Tactile Communication of Speech

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Goals and Significance

The long-term goal of this research is to develop tactual aids for persons who are profoundly deaf or deaf-blind to serve as a substitute for hearing in the reception of speech and environmental sounds. This research can contribute to improved speech reception and production, language competence, and environmental-sound recognition in such individuals. This research is also relevant to the development of improved tactual and haptic displays for a broad class of applications (including virtual-environment and teleoperator systems in addition to sensory aids).

Research is being conducted in two major areas. Work in *Area 1* (Basic Studies of Human Touch) is designed to increase our knowledge concerning the transmission of information through the sense of touch. This research includes theoretical and experimental studies concerned with dynamic information transfer as well as experimental work designed to increase our understanding of the psychophysical properties of the sense of touch. Work in *Area 2* (Tactual Displays of Speech and Environmental Sounds) is concerned with the application of tactual displays to sensory aids for persons who are profoundly deaf or deaf-blind. This research includes studies related to the processing and display of speech and environmental sounds through the tactual sense as well as studies concerned with evaluations of performance achieved through these displays.

Current Studies

Basic Studies of Human Touch.

Temporal Order Resolution for Tactual Signals. The temporal resolution of the tactual sense was assessed in a series of experiments examining discrimination of temporal onset order (Yuan et al., 2004; Yuan et al., 2005a) and temporal offset order (Yuan and Reed, 2005b). These studies are motivated by, and highly related to, our work on tactual presentation of a temporal-based cue to consonant voicing.

Temporal Onset-Order Resolution using Redundant Coding of Location and Vibratory Frequency. Tactual temporal-onset order thresholds were measured for two sinusoidal vibrations of different frequencies delivered to two separate locations (left thumb and index finger) of our upgraded tactual stimulating device. The frequency delivered to the thumb was fixed at 50 Hz (T50) and that to the index finger at 250 Hz (I250). The amplitude and duration of each of the two sinusoidal vibrations were roved independently from trial to trial in a one-interval, two-alternative, forced-choice procedure (1A, 2AFC). Performance, measured as a function of stimulus-onset asynchrony (SOA), indicated that the temporal onset-order thresholds averaged 34 msec across four subjects. The data were further classified into subsets according to both the amplitude and duration of the two stimuli in each trial of the roving-discrimination paradigm. The results indicated that the amplitude differences of the two stimuli in each trial had a substantial effect on onset-order discrimination, while duration differences generally had little effect. The effects of amplitude differences can be explained qualitatively in terms of amplitude latency relationships and stimulus interactions such as temporal masking. The results of this experiment are relevant to our speech-based measurements of a temporal asynchrony cue to voicing (Yuan et al., 2004), as well as our perceptual studies of consonant discrimination and identification using a tactual display of a temporal-onset based cue to voicing (Yuan et al., in press).

Effects of Frequency and Site of Stimulation on Temporal Onset-Order Discrimination. This research extends that of our previous study (Yuan et al., 2005a) through an examination of the effects of the frequency spacing of two sinusoidal signals delivered either at two separate fingers (left index and left thumb) or at a single site of stimulation (left index finger) on temporal onset-order resolution. The effects of stimulating frequency were examined for pairs of identical (SF) or different frequencies (WC) from within each of the three major channels of the tactual sensory system as well as pairs of frequencies from across each of the three channels (CC). Redundancy effects were examined in conditions comparing the presentation of the same frequency versus different frequencies in the two-finger condition and conditions comparing the presentation of a given frequency pair at one site versus two sites. In addition, redundancy effects were examined in two conditions in which frequency was independent of site of stimulation but differed as to whether subjects were instructed to respond to temporal onset order on the basis of frequency or site of stimulation. Measurements were obtained using a 1A, 2AFC procedure in which the amplitude and duration of each of the two sinusoidal signals were roved independently from trial to trial. Thresholds were estimated from psychometric functions of d' as a function of SOA. The experimentsFor two-finger stimulation, temporal onset-order thresholds ranged from roughly 20 to 70 msec across subjects and were relatively independent of frequency separation. For one-finger stimulation, a significant effect of frequency separation was observed indicating that temporal onset-order thresholds were larger by a factor of roughly 2.0 for frequencies within a given channel of the tactual sensory system compared to cross-channel frequencies. This study also examined the effects of redundant coding of frequency and stimulation site through experiments employing two-finger stimulation in which frequency and stimulation site were selected independently on a given trial and the subject's task was to determine onset order based either on frequency (independent of site of stimulation) or on site of stimulation (independent of frequency). Results indicated superior temporal resolution for redundant compared to non-redundant coding schemes. This research suggests that temporal onset-order cues may be encoded either through site of stimulation or through the use of cross-channel frequencies at a given site; the optimum coding method appears to vary across subjects.

Temporal Offset-Order Resolution. Tactual resolution for temporal offset order was examined in experiments employing a 2I2AFC procedure with correct answer feedback with two signals: 250 Hz at the index finger (I250) and 50 Hz at the thumb (T50). The amplitude and duration of the two signals were selected at random on each trial from a range of 35 to 40 dB SL and 300 to 800 msec, respectively. Performance was measured as a function of stimulus-offset ansynchrony (SOFA), defined as SOFA=$|\text{Offset Time}_{I250} – \text{Offset Time}_{T50}|$. On one interval of each trial (selected at random) SOFA=0 and in the other interval SOFA was greater than 0. The subject's task was to select the interval in which SOFA≠0. For each of four subjects, performance was measured at two values of SOFA (tested in separate runs) selected to yield performance in the range of 60-85% correct. Data were summarized through psychometric plots of d' versus SOFA and threshold was defined as SOFA in msec required for d'=1.0. Thresholds ranged from 97.6 to 231.2 msec across subjects and averaged 142.4 msec. Temporal resolution for offset order is substantially poorer than for onset order for tactual stimulation (by a factor of roughly 4), perhaps reflecting greater effects of forward compared to backward masking in tactual detection tasks. The results of this experiment are related to the discrimination of final consonant voicing (Yuan et al., 2005b).

Ongoing research in the area of basic human tactual psychophysics also includes work on the effect of roving background parameters on the ability to discriminate the amplitude and frequency of components of multidimensional tactual stimuli.

Effects of Roving Background Parameters on Amplitude and Frequency Discrimination. Using the new controller system (Israr et al., 2004) developed at our sub-contractual site at Purdue University, data have been collected on four subjects for amplitude and frequency discrimination of a given reference stimulus. These experiments provide insight into interactions between the kinesthetic and cutaneous components of the tactual sensory system and are relevant to the design of tactual display schemes. Twelve reference signals were selected with 6 values of frequency (2 and 4 Hz in the low-frequency region; 15 and 30 Hz in the mid-frequency region; 80 and 200 Hz in the high-frequency region) and 2 values of amplitude (20 and 35 dB SL). Frequency and amplitude discrimination were tested for each of the 12 reference signals under four types of background conditions: no-roving background (C1), one roving background stimulus selected from each of the two frequency regions of which the reference signal was not a member (C2 and C3), and two roving background signals from the two non-member frequency regions (C4). For example, when the reference signal was 2 Hz, the masker in C2 was selected from the mid-frequency region, the masker in C3 from the high-frequency region, and the maskers in C4 from the mid- and high-frequency regions, respectively. A three-interval forced choice (3IFC) paradigm with a one-up three-down adaptive procedure was used to estimate thresholds for both frequency and amplitude discrimination. For frequency discrimination, average Weber fractions ranged from 13-38% for C1, increased to 17-155% for C2 and C3, and reached as high as 165% in C4. For intensity discrimination, thresholds ranged from 1.6-3.0 dB for C1, 2.3–5.6 dB for C2 and C3, and 2.6-5.2 dB for C4. Thus, the effects of roving backgrounds appears to have had a much greater effect on frequency discrimination compared to amplitude discrimination.

Tactual Displays of Speech and Environmental Sounds

This research is concerned with the development of tactual aids for the deaf for use in the communication of speech and environmental sounds. In the area of tactual displays of speech, studies are focused on the development and perceptual evaluation of displays of consonant voicing. In the area of tactual displays of environmental sounds, our research has been concerned with the design and administration of a survey concerned with the interest of a broad class of deaf and hard-of-hearing individuals in the use of tactual devices for awareness and recognition of environmental sounds.

Improved Tactual Displays of Consonant Voicing. This research is concerned with the development of tactual displays to supplement the information available through lipreading (which is an important means of communication for many persons with profound hearing impairment or deafness). Because voicing carries a high informational load in speech and is not well-transmitted through speechreading, our efforts have been focused on the development of tactual displays of voicing cues to supplement the information available on the lips of the talker. Our research includes (i) the development of signal-processing schemes to extract information about voicing from the acoustic speech signal, (ii) methods of displaying this information through a multi-finger tactual display, and (iii) perceptual evaluations of voicing reception through the tactual display alone and in combination with speechreading.

Acoustic Cues to Initial and Final Consonant Voicing. Based on the underlying processes associated with the production of the voicing contrast in speech, we have derived a novel acoustic cue for voicing (Yuan et al., 2004; Yuan et al., in press). The signal-processing scheme for extraction of voicing information employs amplitude-envelope signals derived from two filtered bands of speech: a lowpass-filtered band at 350 Hz and a highpass-filtered band at 3000 Hz). Acoustic measurements of temporal properties of these envelope signals (that provide a reliable and robust cue to voicing) were derived from audiovisual recordings of CVC syllables (V = /i a u/) spoken by two female talkers.

C-3-a-i-α. Envelope-Onset-Asynchrony (EOA) Cue for Initial Consonants. Acoustic measurements were made on a set of 1024 C1VC2 syllables representing 16 different values of C1: /p b t d k g f v th tx s z sh zh ch j/ (Yuan et al., 2004). EOA was defined as the difference in time between the onset of the high-frequency envelope and the onset of the low-frequency envelope: EOA=OnsetTime$_L$ – OnsetTime$_H$. The EOA measurements of the 64 tokens representing each value of C1 were used to derive a probability-distribution function (pdf), from which a cumulative distribution function (cdf) was computed. Gaussian fits were then made to the cdf of each C1. For individual voiceless consonants, the means of the best-fitting Gaussian distributions ranged from 54.6 to 233.5 msec (with s.d.s in the range of 24.9 to 107.5 msec). For individual voiced consonants, the means ranged from -122.4 to 68.6 msec (with s.d.s in the range of 2.6 to 69.8 msec). Distribution functions and Gaussian fits were also derived for the two general classes of voiced versus voiceless consonants by pooling the measurements for the 8 voiced consonants /b d g v tx z zh j/ and the 8 voiceless consonants /p t k f th s sh ch/. The results of the best Gaussian fits to the cdsf for these two categories indicated a mean EOA of 142.5 msec for the voiceless category (and s.d. of 77.2 msec) and a mean EOA of -12.4 msec (s.d. of 66.5 msec) for the voiced category. Using the EOA as a perceptual-distance measurement, we calculated the performance of an ideal observer in making the voiced-voiceless distinction using the sensitivity measure d'. The calculations make use of the means and s.d.s of the best Gaussian fits and are computed for a 2I, 2AFC procedure. Across the 8 pairs of voiced-voiceless contrasts, d' values ranged from 3.5 (for the pair /f-v/) to 13.0 (for the pair /s-z/). These results indicate excellent sensitivity: in terms of percent-correct scores the results fall in the range 96% to 100% correct. The EOA measurement thus provides a reliable and robust to initial consonant voicing across a variety of vowel contexts for two different speakers and is independent of manner and place of consonant production. The performance of the EOA measure compares favorably with that reported for voicing-detection algorithms incorporated into schemes for Automatic Speech Recognition (ASR) (Nyogit and Ramesh, 2003; Thomson and Chenglavarayan, 2002).

C-3-a-i-β. Envelope-Offset-Asynchrony (EOFA) Cue to Final Consonant Voicing. Work parallel to that described in Sec. C-3-a-i-α for initial consonants was conducted to identify a temporal cue to voicing in final consonants. In this case, EOFA was defined as the difference in time between the offset of the high-frequency envelope and the offset of the low-frequency envelope: EOFA= OnsetTime$_L$ – OnsetTime$_H$. Measurements of EOFA were made on at least 63 tokens (and as many as 94 tokens) of each of 16 values of C2 in CVC syllables produced by two female talkers with 16 vowels. The same methodologies described above were employed in the current work. That is, for each C2, the distribution EOFA measures was fit to a Gaussian distribution (N(mu, sigma) and distributions for pairs of voiced-voiceless contrasts were used to calculate the performance of an ideal observer. For voiceless consonants, means of the Gaussian fits ranged from 219.2 to 422.0 msec (s.d. range of 37.4 to 156.7 msec) and for voiced consonants the means ranged from -44.1 to 185.5 msec (s.d. range of 67.6 to 90.6 msec). For the two general categories, the best-fitting Gaussian distributions yielded means of 348.3 msec (sd of 104.4 msec) for voiceless consonants and 65.5 msec (s.d. of 98.1 msec) for voiced consonants. Using the Gaussian fits to the EOFA measurements, the performance of the ideal observer (calculated for a 2I, 2AFC procedure) ranged from d' of 3.0 (for /p-b/) to 6.3 (for /s-z/). For the two general categories, d' was 4.0. These results indicate excellent separability of the two classes of final consonants on the basis of the EOFA measurement.

Development of Tactual Display of Temporal Cue to Consonant Voicing. A tactual display was designed for the presentation of envelope-asynchrony cues (EOA or EOFA) through the upgraded version of the Tactuator system. The amplitude envelope of each of the two filtered bands of speech (350 Hz lowpass and 3000 highpass) was extracted in real time through the operations of filtering, rectification, and smoothing. Thresholds were established for the levels of each of the two smoothed amplitude envelopes to eliminate signals arising primarily from random noise fluctuations in the passband but yet sufficient for passing signals driven by the speech waveform. The specific scheme for the presentation of the envelope-asynchrony cues involved the delivery of the two modulated envelopes to two different fingers and employed a different modulation frequency at each finger (selections made to minimize cross-channel masking; e.g., see Verillo et al., 1983; Tan et al., 1999). Specifically, the low-frequency envelope was used to modulate a 50-Hz sinewave at the left thumb and the high-frequency enveloped was used to modulate a 250-Hz sinewave at the left index finger. The level of these speech-derived signals was generally in the range of 20 to 50 dB SL.

Perceptual Evaluations with Speech Signals. The efficacy of the EOA cue was evaluated through perceptual studies that included pairwise discrimination of eight pairs of voicing contrasts in the initial consonant of CVC syllables, identification of a set of 16 initial consonants, and open-set recognition of sentences. In addition, the EOFA cue was evaluated through pairwise discrimination of eight pairs of voicing contrasts in the initial consonant of CVC syllables. These evaluations were generally concerned with examining benefits to lipreading through the addition of the tactual cue to voicing. Three conditions were studied in the discrimination and identification tests: lipreading alone (L), tactual signals alone (T), and the combined condition (L+T). For the sentence-reception task, only conditions L and L+T were examined (the T condition was not included because no significant information was expected for delivery of the tactual cue alone without extended training). These studies employed normal-hearing subjects who wore earplugs and headphones through which masking noise was presented to eliminate the possibility of any auditory cues arising from the vibration of the Tactuator.

Pairwise Discrimination of Voicing in Initial Consonants. The ability to discriminate eight pairs of initial voicing contrasts in CVC syllables was examined using a 2I2AFC procedure. Following training sessions which employed trial-by-trial correct-answer feedback, testing was conducted using a fresh set of speech tokens where each C1 was represented by 24 tokens (2 talkers X 3 vowels X 4 utterances) selected at random on each trial. The sensitivity index d' averaged 0.09 for L, 2.4 for T, and 2.4 for L+T across subjects and pairs indicating performance at a near-chance level for L and similar performance for T and L+T. Some inter-pair variability was observed on the T and L+T conditions, where scores ranged from d' of roughly 3.3 for the pair /xx-xx/ to roughly 1.6 for the pair /xx-xx/. Overall, performance on the T and L+T conditions averaged roughly 90% correct (compared to chance performance of 50% on L) and represents an improvement over that obtained with previous tactual devices (e.g., Reed et al., 1992; Waldstein and Boothroyd, 1995a, b). A rough correspondence was observed between subjects' resolution in the temporal-onset-order discrimination task and their performance on the speech-discrimination task. A comparison of the observed human performance to that of an ideal observer indicates that the observed scores were lower by a factor of roughly 1.6 than those of the ideal observer, suggesting that limitations at the peripheral and/or central levels of processing lead to degraded human performance.

Identification of Initial Consonants. The tactual presentation of the EOA cue was highly effective for pair-wise discrimination of initial voicing contrasts. The purpose of this experiment was to examine the contribution of the tactual voicing cue to the task of consonant identification. The ability to identify the initial consonant of CVC syllables was tested using a 1-interval, 16-alternative forced-choice procedure. Following training sessions which employed trial-by-trial correct-answer feedback, testing was conducted without feedback and with a fresh set of speech tokens (which included 24 tokens of each C1). Overall performance averaged 34%, 12%, and 49%-correct for L, T, and L+T, respectively, demonstrating that the addition of the tactual cue improved lipreading ability by 15 percentage points. Performance was also examined in terms of percentage of unconditional IT for features of voicing, manner, and place. For the feature voicing, %-feature IT was ordered as L<L+T<T, representing an improvement of 30 percentage points for T over L alone and 10 percentage points for T over L+T (indicating that subjects may have had difficulty attending to the tactual cue in the presence of lipreading). For the features of manner and place, information was transmitted primarily through lipreading alone (with 0 %-IT through T alone) and was nearly identical for conditions of L and L+T. Predictions of overall performance under the combined condition L+T, computed using various models of bimodal integration (see Yuan, 2003; Yuan et al., in press), indicated that observed performance was inferior to that of model predictions. The non-optimal integration of the tactual cue with lipreading may arise in part from a lack of experience attending to the tactual modality.

Pairwise Discrimination of Voicing in Final Consonants. The ability to discriminate eight pairs of voicing contrasts in the final position of CVC syllables was examined using the same basic procedures described above for initial consonants (except that the syllables included 16, rather than 3, vowels). The sensitivity index d' averaged 1.2 for L, 2.9 for T, and 3.1 for L+T. Unlike the case of initial consonants, performance through L alone was greater than chance presumably on the basis of vowel-duration cues to final voicing. Performance through T was higher than through L, however, and provided a substantial supplement to lipreading. Compared to the predictions of an ideal observer operating on the EOFA measurements, the human performance (under T alone) was lower by a factor of roughly 1.4 (reflecting limitations at the peripheral or central processing levels for the human observers).

Connected-Speech Reception. Sentence testing was conducted to determine whether the benefits observed for the tactual cue at the segmental level would have immediate carry-over to the task of connected speech reception. The ability to recognize words in CUNY sentences (Boothroyd et al., 1985) was examined using recorded materials presented through conditions of L and L+T. Subjects received only a minimal amount of training on the task in which subjects were permitted multiple repetitions of 36 sentences per condition and were provided correct-answer feedback. The testing employed only one presentation of each sentence (27 lists of 12 sentences each under L and L+T, respectively) and did not employ correct-answer feedback. The results indicated no improvement in performance over time and no difference in performance between the two conditions. Mean word-recognition scores in sentences ranged from 12 to 67% correct across subjects for L (averaging 32.7%) and 11 to 70% for L+T (averaging 32.0%). Segmental performance (which occupied a narrow range from 32-35% correct across subjects) does not appear to be a good predictor of sentence performance. The lack of benefit for the tactual cue to lipreading may be due to a variety of factors, including the limited amount of training with the tactual cue, difficulty integrating tactual and visual cues, the potentially greater role of temporal masking of the tactual signals in continuous speech signals, and an increased variability of the temporal cue arising from additional complexity of continuous speech.

Tactual Displays of Environmental Sounds. Progress in this area includes the publication of two papers concerned with the reception of environmental sounds through tactual aids (Reed and Delhorne, 2004) and cochlear implants (Reed and Delhorne, 2005). The main focus of the research in this area is determining the interest of a broad class of deaf and hard-of-hearing (HOH) individuals (including those with oral and manual backgrounds) in the awareness and recognition of environmental sounds. This goal was accomplished through the development and administration of a survey to determine potential interest in tactual aids as a source of information about non-speech environmental sounds. The work includes development of a pilot survey which was administered to 20 deaf and HOH adults. Based on analysis of the pilot survey, a final questionnaire was developed for administration to several hundred deaf and HOH adults.

Preliminary survey. The pilot survey (Delhorne and Reed, 2003) consisted of 65 multiple-choice questions in four different areas: communication preferences, history of assistive-device use, interest in various types of environmental stimuli, and preferences regarding the design of devices for displaying acoustic environmental stimuli. The respondents were 20 deaf adults who ranged in age from 20 to 52 years, described themselves as either deaf or hard-of-hearing, and were either born deaf or had acquired hearing loss before the age of 2 years. Subjects were divided into two groups based on their linguistic preference: a group who had early exposure to and preferred manual communication and a group who preferred oral communication. The responses of the two groups indicated similar degrees of interest in the reception of various types of environmental sounds and in characteristics related to the design of communication devices. A summary of the major results of the survey indicates that the subjects were most interested in receiving information about sounds associated with warning signals and operation of machinery (such as cars) and prefer a multi-purpose, portable alerting system that can used with minimal training.

Final Survey. The revised survey consists of 52 questions in seven categories: personal information and linguistic history, hearing-aid use, cochlear-implant use, tactual-aid use, alerting-system use, interest in a variety of types of environmental sounds (other than speech), and suggestions for future devices. Respondents to the survey were recruited through advertising on websites and in the newsletters of a variety of organizations for the deaf and hard-of-hearing. The survey was made available for completion through a website which could be accessed by potential respondents. Paper copies were also made available to persons who wished to respond in writing. Data from 240 deaf and hard-of-hearing respondents to the survey are currently being analyzed.

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