Information Transmission with a Multi-Finger Tactual Display

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Introduction

This work was motivated by our interest in using the sense of touch as an alternative communication channel. The potential to receive information tactually is well illustrated by the Tadoma method employed by some individuals who are both deaf and blind. In this method, the user places a hand on the face and neck of a talker and monitors the mechanical actions associated with speech production. Previous research has documented that these people can understand everyday speech at very high levels, allowing rich two-way conversation with both familiar and novel talkers (Reed et al., 1985). Conversely, attempts to develop artificial tactual speech communication devices have had only limited success. The majority of currently available tactile aids are composed of an array of "homogeneous" vibrators that lack distinctive perceptual qualities. In contrast, a talking face for Tadoma is perceptually rich, simultaneously displaying various stimulation qualities that engage both the kinesthetic and tactile sensory systems. A few displays have been developed that can deliver kinesthetic and tactile stimulation (the air-driven finger stimulator by Bliss, 1961; the OMAR system by Eberhardt et al., 1994). To date, however, none of these artificial displays has been shown to enable tactual information reception by human observers at a rate comparable to that estimated to occur in Tadoma speech reception (e.g., Reed et al., 1989).

Previous research efforts in this laboratory has led to an artificial mechanical face display, built around a model plastic skull (Reed et al., 1985), that has shown promise in conveying information important in Tadoma (Leotta et al., 1988; Rabinowitz et al., 1990). The current study was aimed at a more general purpose tactual display that matches the perceptual capabilities of human hands. Specifically, a new multi-finger tactual display was developed to deliver multi-component stimuli that evoke sensations along the entire tactual continuum from kinesthetic to tactile senses. The information transmission capabilities of this display were assessed using a series of absolute identification experiments with human observers. This paper summarizes major results of this work. Interested readers may refer to Tan (1996) for more details.

The Tactuator

Our display, the TACTUATOR, aims at a continuous frequency response so that the perception from low-frequency, large-amplitude motions to high-frequency, small-amplitude vibrations can be studied as a continuum. The overall system consists of three independent motor assemblies that apply independent one-degree-of-freedom stimulation to the fingerpads of the thumb, index, and middle fingers while maintaining a natural hand configuration (see Fig. 1). Each channel has an excitable bandwidth of DC to 300 Hz with amplitudes from absolute threshold (the smallest displacement that can be detected) to about 50 dB above threshold, i.e., 50 dB SL (sensation

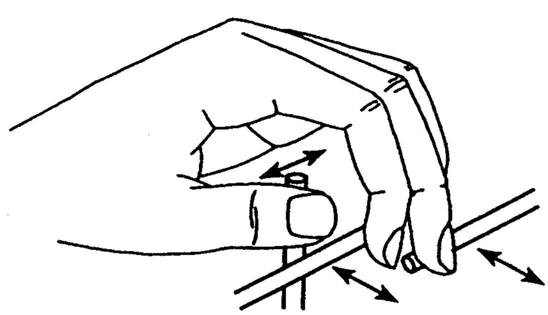

Fig. 1. Schematic drawing illustrating finger placement on the TACTUATOR.

level). At very low frequencies (< 3 Hz), each finger can be moved up to 26 mm (peak-to-peak). At high frequencies (up to 300 Hz), movements as small as 0.3 mm can be delivered. The TACTUATOR can accurately follow arbitrary waveforms with low background noise, harmonic distortion, and inter-channel crosstalk. A detailed description of the TACTUATOR and its performance can be found in Tan and Rabinowitz (1996).

General methods

Subjects

Three subjects (S1, female, age 30; S2, male, age 42; S3, male, age 20) were trained and tested. All subjects are right-handed with no known impairments of their hands.

Stimulus and response sets

The design of stimulus sets followed two principles for maximizing information transmission with human observers: multidimensionality and "frequency segmentation". It has been well established that our ability to process unidimensional stimulus sets is limited to about 2 to 3 bits, and that this limit can be overcome by employing multidimensional stimulus sets (Miller, 1956). To this end, sinusoidal waveforms that varied in amplitude, frequency, and site of stimulation were used to define the intended movement patterns for each of the three digits. It was also found that subjects could naturally categorize motions over the entire frequency range of DC to 300 Hz into three perceptually distinctive groups: slow motion (up to about 6 Hz), a rough or fluttering sensation (about 10-70 Hz), and smooth vibration (above about 150 Hz). Therefore, multi-frequency waveforms were formed by combining sinusoids from the three frequency regions. We call this "frequency segmentation". This strategy for producing a large set of clearly distinguishable stimuli treated different regions of the same physical variable, namely frequency, as separate stimulus attributes. It is different from the construction of a more traditional multidimensional stimulus set where multiple stimulus attributes are varied simultaneously.

Three stimulus sets were constructed. A 500-msec set consisted of the 120 signals resulting from 30 waveforms that could each be presented at any one of 4 stimulation sites. Among the 30 waveforms, 8 were of single frequency and gave rise to one of three percepts (slow motion, fluttering sensation, or vibration); 16 were of double frequency and gave rise to two of the three percepts simultaneously; the other 6 were of triple frequency from which all three percepts could be discerned. Stimulation was applied to either one of three digits (thumb, index, or middle) or to all three digits simultaneously. Because all of the 120 stimulus alternatives were presented with equal a priori probabilities, the stimulus uncertainty was 6.9 (i.e., $\log_2 120$) bits. In order to examine the effect of stimulus duration on information transfer, two more stimulus sets at durations of 250 and 125 msec were constructed with stimulus uncertainties of 6.9 ($\log_2 120$) and 6.2 ($\log_2 76$) bits, respectively. All stimulus sets were constructed with the intent of all alternatives being easily identifiable so as to reduce training and testing time. Each response consisted of two parts: identification of the site of stimulation and of the particular stimulating waveform. To facilitate the learning of stimulus-response mapping, graphic icons that schematized the stimulating waveforms were arranged as circular buttons on a digitizing tablet along with a group of four icons corresponding to the four stimulation sites.

Experimental paradigm for assessing information transfer

During all experiments, a visual shield and masking noise were used to eliminate all visual and auditory cues. The standard absolute identification paradigm was employed. During initial training, each stimulus alternative was presented exactly twice per run (i.e., randomization without replacement) so that the subject had equal opportunity to learn all the signals in the stimulus set. During subsequent testing, however, stimulus alternatives were selected with equal a priori probability (i.e., randomization with replacement) to ensure that stimulus uncertainty remained the same throughout an experimental run. During both training and testing, the subject indicated which stimulus was just received by using a stylus to choose two icons (one for the stimulation site and one for the stimulating waveform) on the response tablet after each trial. A conservative estimate of information transfer was computed as $IT=IS*(1-2e)$, where IS denotes information in the stimulus set (i.e., stimulus uncertainty), and e denotes error rate. All subjects were first trained with each of the three stimulus sets until they had completed three runs over

95% (not necessarily consecutively). They were then tested with the same stimulus sets with the slightly modified paradigm.

Experimental paradigm for assessing information transfer rate

In order to assess the information transfer rate achievable with the TACTUATOR, signals should ideally be presented continuously at a regular rate. The subject would then be asked to repeat the whole presentation sequence afterwards. According to Miller (1956), however, the number of chunks people can recall correctly is limited to about seven. To be able to repeat a long sequence of signals, a subject must learn to organize individual signals into meaningful chunks, assign labels to these chunks, and then store these labels in short-term memory for later retrieval. This training process can take years. To bypass this training problem, we used an identification paradigm with forward and backward masking (Fig. 2). On each trial, the subject was presented with a triplet of signals. Each signal was selected randomly from the same stimulus set. The subject was asked to identify only the middle signal, X, sandwiched

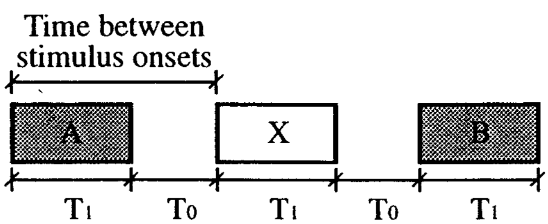

Fig. 2. Experimental paradigm used to estimade IT rate.

between two interfering maskers A and B. The signal duration was fixed at T_I, and the gap duration was fixed at T_0. The three stimulus sets developed earlier (T_I = 500, 250, and 125 msec) were used.

Gap durations from 500 to 20 msec were used with each stimulus duration. This paradigm evaluated the deterioration in performance due to the masking effects of "neighboring" signals. Using the measured IT and assuming that subjects could eventually (i.e., with sufficient training) learn to chunk continuous stimulus streams with the same accuracy per stimulus, we calculated estimates of IT rate (in bits/sec) as IT divided by T_0+T_I, the time between stimulus onsets.

Results

Information transfer with the 500-, 250-, and 125-msec stimulus sets

The estimated information transfers averaged over the three subjects were 6.5, 6.4, and 5.6 bits for stimulus durations of 500, 250, and 125 msec, respectively (Fig. 3, left panel). The horizontal solid lines (above each bar) indicate the respective stimulus uncertainties, or equivalently, the maximum IT that could have been obtained. The equivalent number of perfectly identifiable items are 90, 84, and 50 for stimulus durations of 500, 250, and 125 msec, respectively (Fig. 3, right panel). The corresponding number of stimulus alternatives are shown with the horizontal solid lines.

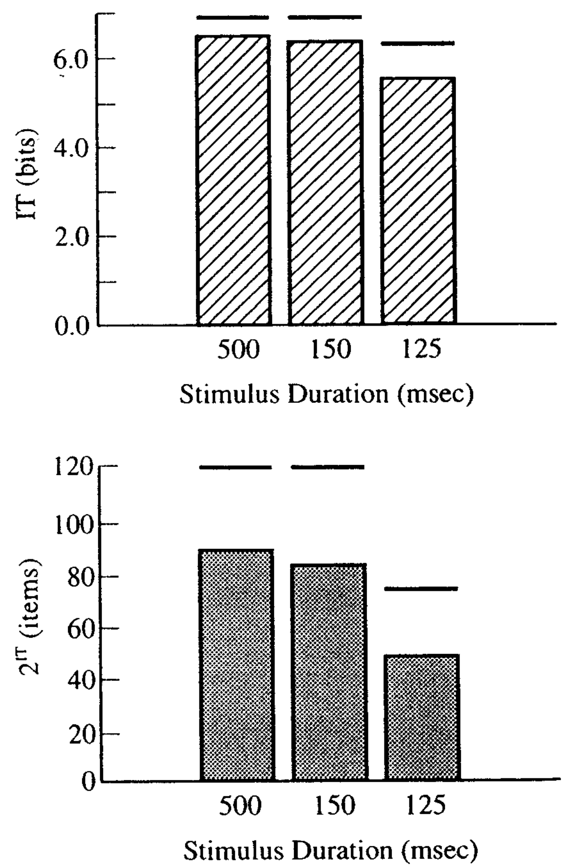

Fig. 3. Information transfer and equivalent number of perfectly indentifiable items.

Information transfer rate

Results for one subject (S1) are shown in Fig. 4 in terms of percent correct scores (left panel) and estimated IT rate (right panel) as a function of the time between stimulus onsets (i.e., T_0+T_1). From the left panel, it can be seen that performance was dependent on time between stimulus onsets, or equivalently, stimulus presentation rate, but not on stimulus (or gap) duration alone. From the right panel,

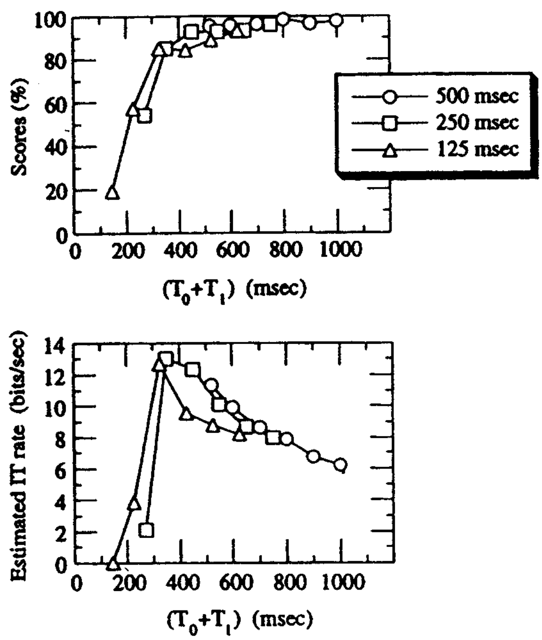

Fig. 4. Percent-correct scores and estimated information transfer rates for subject S1.

it can be seen that the estimated IT rate reached a peak near 350 msec, or 3 items/sec. Results for the other two subjects are similar to those shown in Fig. 4; the optimal presentation rates for S2 and S3 were 3 and 2 items/sec, respectively. The maximum estimated IT rate averaged over the three subjects was 12 bits/sec.

Discussion

The information transfer rates obtained with several tactual communication devices can be compared. Using his air-drive finger stimulator, Bliss (1961) reported an IT rate of 4.5 bits/sec for one experienced typist who received letters and a few punctuation symbols. Using the display for the Vibratese language, Geldard (1957) reported that one subject was able to handle 38 wpm, or equivalently, 5.1 bits/sec (assuming 2 bits/letter according to Shannon, 1951, and 4 letter/word). Using the Optacon device, Cholewiak et al. (1993) reported that their best subject was able to reach a word rate of 40 wpm, or equivalently, 5.4 bits/sec. Overall, the IT rates measured with these man-made tactual displays are much lower than the rates demonstrated by natural tactual communication methods. Specifically, Reed et al. (1992) estimated that the IT rate for Tadoma is about 12 bits/sec. Our estimated IT rate of 12 bits/sec with the TACTUATOR appears promising. To the extent that this IT rate can be substantiated by future research using English (or other continuous) material, we may finally be able to communicate through a tactual device at a rate comparable to that achieved by Tadoma users.

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Abstract

Motivated by the highly successful Tadoma method of speech communication, a multi-finger positional display (the TACTUATOR) was developed to study perception via the kinesthetic and vibrotactile aspects of the tactual sensory system of the hand. The information transmission capabilities with the TACTUATOR were assessed through a series of absolute identification experiments. An information transfer (IT) of 5.6 to 6.5 bits for stimulus durations of 125 to 500 msec was obtained in absolute-identification experiments with sets of signals derived by varying frequency, amplitude, and site of stimulation of multicomponent waveforms. An estimated IT rate of 12 bits/sec was obtained by sequencing three random stimuli and (a) having the subject identify only the middle stimulus and (b) extrapolating

this IT to that for continuous streams. This IT rate is roughly the same as that achieved by Tadoma users in tactual speech communication.

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