) is the exponent.

The power law relating sensation and stimulus intensity, was first put forward by S.S. Stevens.
<table>
<thead>
<tr>
<th>Observers</th>
<th>Vibrator input voltage re 0.05 V RMS, linear scale</th>
<th>Number of fingers stimulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Observer 1</td>
<td>4</td>
<td>7.03</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>12.6</td>
<td>17.13</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
<td>21.67</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>31.4</td>
</tr>
<tr>
<td>Observer 2</td>
<td>4</td>
<td>5.87</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
<td>10.57</td>
</tr>
<tr>
<td></td>
<td>12.6</td>
<td>18.37</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>39.73</td>
</tr>
<tr>
<td>Observer 3</td>
<td>4</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
<td>11.36</td>
</tr>
<tr>
<td></td>
<td>12.6</td>
<td>18.43</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
<td>26.93</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>38.73</td>
</tr>
<tr>
<td>Observer 4</td>
<td>4</td>
<td>5.76</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
<td>10.37</td>
</tr>
<tr>
<td></td>
<td>12.6</td>
<td>18.67</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
<td>28.03</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>40.33</td>
</tr>
</tbody>
</table>
The response distributions showed no systematic tendency of negative or positive skewness; accordingly arithmetic means were computed for each stimulus condition, i.e. vibration amplitude and combination of digits. As the means for the individual fingers for an observer were all nearly identical, the responses to each stimulus level were collapsed into one cell. The same thing was true for the combinations of two fingers. With this point of departure we were able to construct the individual scales which are plotted in log-log coordinates. The linear trend of the points indicates a power function, the logarithmic form of which is

$$\log Y = \log c + \beta \log(q - \alpha).$$

The simplest form of the power function, in which $\alpha=0$, does not apply to the present data, whereas the generalized form yields a satisfactory fit. The constant $\alpha$ determined by a graphic technique (17)(18) turned out to be 2.5 for each of the four observers. This constant is in some way related to the threshold as extrapolated from a supraliminal state of adaptation of the organism. The parameters of the functions are obtained by the method of least squares applied to the log-log plots. The functions are presented in Figs. II-C-5 to II-C-8.

The equations fitted to the individual data in Figs. II-C-9 to II-C-12 are shown below, where $Y_I$ = monodigital function, $Y_{II}$ = bidigital function, and $Y_{III}$ = tridigital function.
Fig. II-G.5. Sensation magnitude as a function of vibrator input voltage relative to 0.05 V RMS in log-log coordinates.

- Circles: 1 finger stimulated.
- Crosses: 2 fingers stimulated.
- Triangles: 3 fingers stimulated.

Each point is the mean of 30 observations.
Fig. II-C-7. Sensation magnitude as a function of vibrator input voltage relative to 0.05 V RMS in log-log coordinates. Circles: 1 finger stimulated. Crosses: 2 fingers stimulated. Triangles: 3 fingers stimulated. Each point is the mean of 30 observations.

Observer 3

Observer 4

Vibrator input voltage re 0.05 V RMS
Magnitude estimation

Vibrator input voltage re 0.05V RMS

Observer 1

Observer 2
Observer 1:
\[ y_1 = 6.04(\varphi - 2.5)^{0.45} \]
\[ y_{II} = 8.49(\varphi - 2.5)^{0.45} \]
\[ y_{III} = 10.7(\varphi - 2.5)^{0.43} \]

Observer 2:
\[ y_1 = 4.44(\varphi - 2.5)^{0.61} \]
\[ y_{II} = 6.93(\varphi - 2.5)^{0.58} \]
\[ y_{III} = 8.87(\varphi - 2.5)^{0.56} \]

Observer 3:
\[ y_1 = 4.65(\varphi - 2.5)^{0.59} \]
\[ y_{II} = 5.71(\varphi - 2.5)^{0.63} \]
\[ y_{III} = 7.91(\varphi - 2.5)^{0.58} \]

Observer 4:
\[ y_1 = 4.35(\varphi - 2.5)^{0.62} \]
\[ y_{II} = 6.16(\varphi - 2.5)^{0.60} \]
\[ y_{III} = 8.51(\varphi - 2.5)^{0.54} \]

The intraindividual variations with regard to the exponents are inconsiderable. The interindividual values of the exponents show a good agreement as far as observer 2, observer 3, and observer 4 are concerned. The constant \( \alpha \) is the same over subjects. The parameter \( c \) of eq. (1) will be discussed below.

THEORETICAL MODELS

The data obtained in this study are compared with two simple mathematical models, which are based on different assumptions about the neural organization of the nervous system. A prerequisite for the models is that the power law \( y = c(\varphi - \alpha)^{B} \) holds for individual subjects (or groups of subjects). The models are descriptive and predictive in character. They contain no free parameters. The set of parameters is invariant over conditions and subjects.
Model 1

The independent components model is founded on the assumption that the amounts of energy of the channels (digits) are linearly summated. This implies that no interaction of the afferent flow occurs as the nerve impulses ascend from the physiological transducers up to the brain.

Let $Y_T$ denote total sensation magnitude and $Y_1, Y_2, \ldots, Y_i, \ldots, Y_n$ the sensation magnitudes of the individual channels.

A linear summation gives the polynomial

$$Y_T = Y_1 + Y_2 + \ldots + Y_i + \ldots + Y_n.$$  

If $Y_1 = Y_2 = \ldots = Y_n$,

then $Y_T = nY_i$.  \hspace{1cm} (2)

Given the sensation magnitude of the separate channels, the total sensation magnitude could be derived by simply summing the psychological magnitudes of the individual channels.

Compared with the experimental data Model 1 gives a systematic overestimation of the summation process and therefore it is rejected as a description of the perceptual mechanism under investigation.

Model 2

The dependent components model is based on the general assumption that interaction occurs at one or several locations of those previously mentioned in Fig. II-C-1. A simple alternative to the principle of linear summation implied in Model 1 would be the principle of vector summation,

$$Y_T = (Y_1^2 + Y_2^2 + \ldots + Y_i^2 + \ldots + Y_n^2)^{1/2}.$$  

If $Y_1 = Y_2 = \ldots = Y_i = \ldots = Y_n$,

then $Y_T = \sqrt{n}Y_i$. \hspace{1cm} (3)

From eq. (3) we are in position to predict the perceptual outcome for the simultaneous stimulation of several digits provided that the sensation magnitude for the individual fingers is determined.
Theoretical estimates derived from Model 2 (eq. (3)) are plotted against empirical estimates of psychological magnitude for combinations of 2 and 3 fingers (see Figs. II-C-13 to II-C-16). The model is in close agreement with the data.

Studying the constants \( c_I \), \( c_{II} \), and \( c_{III} \) related to the monodigital, bidigital, and tridigital functions respectively, the following ratios are obtained for the observers (see Table II-C-3).

<table>
<thead>
<tr>
<th>Observers</th>
<th>( c_{II}/c_I )</th>
<th>( c_{III}/c_I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer 1</td>
<td>( \frac{8.42}{6.04}=1.406 )</td>
<td>( \frac{10.7}{6.04}=1.772 )</td>
</tr>
<tr>
<td>Observer 2</td>
<td>( \frac{6.93}{4.44}=1.561 )</td>
<td>( \frac{8.87}{4.44}=1.998 )</td>
</tr>
<tr>
<td>Observer 3</td>
<td>( \frac{5.71}{4.65}=1.228 )</td>
<td>( \frac{7.91}{4.65}=1.701 )</td>
</tr>
<tr>
<td>Observer 4</td>
<td>( \frac{6.16}{4.35}=1.416 )</td>
<td>( \frac{8.51}{4.35}=1.956 )</td>
</tr>
<tr>
<td>Group</td>
<td>( \frac{6.82}{4.87}=1.400 )</td>
<td>( \frac{9.0}{4.87}=1.848 )</td>
</tr>
</tbody>
</table>

Small deviations from the expected ratios are observed.

DISCUSSION

Interesting features of the results are, among others, (1) that the power law seems to hold for individual subjects, (2) that the interindividual differences are moderate with the exception of observer 1, and (3) that there is a systematic difference between the functions obtained when 1, 2, or 3 fingers are stimulated.

Intraindividual differences

Variations of the exponents within a subject may depend upon that the lowest values get too great a weight in a least square solution of the log-log plots. Also, near threshold the observer runs into difficulties in estimating with certainty the magnitude of the signals.
Fig. II.C.13. (Text, see below)

Fig. II.C.14. Empirical estimates of sensation magnitude for combinations of 2 and 3 fingers plotted against theoretical estimates derived from Model 2. The diagonal line implies perfect agreement.
Empirical estimates of sensation magnitude for combinations of 2 and 3 fingers plotted against theoretical estimates derived from Model 2. The diagonal line implies perfect agreement.

Fig. II.C.15. Empirical estimates of sensation magnitude for combinations of 2 and 3 fingers plotted against theoretical estimates derived from Model 2. The diagonal line implies perfect agreement.
Interindividual differences

The interindividual differences of the exponents may have several sources of variation. Two of them are conventionally put forward. (1) The assignment of the numbers reflects the decoding mechanism of the sense modality under observation, in this case, the sense of touch. But little is known about how information is coded in nerve pulses and assimilated into tactual percepts by the brain. (2) The subjects differ in their manner to handle the numbers. It is in no way a matter of course that the numbers assigned to the percepts possess all the properties numbers have in elementary algebra (19).

At the present stage of knowledge these two questions still wait for a definite answer.

Measurement at a ratio scale level

This study contains certain indications of the observer's ability to report quantitative perceptual relations at a ratio scale level. The relationship between the percepts reported when combinations of 1, 2, and 3 fingers were subjected to vibratory stimulation, was as follows

$$\frac{\psi_{II}}{\psi_I} = \sqrt{2}, \quad \frac{\psi_{III}}{\psi_I} = \sqrt{3}, \text{ and } \frac{\psi_{III}}{\psi_{II}} = \sqrt{\frac{3}{2}}.$$  

These parameter relations were invariant over conditions and observers.

Distance function

Since no systematic differences between the sensation magnitudes were observed when all combinations of two fingers (index and middle fingers, index and ring fingers, middle and ring fingers) were simultaneously stimulated, it was not possible to construct any distance function for the digits under investigation.
CONCLUSIONS

The results of the present study indicate a convincing evidence that the power law is able to describe the individual observers' input-output characteristics.

By the good agreement between the empirical data and the theoretical estimates derived from Model 2 it may be concluded that the dependent components model offers an adequate description of the summation process.

The deviation from a linear summation implies that interaction between the channels takes place.

Finally, we are looking for a neurophysiological explanation of how and where the nerve impulses interact in the afferent flow. These questions will be tentatively answered by the neurophysiological studies that are in progress (see Franzén and Wennberg, part II.B in this issue, pp. 11-13).

References


cont.


(19) Åkesson, C., Psychological Laboratories, University of Stockholm. Personal communication.