Tactile Communication of Speech

RLE Group
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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 over the past year has focused on two projects: (1) psychophysical studies of tactual detection and tactual temporal resolution in adults with profound, early-onset hearing impairment; and (2) psychophysical studies of the perceptual interactions of near-threshold stimuli in the tactual and auditory sensory modalities.

Current Studies

Measures of Tactual Detection and Temporal Order Resolution in Adults with Profound Hearing Impairment

In a previous series of studies conducted in our laboratory (Yuan et al., 2004a, 2004b, 2005a, 2006; Parachuru, 2003), the temporal resolution of the tactual sense was assessed in normal-hearing subjects through measurements of the ability to detect the temporal order of tactual stimuli. These studies are motivated by, and highly related to, our work on tactual presentation of a temporal-based cue to consonant voicing as a supplement to lipreading in tactual speech-communication aids for persons with profound auditory impairment (e.g., Yuan et al., 2003, 2005b).

The current series of studies (Moallem et al., 2007) was undertaken to examine basic temporal resolution in persons with early-onset profound deafness. This research was motivated in part by a recent report in the literature indicating that the temporal resolution of deaf subjects with congenital or early-onset deafness may be inferior to that of normal-hearing subjects in both the tactual and visual modalities (Heming and Brown, 2005). In the tactual modality, subjects were tested on a task which required them to judge the simultaneity of two brief mechanical taps presented to each of two fingers. The relative onset of the timing of the two taps was varied across stimulus presentations. The deaf participants exhibited significantly higher thresholds for the percept of simultaneity (mean threshold of roughly 90 msec) than normal-hearing subjects (mean threshold of roughly 25 msec) for the tactual task. A similar pattern of results was observed on a visual counterpart of this task employing LED stimuli. In the procedure and analysis used by Heming and Brown (2005), it is conceivable that perceptual sensitivity and response bias were confounded in their measurement of standard error and that the higher thresholds of the deaf compared to normal-hearing subjects were due to bias shifts, rather than to differences in sensitivity. In contrast to the procedure employed by Heming and Brown (2005), our psychophysical studies of temporal resolution are based on signal-detection theory which permits us to examine sensitivity (d’) separate from response bias.

Tactual Stimulating Device

Psychophysical studies were conducted with deaf subjects and age-matched normal-hearing controls in which tactual stimuli were delivered to the index finger and thumb of the left hand using a multi-finger tactual stimulating device developed in our previous research (Tan and Rabinowitz, 1996; Brughera, 2002). This device consists of three rods that interface with the thumb, index finger and middle finger oriented in a manner that allows for a natural hand configuration (see bottom panel of Fig. 1). A photograph of the motor assembly (with labeled components) associated with one of the rods is provided in the upper panel of Fig. 1. The device is well-suited for use in psychophysical tactual experiments based on its capability for delivering a wide range of motions encompassing frequencies along a continuum from dc to 300 Hz, its linear response properties, and its insensitivity to loading of a finger on the rods.

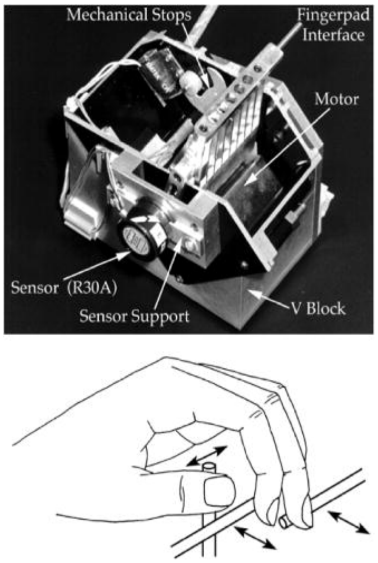

FIG 1. Diagram of Tactuator.

Subjects

Seven adults with profound hearing loss present at birth participated in the experiments. These subjects (five females and two males) ranged in age from 18 to 56 years. The methods of communication currently employed by these subjects included American Sign Language (ASL) exclusively (three subjects), both ASL and English (three subjects), and Cued Speech (one subject). A group of five normal-hearing subjects (one female and four males) who were native speakers of English and ranged in age from 23 to 58 years, also participated in the study.

Experiment 1: Tactual Detection of Sinusoidal Signals

Absolute detection thresholds for sinusoidal vibrations were measured at each of two sites (left index finger and left thumb), using nine stimulus frequencies in the range of 2 to 300 Hz. Measurements were obtained using an adaptive two-interval, two-alternative forced-choice (2I-2AFC) procedure with trial-by-trial correct-answer feedback. Thresholds in dB re 1 micrometer peak displacement are presented in Fig. 2 below for the individual deaf subjects, along with the average data across the five normal-hearing subjects.

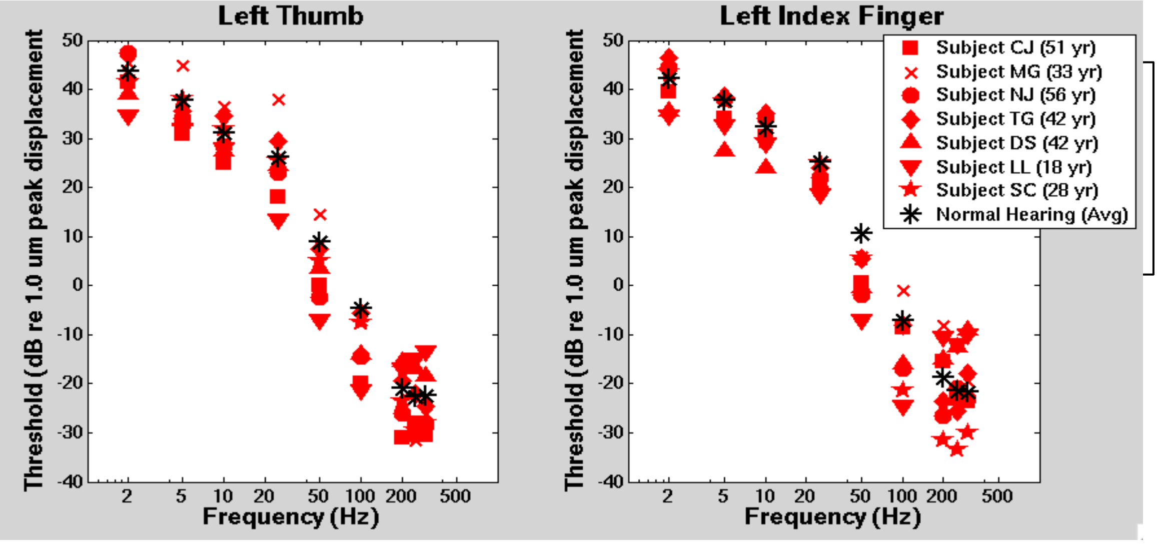

Fig. 2: Tactual Detection Thresholds as a Function of Frequency

These results indicate that the absolute detection thresholds are similar for deaf and normal-hearing subjects, both of which are consistent with other data on tactual thresholds of normal-hearing subjects reported in the literature (e.g., Bolanowski et al., 1988).

Experiment 2: Tactual Temporal-Onset Order Discrimination

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 the tactual stimulating device (see Fig. 1). 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

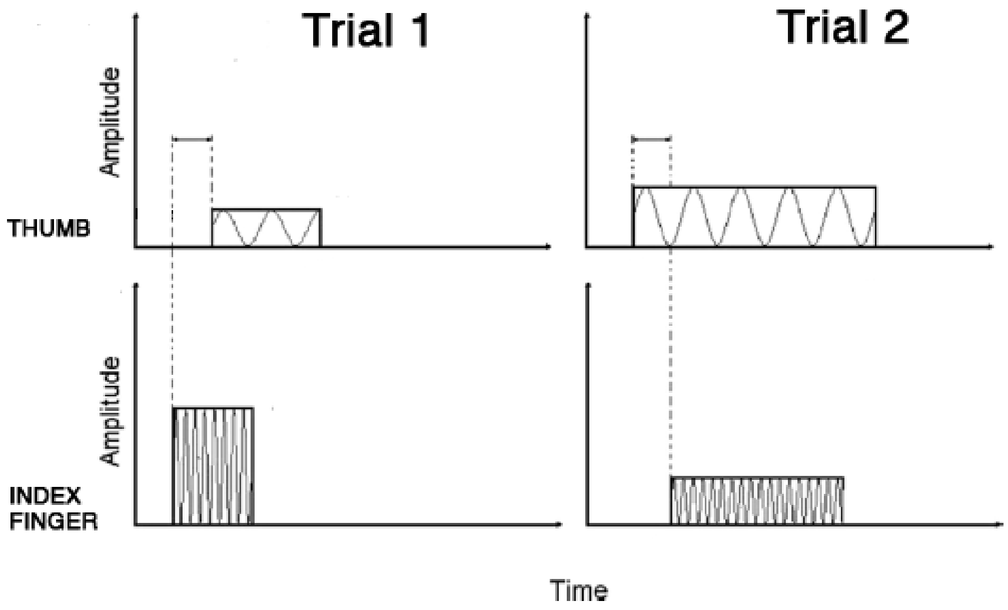

Fig. 3: Time Line of Temporal Onset-Order Experimental Paradigm

sinusoidal vibrations were roved independently from trial to trial in a one-interval, two-alternative, forced-choice procedure (1I-2AFC), as shown in Fig. 3. Within a given run of trials, the absolute value of stimulus-onset asynchrony (|SOA|) of the signals delivered at the index finger relative to those at the thumb was fixed, and on each trial, the subject indicated which of the two stimuli had an earlier onset. Several values of |SOA| were tested to yield performance in percent-correct in the range of roughly 55 to 90%. Measures of sensitivity (d') and bias were calculated from the stimulus-response matrix obtained on each run. Threshold was defined as |SOA| required for d'=1.0.

Results for individual normal-hearing and deaf subjects are presented in Fig. 4, where values of d' are plotted as a function of |SOA| for each individual subject. Temporal onset-order discrimination thresholds for the normal-hearing subjects (shown in the left side of Fig. 4) ranged from roughly 50 to 100 msec. Results for the deaf subjects (shown in the right side of the figure) indicate thresholds in the range of 50-75 msec for five of the subjects and substantially larger values on the order of 150 msec for the remaining two subjects. Although individual variation was observed across deaf subjects, the performance of the majority of these subjects was comparable to that of the normal-hearing subjects. Thus, our results do not support the conclusion of Heming and Brown (2005) regarding compromised tactual temporal resolution for deaf compared to normal-hearing subjects.

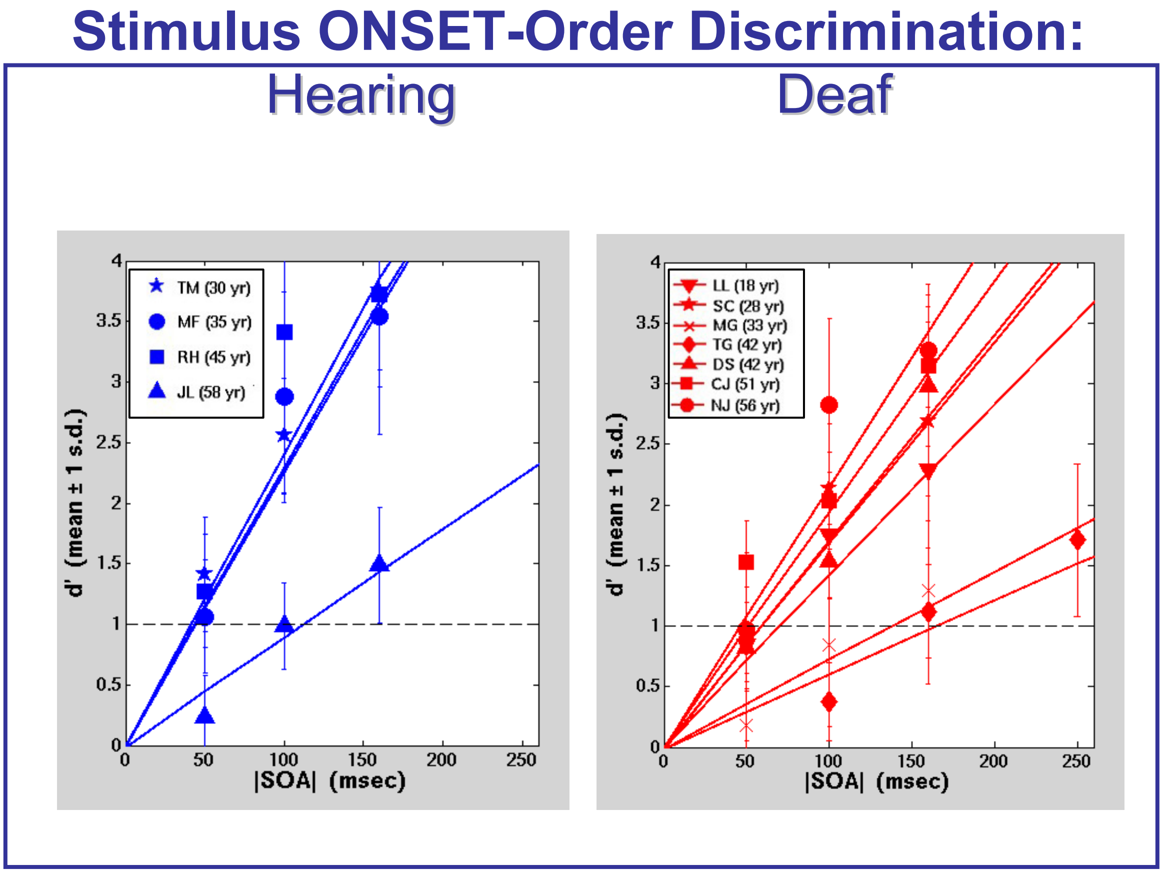

Fig. 4: Results of tactual temporal-onset order experiment. Sensitivity d' is plotted as a function of the absolute value of stimulus-onset asynchrony (SOA) in msec.

Experiment 3: Tactual Temporal-Offset Order Discrimination

The procedure for measuring tactual temporal-offset order discrimination was basically identical to that employed in the onset-order discrimination task described above, with exceptions that subjects were asked to judge which of the two stimuli had the later offset and that discrimination thresholds were measured as a function of stimulus-offset asynchrony (|SOFA|). The results of this experiment are presented in Fig. 5 for individual normal-hearing subjects (left side of the figure) and deaf subjects (right side). In general, offset-order thresholds were on the order of twice those of the onset-order thresholds. The range of thresholds across individual subjects was quite similar for normal-hearing and deaf subjects, with the most-sensitive subjects exhibiting thresholds of roughly 100 msec, ranging up to 250 msec for the least-sensitive subjects. Thus, there is no indication of differences in performance between normal-hearing and deaf subjects on this task.

Overall, our results do not support previous claims of compromised tactual temporal resolution in adults with profound, early-onset deafness. The temporal-resolution ability of deaf subjects appears to be sufficient to take advantage of envelope-onset asynchrony cues to consonant voicing in the development of tactual aids to lipreading.

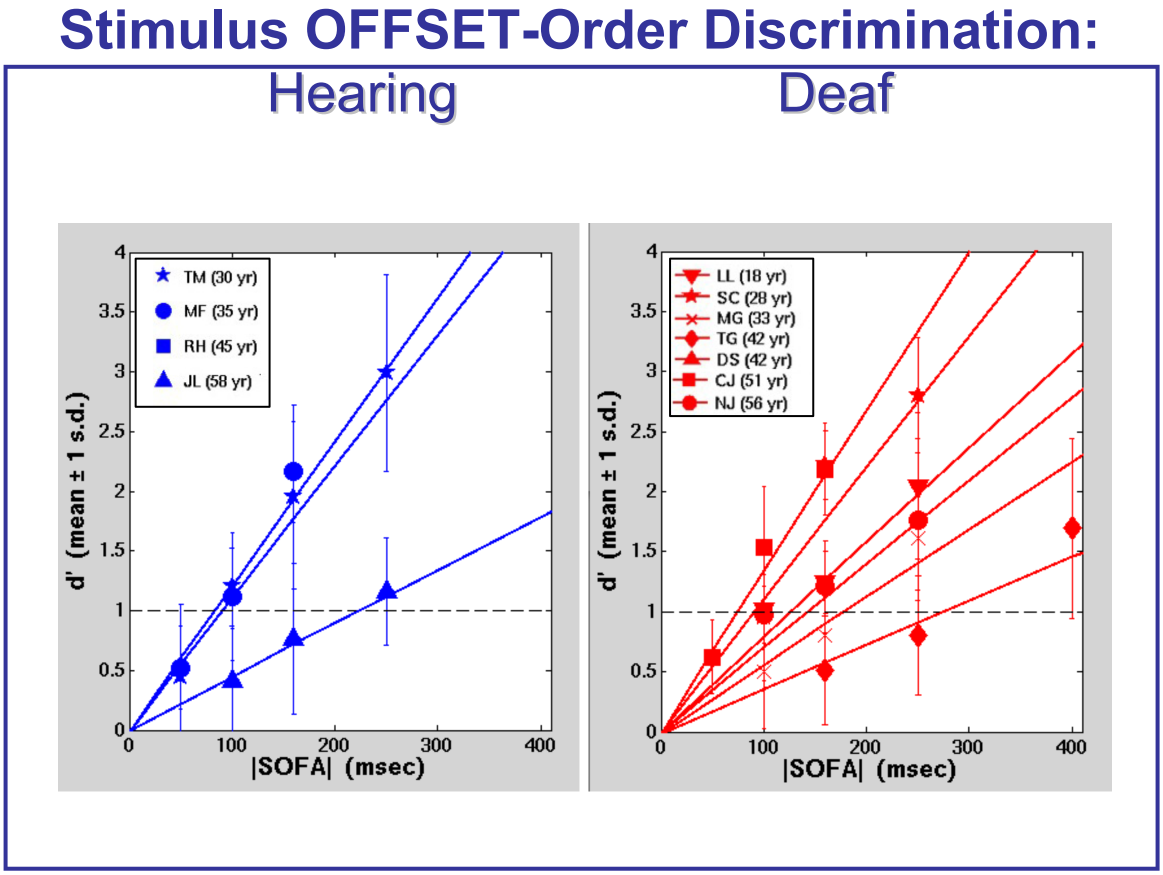

Fig. 5: Results of tactual temporal-offset order experiment. Sensitivity d' is plotted as a function of the absolute value of stimulus-offset asynchrony (SOFA) in msec.

Perceptual Studies of the Integration of Auditory and Tactile Stimulation

Research has been initiated to explore the perceptual interactions between auditory and tactile stimuli in a series of psychophysical studies (Wilson et al., 2007). This research is motivated by the observation that, in daily life, many sensory experiences are derived naturally from multisensory inputs. Numerous examples exist in the research literature demonstrating the influence of input from one sensory input over the perception of a stimulus in a second sensory modality. For example, the presence of an auditory signal can alter judgments regarding the intensity, numerosity, and motion of visual signals (Stein et al., 1996; Bhattacharya et al., 2002; Sekuler et al., 1997) or judgments of tactual texture (Jousmaki and Hari, 1988); vibrotactile stimulation can influence judgments of auditory loudness (Schurmann et al., 2004) or visual location (Spence et al., 1998); and the location of a visual stimulus can modify the perceived location of an auditory signal (as in the ventriloquism effect—see Woods and Recanzone, 2004). In the area of speech perception, the McGurk effect (McGurk and MacDonald, 1976) provides a powerful demonstration of the ability of visual cues derived from lipreading to influence the perception of auditory speech cues. Research has begun to unveil mechanisms for cross-modal interactions through single-cell recordings in animals (e.g., Stein and Meredith, 1993; Stein, 1998) as well as through imaging studies of cortical activity in animals and humans (Kayser et al., 2005; Molholm et al., 2002). Recent results provide evidence for multi-sensory convergence not only in the higher-order association areas of the cortex, but also at lower levels of cortical organization previously regarded as supporting primarily unisensory stages of processing (Schroder et al., 2003; Foxe and Schroeder, 2005; Schroeder and Foxe, 2005). From a structural and functional point of view, the neural circuitry of the brain demonstrates a variety of mechanisms for multisensory convergence (Schroeder and Foxe, 2004).

In the area of perceptual studies of auditory and tactile integration, previous research by Schurmann et al. (2004) examined whether the perceived loudness of a low-intensity 200-Hz auditory signal was enhanced by the simultaneous presentation of a 200-Hz vibrotactile stimulus delivered to the fingers. Subjects were instructed to adjust the level of a 200-Hz auditory probe tone to match a reference 200-Hz auditory tone presented in a background of white noise at 60 dB SL. The task was conducted under two conditions: auditory probe tone presented alone or with the simultaneous presentation of a 200-Hz vibrotactile stimulus at a level of roughly 26 dB SL. Averaged across nine normal-hearing subjects, the results indicated a decrease of roughly 12% (on the order of 1 dB) in the level of probe-tone adjustment when the vibrotactile signal was present compared to the auditory condition alone.

The goal of the current research was to obtain objective measurements of auditory-tactile interactions for near-threshold signals through psychophysical experiments conducted within the framework of signal-detection theory, using d-prime (d') as a measure of detectability. Our hypothesis states that if the auditory and tactile systems do integrate into a common neural pathway, then the d' measure of the two sensory stimuli presented simultaneously will be significantly greater than the d' measure of the individual sensory stimuli. Specifically, if the stimuli are judged independently of one another, the resulting d' will be close the root-squared sum of the individual sensory d' values. If, on the other hand, the stimuli are integrated into a single percept, the resulting d' will be close to the sum of the individual d' values.

Basic Experimental Design and Methods

Subjects: The experiments reported here were conducted with normal-hearing subjects (age range of 20 to 48 years) screened for audiometric thresholds of 20 dB HL or better at the octave frequencies in the range of 125 to 8000 Hz.

Procedures: Detection thresholds were measured under three basic conditions (Auditory alone, Tactile alone, and Auditory plus Tactile) with the goal of comparing performance on the multisensory conditions with baseline performance measured within each of the unisensory modalities. The auditory stimuli were pure tones presented bilaterally over headphones in a background of white noise whose level was 50 dB SPL. The tactile stimulus was a 250-Hz sinusoid presented through a single-channel vibrator to the fingerpad of the left middle finger. All signals had a duration of 500 msec with 20-msec rise/fall times. A basic block diagram for the presentation of the auditory and tactile signals is provided in Figure 6.

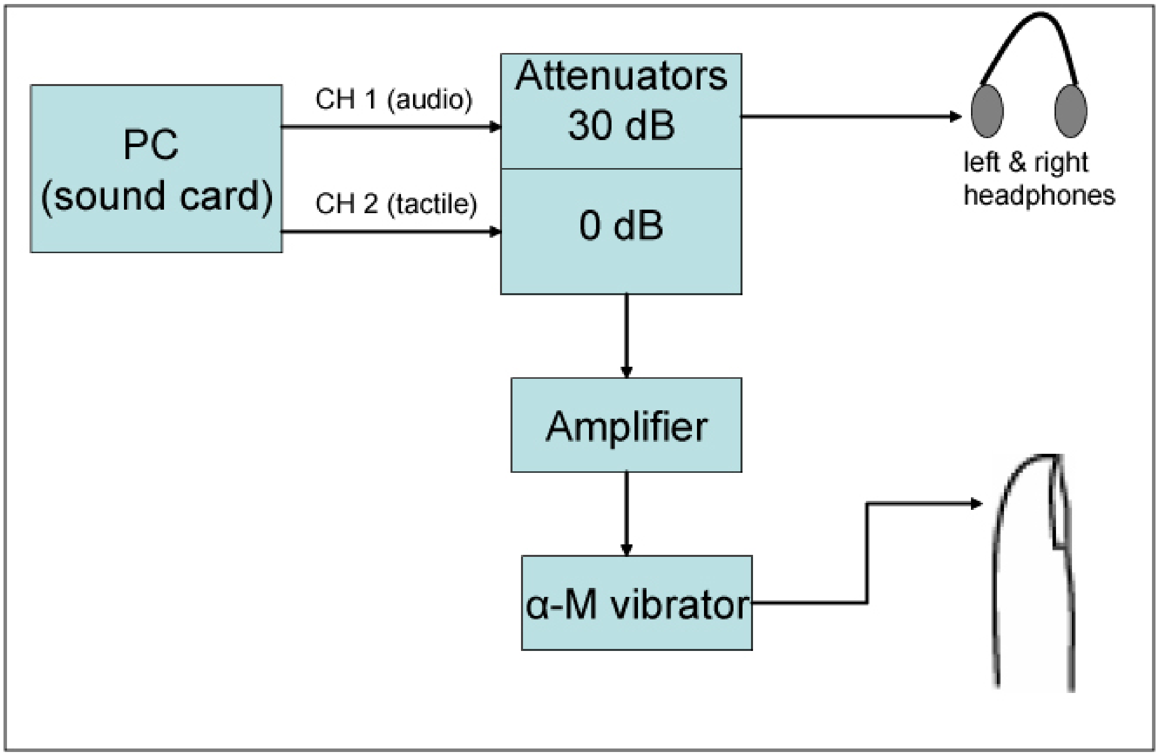

Figure 6. Block Diagram for Delivery of Auditory and Tactile Stimuli

Baseline Threshold Measurements: Absolute-detection thresholds in each of the two unisensory modalities were first approximated using an adaptive 3-interval, 2-alternative, forced-choice procedure whose adaptive rule (1-up, 2-down) estimates the level of the signal required for 70.7% correct detection. These threshold levels were then used in performing fixed-level experiments conducted with a 2-interval, 2-alternative forced-choice procedure with trial-by-trial correct-answer feedback. Measurements of d' were obtained from individual 75-trial runs conducted for Auditory Alone, Tactile Alone, and Auditory plus Tactile conditions (using the same stimulus levels as in the single-modality conditions). This set of baseline measurements was obtained at the start of each day of testing for each individual subject. Performance on the fixed-level task was also repeated at the end of the sessions to determine if performance had remained stable throughout the session. Subjects whose thresholds showed substantial drift over the course of the session were terminated from the study after two such sessions.

Preliminary results have been obtained in experiments exploring the effects of the following properties in creating the Auditory plus Tactile conditions: (1) relative phase of a 250-Hz sinusoidal signal presented simultaneously to both modalities; (2) temporal asynchrony between the auditory and tactile stimulation; and (3) frequency of the auditory stimulus relative to the tactile stimulating frequency.

Experiment 1: Effect of Phase

Performance was measured on four different Auditory Plus Tactile conditions. In all four conditions, the auditory stimulus was a 250-Hz tone, the tactile stimulus was a 250-Hz vibration, and the onset of the auditory and tactile stimuli was simultaneous. The conditions differed in the phase of the tactile stimulus relative to the auditory stimulus, which took on values of 0, 90, 180, and 270 degrees. Presented here are data from 8 subjects with 4-8 sessions per subject.

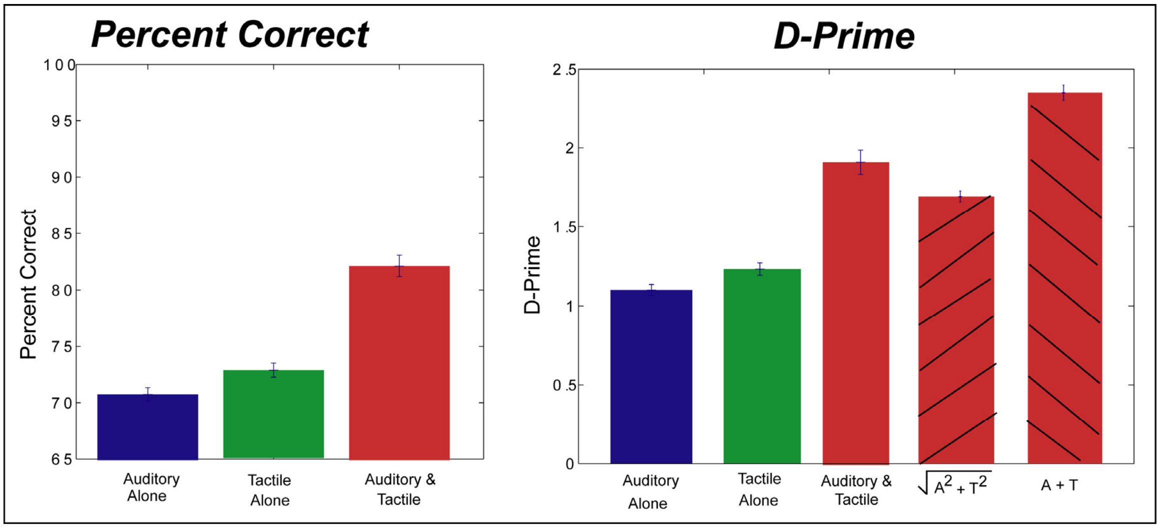

Figure 7. Percent Correct and d-prime scores from 8 subjects, each with 4-8 sessions a piece. Error bars are one SEM.

Results are presented in Fig. 7 for the three baseline conditions of Auditory Alone, Tactile Alone, and Auditory plus Tactile (0 degrees relative phase) in terms of percent-correct scores (left) and d' scores (right). Also included in the right half of the figure are predicted results for Pythagorean summation and direct summation. The results indicate average performance of roughly 70% correct for each of the single-modality conditions compared to roughly 84% correct for the combined condition. The combined-condition performance exceeds the Pythagoreaon prediction, but is slightly smaller than the direct-sum prediction.

The effect of manipulating the phase of the tactile stimulus is shown in Fig. 8 where percent-correct performance is shown on the left and d' scores on the right. The results presented here are a group average of all 8 subjects, and include 2 subjects who do not show a significant difference between their unisensory and multisensory stimuli responses. The results indicate that the combined-condition score falls in the range of roughly 82 to 85% correct regardless of relative phase, suggesting that the envelope of the signals (rather than their fine structure) plays a role in their interaction.

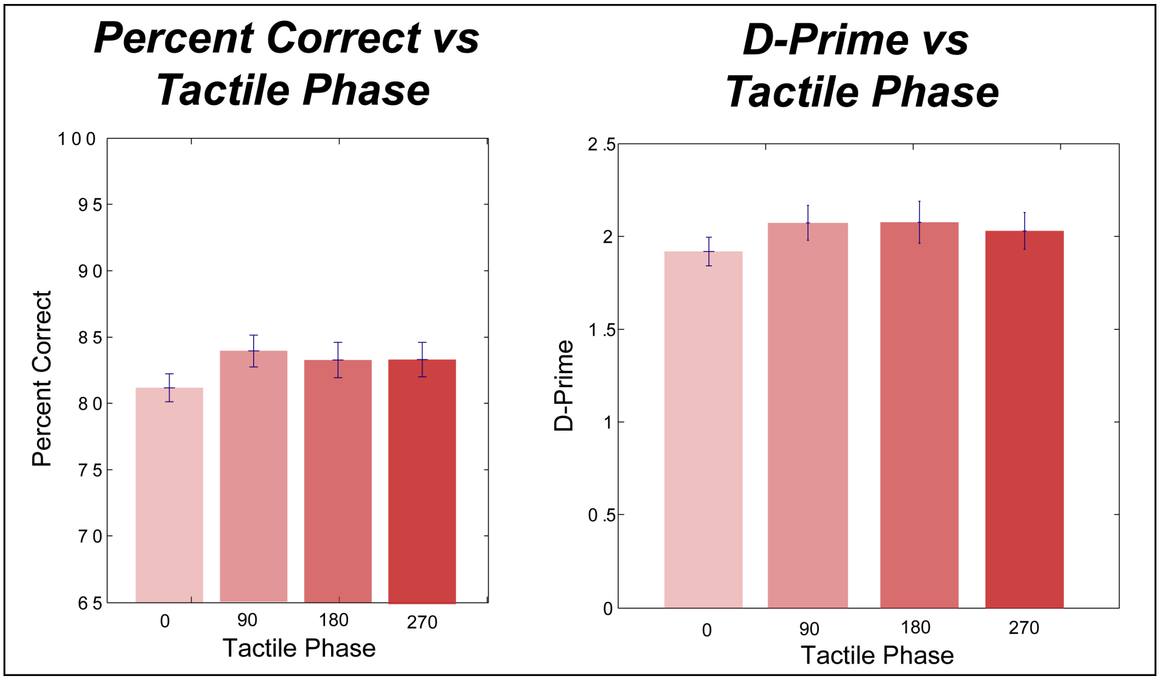

Figure 8. Effect of changing the relative phase between Auditory and Tactile stimuli. 8 Subjects, 4-8 runs per subject. Error bars are one SEM.

Experiment 2: Effect of Temporal Asynchrony

This experiment explored the effect of increasing the time of onset of the second stimulus (either auditory or tactile 250-Hz signal with 0-degree phase) relative to the offset of the first stimulus in a combined-sense presentation (either Auditory followed by Tactile or Tactile followed by Auditory). This inter-stimulus interval (ISI) took on values of 0, 50, 100, 150, 200, and 250 msec. A complete set of preliminary results is currently available on only two subjects. The pattern of results emerging thus far indicates a somewhat different effect of ISI when the tactile stimulus is leading compared to when the auditory stimulus is leading. Specifically, when the tactile stimulus is presented first, performance on the small ISI values (i.e., 0, 50 and 100ms) is similar in magnitude to that obtained in the simultaneous multisensory condition, indicating possible continued integration of stimuli from the two modalities. On the other hand, when the auditory stimulus is presented first, the performance is similar at all values of ISI, and is consistent with the unisensory performance. These preliminary results suggest that the tactile stimulus has a longer time constant for neural persistence compared with the auditory stimulus, consistent with results obtained previously in temporal masking experiments (e.g., Gescheider & Migel, 1995).

Experiment 3: Effect of Frequency of Auditory relative to Tactile Stimulus

In this experiment, different Auditory plus Tactile conditions were created by varying the frequency of the auditory stimulus while holding the he frequency of the tactile stimulus constant at 250 Hz. The onset time and starting phase of the auditory and tactile stimuli were always equivalent. The frequency of the auditory stimulus assumed values of 125, 250, 500, 1000, 1500, and 2000. Results have been obtained thus far on 3 subjects with approximately 2-6 sessions per frequency.

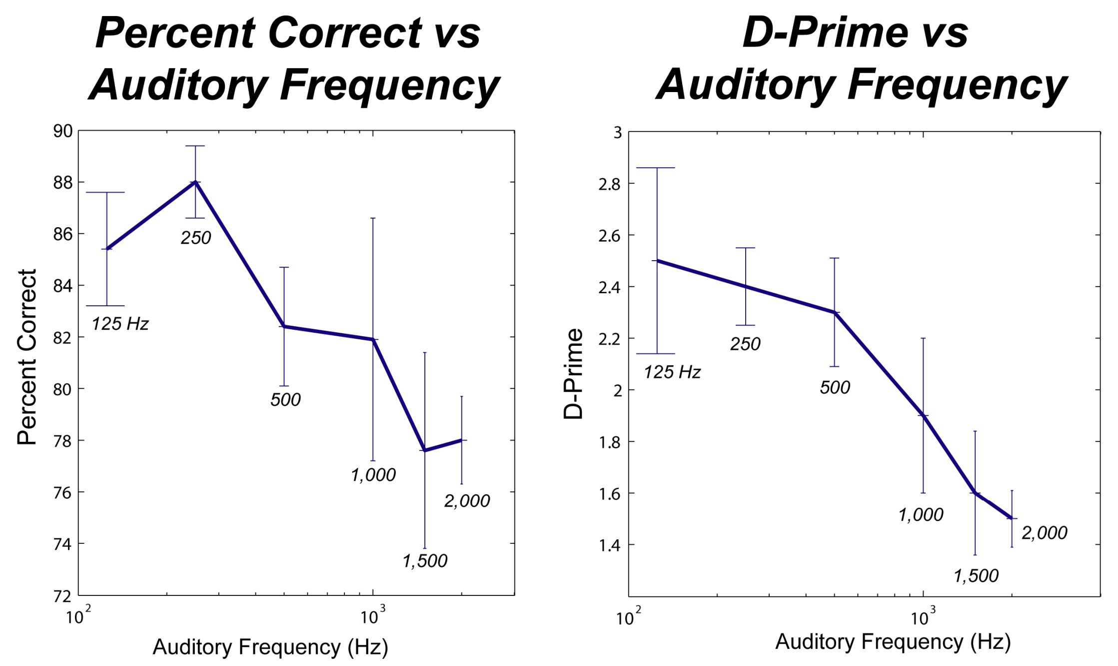

Figure 11. Effect of Changing the auditory frequency while holding the tactile frequency constant at 250 Hz. 3 subjects, 2-6 sessions a piece per frequency. Error bars are one SEM.

Performance on the combined Auditory plus Tactile condition is shown in Fig. 11, where percent-correct score (right side of figure) and d’ (left side of figure) are shown as a function of the frequency of the auditory stimulus. Results averaged over three subjects indicate that performance remains fairly constant at roughly 85% correct for auditory frequency values in the range of 125 to 250 Hz, with a decline in performance first noted at 500 Hz. Above 1000 Hz, performance decreases rapidly with frequency, dropping to roughly 76% correct at 2000 Hz. The frequency effect observed here suggests that optimal integration occurs when the auditory frequency lies within the frequency-response characteristic of the tactile sense (which is most sensitive at 250 Hz and decreases at frequencies above 500 Hz).

Research is continuing in this area both to complete data collection in the preliminary studies described above and to initiate work concerned with auditory-tactile integration effects for other tasks (such as intensity discrimination) and for hearing-impaired as well as normal-hearing subjects. In addition, experiments are being planned to examine the role of temporal masking effects in cross-modal integration.

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Wilson, E.C., Braida, L.D., and Reed, C.M. “Auditory-Tactile Integration: A Perceptual Study,” Ninth International Sensory Aids Conference (ISAC-03), Portland, ME, May 17.

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