A Bidirectional Vibrotactile Communication System: Tactual Display Design and Attainable Data Rates

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Abstract
A series of experiments with a bidirectional vibrotactile communication system examined the effectiveness with which a person can receive and react to vibratory stimuli applied to the skin. In order to design an effectual tactual display, vibratory patterns that varied in duration and shape were presented on the Optacon's 6x24 vibrotactile array. In determining the maximal set of unambiguously discriminable tactual patterns, the results of the first experiment indicate that higher resolution, a larger element size and larger inter-element spacing are desirable, yet potentially conflicting, characteristics for a tactual display. In the second experiment, a maximum data rate of approximately 10 bits per second was attained through the tactual channel of the fingertip using vibratory stimulation. The results indicate that low resolution tactual displays are just as effective in transmitting information as tactual displays with a larger number of elements.

Introduction
Experimental research has been limited in the field of tactual perception, save for the design of several application-specific tactual communication aids. Rather than attack one specific problem, such as tactually communicating with the blind or presenting visual information to the pilot of a vehicle, this research is aimed to build a practical general-purpose tactual communication system in which the stimuli are unambiguously discriminable. The goal is to design the most effective tactual interfaces to produce maximum performance. This system can then be tailored by other researchers for their particular objectives.

The success of several previous tactual communication systems suggests that moderate amounts of information may be transmitted via the skin. The results from a number of experiments [1, 2, 3] indicate that the tactual channel of the human fingertip can process vibratory signals at a rate up to approximately 10 bits per second. Clearly, the tactual channel cannot convey information nearly as quickly as either the visual or aural channels. Unfortunately, many previous attempts at tactual communication aids met with limited success because too much information — normally processed by the visual or aural channels — was directly presented to the skin, inundating the tactual channel. A series of experiments was conducted to determine the effectiveness with which a person can receive and react to vibratory stimuli applied to the distal phalanx of the index finger. In order to maximize the rate at which data is transferred in the communication system, a coding scheme that utilizes the capabilities and realizes the limitations of the tactual channel in the human fingertip has been developed.

Experiment 1: Tactual Display Design
In the first experiment, the maximal set of unambiguously discriminable spatial patterns was determined as a function of array configuration and duration of presentation. The size of the maximal set of discriminable spatial patterns, or "alphabet," provides one measure of the efficacy of the design of a tactual display. The three components of the array configuration examined were the array resolution, the element size, and the inter-element spacing. Three examples illustrate how these components are interrelated (figure 1).

Array resolution
Three array resolutions — 2x2, 3x3, and 5x5 — were used in this experiment. Fifteen non-blank spatial patterns are realizable with a 2x2 array configuration, 511 patterns with a 3x3 array configuration, and over 32 million patterns with a 5x5 array configuration. But does the number of spatial patterns that are discriminable increase as the array resolution increases? Or does the resolution capabilities of the fingertip limit the number of spatial patterns that can be recognized?

Element size
As an element increases in size, a larger area of the fingertip is stimulated when the element is activated, which may enhance the subjects' ability to recognize that the element is activated and to identify the spatial pattern. The size of an element may be varied by clustering a number of neighboring stimulators. For example, six stimulators in a two-column-by-three-row group may constitute a single element in the array (cf. first two examples in figure 1). 1x2, 2x3, and 2x5-sized elements were used in this experiment.

Inter-element spacing
As the spacing between elements increases, the spatial pattern will spread over a larger area of the fingertip. The individual elements may be perceived as more distinct, which may enhance the subjects' ability to identify the spatial pattern. In this experiment, the elements that comprise the array were horizontally separated by zero, one, or two inactive rows. The array elements were vertically separated by zero, two, three, or five inactive rows.

Method
Subjects
An initial tactual screening test was performed with eight sighted subjects, all associated with Stanford University. The four subjects with the top scores, one man and three women, were selected to participate in this experiment, and were paid an hourly wage. The subjects had no prior Optacon experience, and received no additional training.

Apparatus
A system comprised primarily of an IBM PC-XT microcomputer and an Optacon has been used in these vibrotactile experiments. The Optacon (Optical-to-Tactile CONVERTER) is a portable, electronic reading aid for the blind [4]. The Optacon's vibrotactile display unit is about the size of a pack of cigarettes, and encases 144 individually-controlled tactile stimulators, arranged in a rectangular array of 6 columns by 24 rows. The rows are on 50-mil (1.27-millimeter) centers, and the columns are on 100-mil (2.54-millimeter) centers. Each stimulator, built using 10-mil (0.25-millimeter) diameter wire, vibrates at 230 Hertz when activated.

The Optacon's vibrotactile display unit was linked to the IBM PC-XT by special driver hardware designed and built in this laboratory. The IBM PC-XT was used to control the information presented on the Optacon's vibrotactile display unit and record the responses made by the subjects.

Procedure
Subjects placed the distal phalanx of the right index finger on the Optacon's vibrotactile array, which measures one-half inch (12.7 millimeters) wide and slightly more than one inch (29.2 millimeters) long. A spatial pattern was selected at
random and presented on the vibrotactile array for a given duration of time. The static mode of pattern generation, in which all the stimulators that comprise a spatial pattern are activated and de-activated together, was used in this research [5]. The possible stimuli were displayed sequentially on the monitor of the IBM PC-XT. The subjects indicated which spatial pattern was perceived by typing a number on the IBM PC-XT keyboard. No time limit was imposed on the subjects to respond. If a correct response was given, the word “correct” was displayed on the monitor. If an incorrect response was given, the spatial pattern that was presented on the vibrotactile array was highlighted on the monitor. One second elapsed before the next spatial pattern was presented on the vibrotactile array.

During the course of these experiments, earphones through which white noise was presented were placed in the subjects’ ears. Additionally, sound-attenuating headphones were worn by the subjects to muffle the sounds emanating from the Optacon’s vibrotactile display unit.

In each block of trials, each spatial pattern was presented ten times. The duration of presentation — either 8, 25, 50, 100, or 200 milliseconds — was held constant in each block of trials.

Stimuli All fifteen non-blank spatial patterns realizable using a 2x2 tactile display were used in this experiment. The inter-element spacing was varied to yield the three 2x2 array configurations that were tested:
- Pattern set 1 — a 2x2 element size, no horizontal or vertical inter-element spacing.
- Pattern set 2 — a 2x3 element size, a horizontal inter-element spacing of one column, and a vertical inter-element spacing of three rows.
- Pattern set 3 — a 2x3 element size, a horizontal inter-element spacing of two columns, and a vertical inter-element spacing of five rows.

Based on preliminary tests, 41 of the 511 spatial patterns realizable using a 3x3 tactile display were selected as stimuli. The element size and the inter-element spacing were varied to yield the three 3x3 array configurations that were tested:
- Pattern set 1 — a 2x3 element size, no horizontal or vertical inter-element spacing.
- Pattern set 2 — a 2x3 element size, no horizontal inter-element spacing, and a vertical inter-element spacing of three rows.
- Pattern set 3 — a 2x3 element size, no horizontal or vertical inter-element spacing.

The same 41 spatial patterns used in the 3x3 experiment were selected as stimuli in the 5x5 experiment. The inter-element spacing was varied to yield the two 5x5 array configurations that were tested:
- Pattern set 1 — a 1x2 element size, no horizontal or vertical inter-element spacing.
- Pattern set 2 — a 1x2 element size, no horizontal inter-element spacing, and a vertical inter-element spacing of two rows.

Results and Discussion

The following criteria of discriminability were used:
- The confusion between a spatial pattern and other acceptable spatial patterns should be 5% or less.
- The average confusion between all acceptable spatial patterns should be 2% or less.

The number of discriminable patterns at each duration of presentation is tabulated for the 2x2, 3x3, and 5x5 array configurations [table 1]. Eleven, 24, and 31 spatial patterns were unambiguously identifiable using the optimal 2x2, 3x3, and 5x5 array configurations, respectively.

Array resolution With all other variables equal, intuitively, the number of discriminable spatial patterns should increase as the number of elements that constitute the tactile display increases, as long as the resolution capability of the fingertip is not exceeded. Two pattern sets that illustrate the effect of varying only the array resolution are pattern set 1 (2x2 array) and pattern set 1 (3x3 array). At all durations of presentation, more spatial patterns were discriminable using the 3x3 array resolution versus the 2x2 array resolution.

Element size Two pattern sets that illustrate the effect of varying only the element size are pattern sets 1 and 3 (3x3 array resolution). At all durations of presentation, more spatial patterns were discriminable when the patterns were constructed from 3x3-sized elements rather than from 2x2-sized elements.

Inter-element spacing With all other variables equal, intuitively, the number of discriminable spatial patterns should increase as the spacing between elements of the tactile display increases, at least until the size of the tactile display begins to exceed the area of sensitive skin that is to be stimulated. Three examples illustrate the effect of varying the inter-element spacing: Pattern sets 1, 2, and 3 (2x3 array resolution); pattern sets 1 and 2 (3x3 array resolution); and pattern sets 1 and 2 (5x5 array resolution). At nearly every duration of presentation, more spatial patterns were discriminable when the patterns were constructed from the more widely spaced elements rather than from the more closely spaced elements.

Duration of presentation Previous experiments conducted by Craig [5, 6] have repeatedly shown that only brief presentations are necessary to identify spatial patterns presented on the Optacon’s vibrotactile display unit at above-chance performance levels. Asymptotic performance levels were exhibited when the duration of presentation exceeded 100 milliseconds. Also, performance deteriorated as the duration of presentation fell below 25 milliseconds. The results presented here support these findings.

Experiment 2: Attainable Data Rates

In the second experiment, the maximum information data rate that may be transmitted through the tactile channel of the human fingertip using vibratory stimulation was determined. The data rate is defined as the amount of information conveyed per unit time, and provides a measure of the efficiency of a communication system.

A number of previous experiments [7, 8, 9, 10, 11, 12] have shown that identifying the components of a stream of temporally presented spatial patterns is a more difficult task than identifying solitary spatial patterns. Craig [9, 10] concluded that the stimulus onset asynchrony (SOA), or the time between the onsets of two spatial patterns, played the critical role in the recognition of temporally presented spatial patterns. Thus, in this experiment, the duration of presentation was fixed at one value for each of the array configurations (2x2, 3x3, and 5x5), and the inter-stimulus interval (ISI) was varied to change the rate at which spatial patterns were presented on the Optacon’s vibrotactile array.

Method

Subjects The same four subjects that performed the first experiment were used in this experiment.

Procedure The procedure was similar to that described for the first experiment, except that the subjects were asked to identify the penultimate spatial pattern in a stream of three, four or five patterns selected at random and temporally presented on the vibrotactile array. In this way, the subjects were required to observe each of the spatial patterns presented, since the length of each stream of spatial patterns was selected at random. The first pattern served as a "get-ready" signal. A block of trials was

<table>
<thead>
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<th>number of discriminable spatial patterns</th>
<th>duration of presentation (milliseconds)</th>
<th>2x2 array</th>
<th>3x3 array</th>
<th>5x5 array</th>
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<td></td>
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<td>set 2</td>
<td>set 3</td>
<td>set 1</td>
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<td>6</td>
<td>9</td>
<td>11</td>
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Table 1: The number of discriminable spatial patterns at each duration of presentation for each array configuration.
conducted with the SOA initially set to 1500 milliseconds for the 2x2, 3x3, and 5x5 array experiments. The SOA of each succeeding block of trials was decreased by 50–100 milliseconds (by decreasing the ISI) until the performance level fell below 50%.

The procedure was slightly modified for the case of a single element tactual display, because only two spatial patterns were possible. The subjects were asked to identify the intermediate three stimuli in a stream of five spatial patterns temporally presented on the tactual array. The first and last stimuli were always non-blank to demarcate the stream, while the middle three stimuli were selected at random. A block of trials was conducted with the SOA initially set to 500 milliseconds. The SOA of each succeeding block of trials was decreased by 50 milliseconds (by decreasing the ISI) until the performance level fell below 50%.

Stimuli: The tactual stimuli consisted of the discriminable spatial patterns from the optimal array configurations determined in the first experiment. For the 2x2 array, the eleven discriminable spatial patterns in pattern set 3 were the stimuli. For the 3x3 array, the 24 discriminable spatial patterns in pattern set 3 were the stimuli. For the 5x5 array, the 31 discriminable spatial patterns in pattern set 2 were the stimuli.

Results and Discussion

The results of this experiment indicate the rate at which temporally presented spatial patterns may be correctly identified. The data rate transmitted through the tactual channel of the fingertip may be calculated by ascertaining the number of bits of information each spatial pattern contains. Since only two spatial patterns -- on and off -- are possible, the single element tactual display results represent an upper limit to the rate at which information may be transmitted through the tactual channel.

For all four subjects, the data rate was highest for the single element tactual display, which indicates that the task of detecting the presence or absence of a vibratory stimulus is easier than the task of identifying one of many possible spatial patterns. Thus, the single element tactual display results represent an upper limit to the amount of information that may be transmitted through the fingertip using vibratory stimulation.

No superiority was established for any of the higher resolution displays based upon the rate of data reception. Although a larger number of spatial patterns are discriminable using tactual arrays with higher resolutions, a longer time is necessary to identify the components of a stream of temporally presented patterns.

General Discussion

The results of this present study indicate that a low resolution tactual display may be used as effectively as a higher resolution display. Indeed, the results with a single element tactual display seem to present an upper limit to the rate at which information may be temporally perceived using vibratory stimulation.

The deciding factor in which display resolution to use is the number of discriminable patterns that are desired for coding purposes. With a single element tactual display, information is transmitted in a binary code, with the user obliged to decode the incoming stream of stimuli. With a higher resolution array, more spatial patterns are available for encoding information.

In the design of a tactual display, the elements in the array should be spaced far apart from one another, with each element as large as possible. Of course, the size of the tactual display must not exceed the boundaries of the sensitive fleshy portion of the fingertip. Increasing the array resolution beyond 5x5 may not prove beneficial, since the individual elements would be so closely spaced as to exceed the resolution capabilities of the fingertip.