Tactile Communication of Speech

RLE Group
Sensory Communication 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., 2004, 2005a, 2005b, 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. Conflicting evidence appears in the literature regarding the tactual-perception abilities of deaf compared to normal-hearing individuals. Previous studies of tactual perception in deaf children have suggested some degree of enhanced performance, relative to normal-hearing controls, on a variety of tasks, including two-point discrimination and line-orientation discrimination. Cranney and Ashton (1982) reported enhanced tactile spatial discrimination in deaf subjects, relative to normal-hearing controls, in various age groups. Levanen and Hamdorf (2001) tested tactile sensitivity in congenitally deaf adults. They found that deaf subjects performed either comparably to or better than normal-hearing controls on two tasks involving tactual detection of changes in vibratory frequency in the range of 160-250 Hz.

Contrary to these reports of enhanced tactual perception in deaf individuals, Heming and Brown (2005) report decreased temporal-resolution ability in congenitally deaf compared to normal-hearing subjects. Heming and Brown (2005) examined the perception of simultaneity of two tactile stimuli in subjects who had been profoundly deaf in both ears from before two years of age. Punctate mechanical stimuli were delivered, in pairs, to the pads of the index and middle fingers of either the left or right hand. Subjects were asked to indicate whether the two stimuli were "perceived simultaneously or non-simultaneously". Thresholds for perceived simultaneity on this task were significantly higher for deaf subjects (84.18 ± 25.34 ms) than for age-matched, normal-hearing controls (21.59 ± 14.99 ms). These results reflect pooled data from the left and right hands, which were similar to one another in both groups. Importantly, all subjects in this study were between 18-32 years of age. By contrast, in a previous study utilizing the same experimental technique, normal-hearing adults over 60 years of age had a mean threshold of 61.40 ms (Brown & Sainsbury, 2000), suggesting that these simultaneity threshold values have strong dependencies that cannot be related simply to auditory experience. Furthermore, the perceptual judgment of "simultaneity" required of subjects in these studies is entirely subjective --- the stimuli are always presented with some amount of asynchrony --- and so differences in judgment criteria cannot be separated from the subjects' actual sensitivity. It should also be noted that normal-hearing subjects in Heming and Brown's study were instructed in English, while profoundly deaf subjects were instructed in ASL. English and ASL are fundamentally different languages, and it is reasonable to consider that semantic factors might contribute to differences in decision criteria adopted by subjects in the two experimental groups. Our experimental paradigm for assessing temporal order resolution requires subjects to discriminate well-defined perceptual attributes, largely avoiding any semantic ambiguities.

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. Three studies conducted with profoundly deaf subjects are reported below: (1) Absolute detection thresholds for sinusoidal vibrations in the range of 2 to 300 Hz; (2) Temporal onset-order discrimination for pairs of sinusoidal vibrations; and (3) Temporal offset-order discrimination for pairs of sinusoidal vibrations. During the current year, results have been obtained on additional subjects and further data analyses have been conducted.

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.

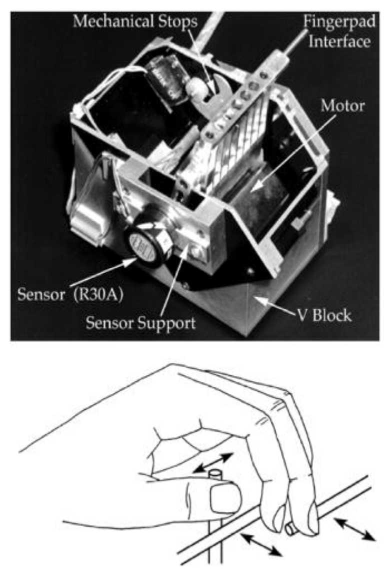

FIG 1: Diagram of Tactuator.

Subjects

Nine adults with profound hearing loss present at birth participated in the experiments. Table 1 describes the subjects in terms of age, sex, and methods of communication used both early in life and currently. The current methods of communication used by the subjects include American Sign Language (ASL) employed exclusively (five 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.

Subject	***Age***	***Sex***	***Communication***		***Onset / Etiology***
			Early	***Current***	
CD1	18	F	Cued English (w/ some signing)	Cued speech	congenital / unknown
CD2	28	F	PSE, then ASL	ASL and English	congenital / unknown (also has mild CP)
CD3	33	M	SEE to pre-teen, then ASL	ASL	congenital / unknown
CD4	42	F	Oral	ASL	congenital / unknown
CD5	42	F	Oral to age 19, then ASL	ASL	congenital / Rubella
CD6	45	M	Total Communication, ASL	ASL	congenital / unknown
CD7	47	M	Oral	ASL	congential (premature birth)
CD8	51	F	Oral to age 18, then Total Communication	ASL and English	congenital / unknown
CD9	56	M	ASL	ASL and Engllish	congenital / hereditary

Table 1: Description of Subjects with Profound Deafness.

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 Figures 2 (deaf subjects) and 3 (normal-hearing subjects) below. Results are provided for the left thumb and left index finger.

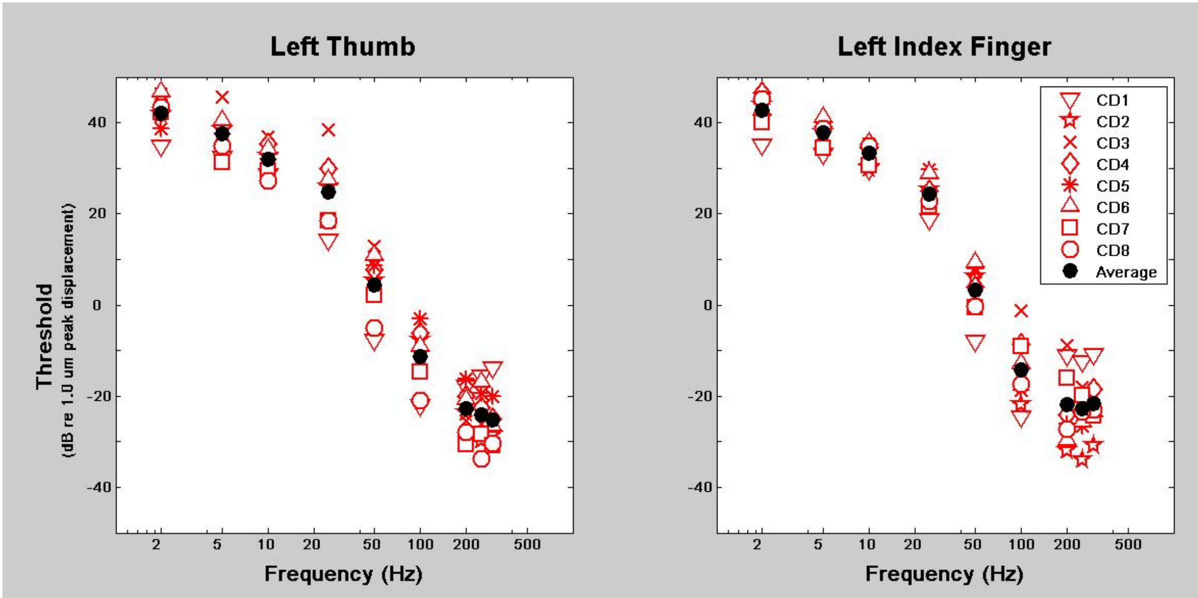

FIG 2: Tactual Detection Thresholds of Profoundly Deaf Subjects

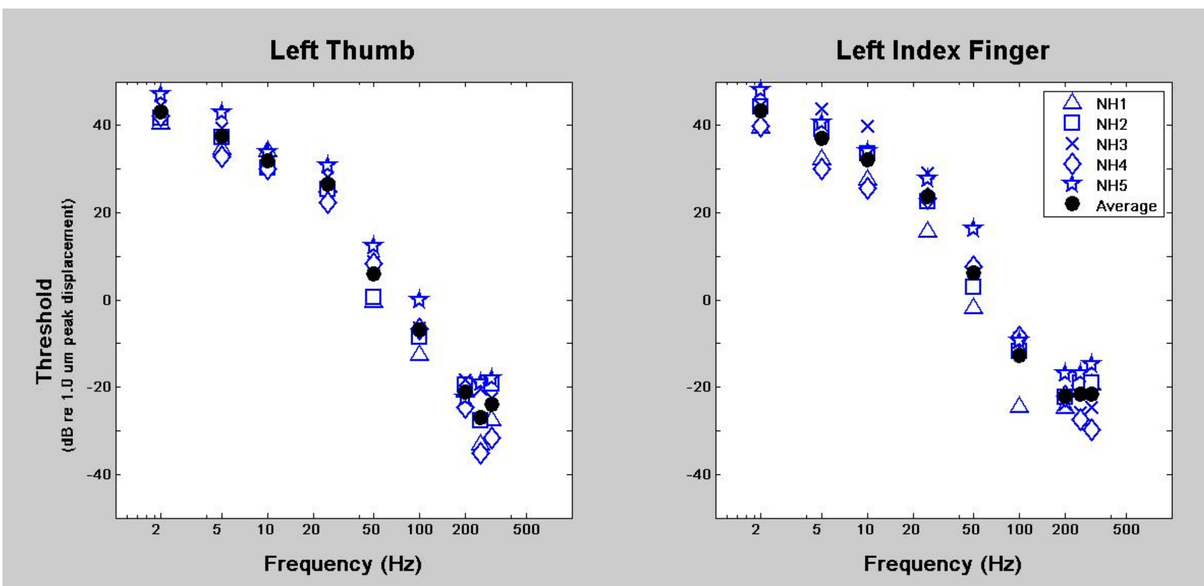

FIG 3: Tactual Detection Thresholds of Normal-Hearing Subjects

These data 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

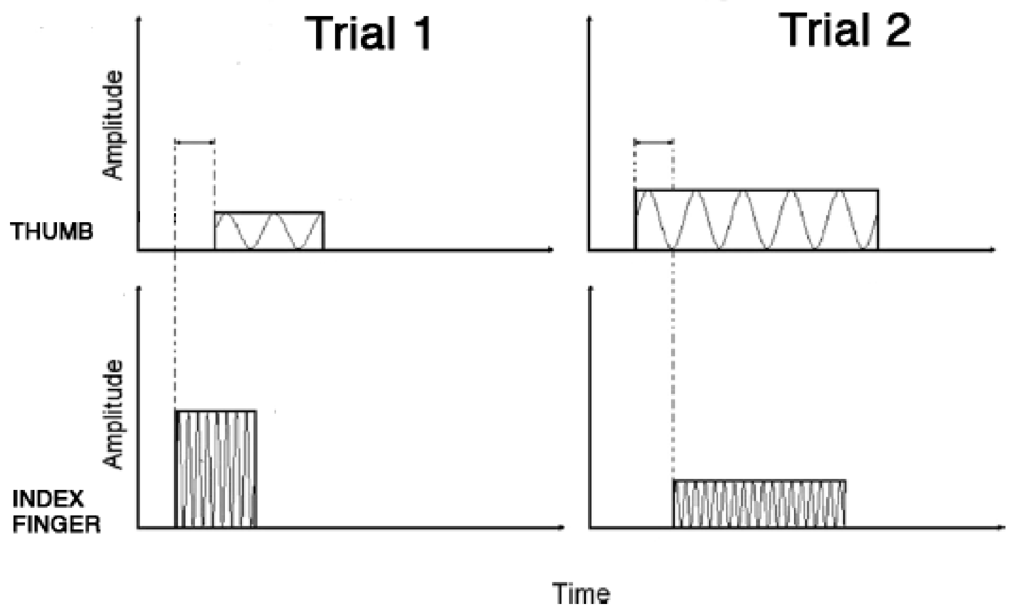

FIG 4: Time Line of Temporal Onset-Order Experimental Paradigm

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 are presented in Fig. 5 for individual deaf (left side of plot) and normal-hearing (right side of plot) subjects. Measured values of sensitivity d' (upper panels) and bias (lower panels) are plotted as a function of |SOA| for each individual subject. Temporal onset-order discrimination thresholds for the normal-hearing subjects ranged from roughly 41 to 44 msec for three of the subjects, while the remaining subject had a much larger threshold of 112 msec. Results for the deaf subjects indicate thresholds in the range of 47 to 82 msec for seven of the nine 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 majority of these subjects' thresholds are within the total range of tactual onset-order thresholds observed in subjects with normal hearing. The mean threshold of the deaf subjects (83 msec ∀41msec s.d.), however, was higher than that of the normal-hearing subjects (60 msec ∀35 msec s.d.). The corresponding bias (β) values are plotted in the bottom panels of Fig, 5; each data point represents the mean bias over all runs of the same |SOA| for a given subject. Positive bias indicates a tendency to respond that the stimulus at the thumb had an earlier onset. For both congenitally deaf and normal-hearing subjects, bias is generally negligible. In no case did |β| exceed 0.5.

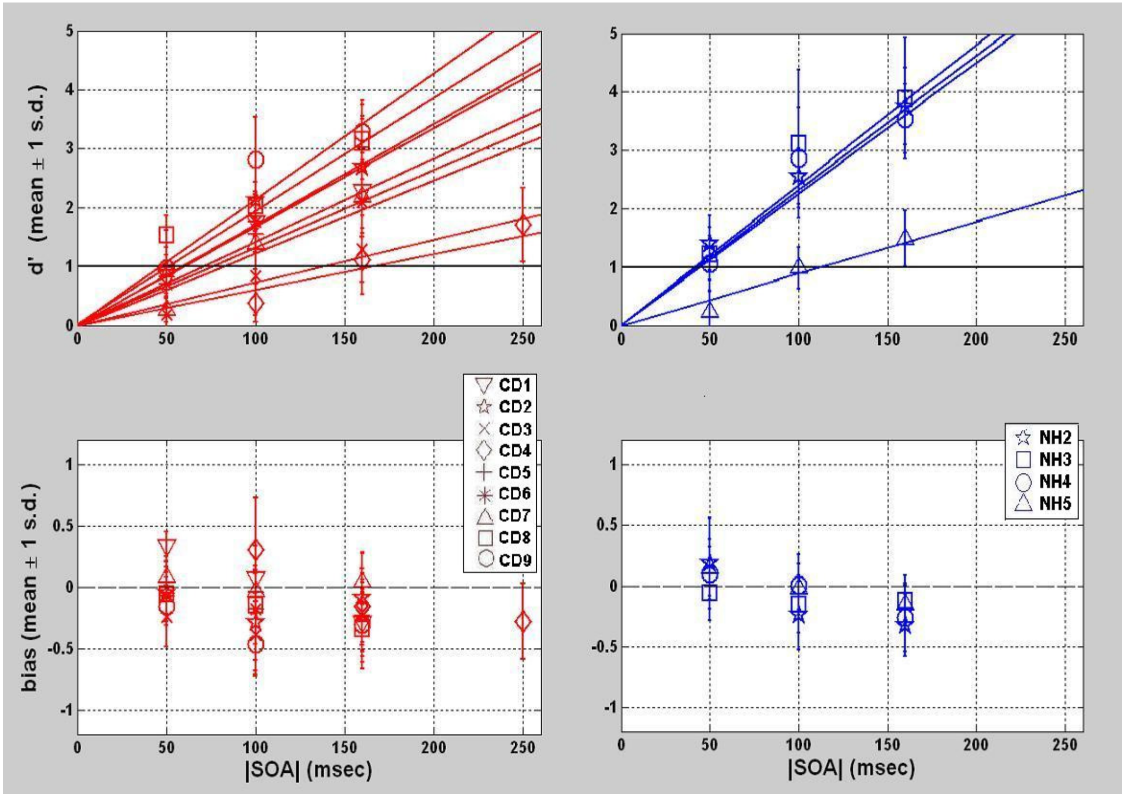

FIG 5: Results of temporal-onset order discrimination for congenitally deaf (left) and normal-hearing (right) subjects. Sensitivity d' (upper panels) and response bias (lower panels) are plotted as a function of |SOA| in msec. Error bars are ∀1 s.d.

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 the offset-order experiment are presented in Fig. 6 for individual deaf (left side of the figure) and normal-hearing subjects (right side). Sensitivity d' (upper panels) and response bias (lower panels) are plotted as a function of |SOFA| Thresholds ranged from 75 ms to 276 ms in congenitally deaf subjects, with a mean threshold of 139 ms (± 66 ms s.d.). In normal-hearing subjects, the thresholds ranged from 65 ms to 221 ms, with a mean of 121 ms (± 63 ms s.d.). The corresponding β values are shown in the bottom panels of Figure 9; each data point indicates the mean bias over all runs of the same |SOFA| for a given subject. Positive bias indicates a tendency to respond that the stimulus at the thumb had a later offset. For congenitally deaf and normal-hearing subjects, bias is minimal overall. In no case did |β| exceed 0.5.

In general, the offset-order thresholds were on the order of twice those of the onset-order thresholds. The range of offset-order 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.

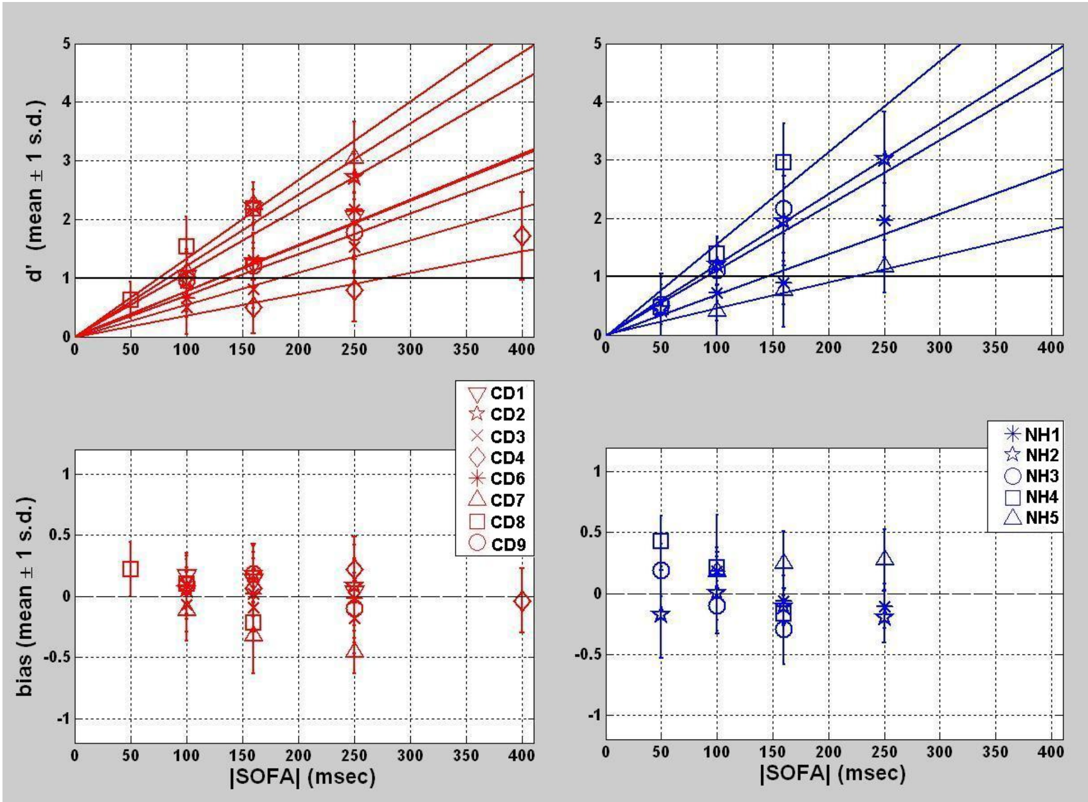

FIG 6: Results of temporal-onset order discrimination for congenitally deaf (left) and normal-hearing (right) subjects. Sensitivity d’ (upper panels) and response bias (lower panels) are plotted as a function of |SOA| in msec. Error bars are ∀1 s.d.

Discussion

In comparing the results of our tactual experiments conducted with subjects with profound deafness to those with normal hearing, it appears that the performance of the two groups of subjects was generally equivalent on two of the three experiments reported here (Experiment 1 and Experiment 3). The results of Experiment 1 (see Figure 2) indicate that detection thresholds of the two groups were comparable at both the thumb and index finger across the frequencies tested. No significant differences were found at any stimulus frequency between the two subject groups or between the two sites of stimulation. The results of Experiment 3 (see Figure 6) indicate comparable ranges and means of temporal-offset order thresholds across subjects in the deaf and normal-hearing groups.

The results of Experiment 2 (see Figure 5) do, however, indicate possible differences in performance between deaf and normal-hearing subjects on the temporal onset-order discrimination task. A significant difference in mean onset-order thresholds was observed between the two groups. Results obtained on normal-hearing listeners in the present study and in previous work performed in our laboratory (Yuan et al., 2005a) indicate that 8 out of 9 normal-hearing subjects had thresholds in the range of 18-44 msec (with one outlier value of 112 msec). The range of onset-order thresholds observed in the deaf subjects was typically 47-82 msec (with two outlier points of 138 and 165 msec). These results are generally in agreement with the results of Heming and Brown (2005) showing larger thresholds in deaf compared to normal-hearing subjects.

Because the normal-hearing listener with the highest temporal onset-order threshold was also the oldest subject in this group (at age 58), we might consider the possibility that his elevated SOA threshold is associated with age. Several previous studies have demonstrated altered tactual temporal processing among older individuals (e.g., Van Doren et al., 1990; Gescheider et al., 1992). Elevated thresholds for judgments of simultaneity were previously observed in adults over 60 years of age (Brown & Sainsbury, 2000), suggesting a possible correlation between age and temporal resolution. The relation between age and measures of temporal onset and offset order discrimination is shown in Figure 7. There appears to be little if any correlation between age and performance on these tasks. In fact, the two oldest deaf subjects in this study, CD8 (age 51) and CD9 (age 56), were found to have the two lowest SOA thresholds in the deaf group (51 and 47 ms, respectively).

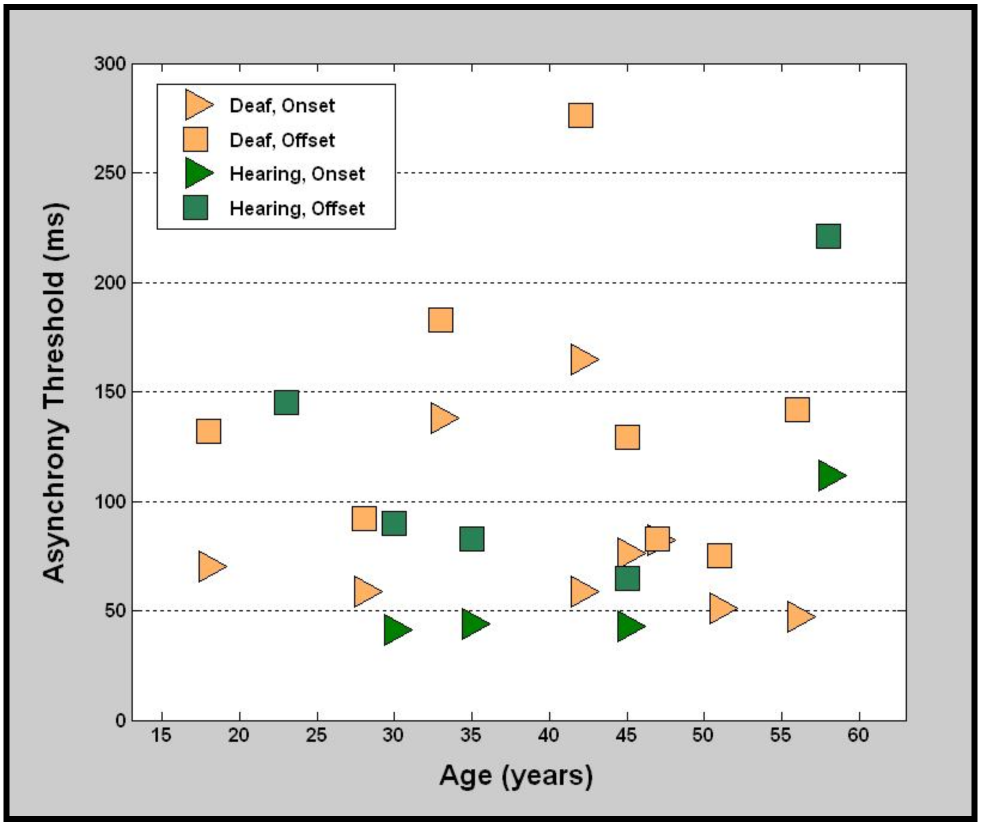

FIG 7: Temporal onset- and offset-order thresholds in msec plotted as a function of age for individual deaf and normal-hearing subjects.

The perceptual processes involved in performing temporal onset and offset-order discrimination appear to be related in that a correlation was observed between individual-subject thresholds on the two tasks. In Figure 8, the tactual offset-order threshold is plotted as a function of the onset-order threshold for each individual subject from the deaf and normal-hearing groups who participated in both components of the study. Some correlation is apparent showing a trend for an increase in offset-order threshold with the magnitude of the onset-order threshold.

Despite the increased tactual temporal onset-order thresholds observed for profoundly deaf compared to normal-hearing subjects, our results suggest that most of the deaf subjects who participated in this study should have sufficient temporal resolution to take advantage of tactually-presented temporal cues that have been proposed as a supplement to lipreading (Yuan et al., 2005b). Future research will examine the performance of deaf subjects on a speech task in which tactual cues are presented to provide information about voicing, which is poorly received through lipreading alone.

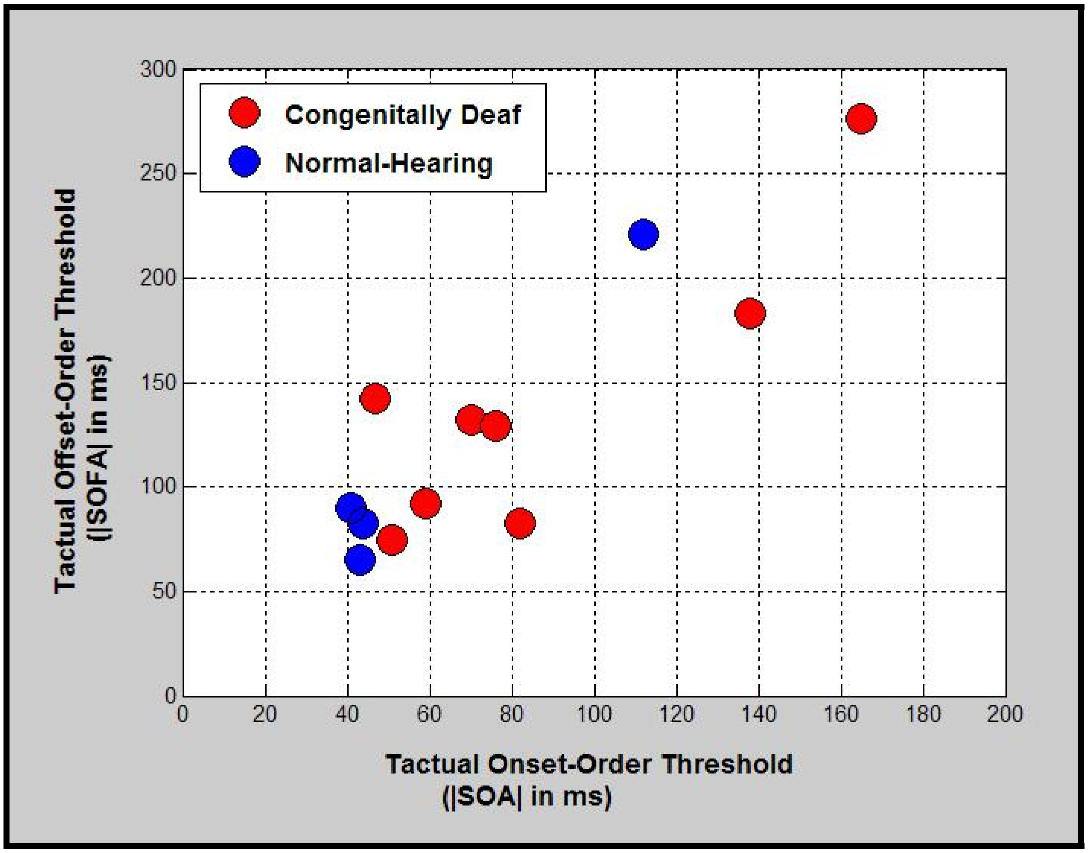

FIG 8: For individual deaf and normal-hearing subjects, the tactual offset-order threshold (in ms) is plotted as a function of tactual onset-order threshold (in ms).

Perceptual Studies of the Integration of Auditory and Tactile Stimulation

We have continued our research exploring perceptual interactions between the sense of hearing and touch (Wilson et al., 2007, 2008a, 2008b). This research is motivated by recent results in the anatomical and physiological literature that demonstrate significant interactions between these two sensory systems. For example, in the brainstem, the trigeminal nerve sends somatosensory input to the cochlear nucleus of the guinea pig (Shore & Zhou, 2006), while in the thalamus, somatosensory projections are sent to non-primary areas of the auditory cortex of the macaque monkey (Hackett et al., 2007). Projections within the cortex have been found from the secondary somatosensory cortex to the primary auditory cortex of the marmoset monkey (Cappe & Barone, 2005) as well as to non-primary auditory cortical areas of the macaque monkey (Smiley et al., 2007). Additionally, recent physiological studies in humans (using non-invasive imaging) as well as in non-human primates (using electrophysiology) suggest that the auditory cortex is an active multisensory area, responding to somatosensory input alone (Schroeder et al., 2001; Foxe et al., 2002; Fu et al., 2003; Caetano and Jousmaki, 2005; Schurmann et al., 2006) as well as to combined auditory and tactile stimuli in a manner that is different from responses to auditory-only stimulation (Kayser et al., 2005). While the previous studies showed auditory and tactile responses in the non-primary auditory cortex, Lakatos et al. (2007) have shown that the primary auditory cortex also responds to tactile stimulation.

Although there is increasing anatomical and physiological evidence that tactile and auditory stimuli interact in the perceptual process, there is less direct perceptual evidence for this interaction. Several recent perceptual studies have examined the effects of tactile stimulation on the perceived loudness of auditory stimuli (Schurmann et al., 2004; Gillmeister and Eiler, 2007; and Yarrow et al., 2008) and shown that, given certain temporal, spectral, and intensive properties, a tactile stimulus can lead to enhanced loudness of an auditory stimulus. 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’ (and %-Correct) as a measure of detectability. Our hypothesis (derived from a general model proposed by Green, 1958) states that if the auditory and tactile systems do integrate into a common neural pathway, then the detectability of the two sensory stimuli presented simultaneously will be significantly greater than the detectability of the individual sensory stimuli. Specifically, if the stimuli are judged independently of one another, the resulting d’ will be close to 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.

Experiments have been completed examining the effects of phase and stimulus onset-asynchrony on the perceptual interactions between auditory pure tones and vibrotactile sinusoidal signals. In addition, we report preliminary results from studies exploring the effect of frequency of stimulation on these perceptual interactions.

Basic Experimental Design and Methods

Subjects: The experiments reported here were conducted with normal-hearing subjects (age range of 18 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 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.

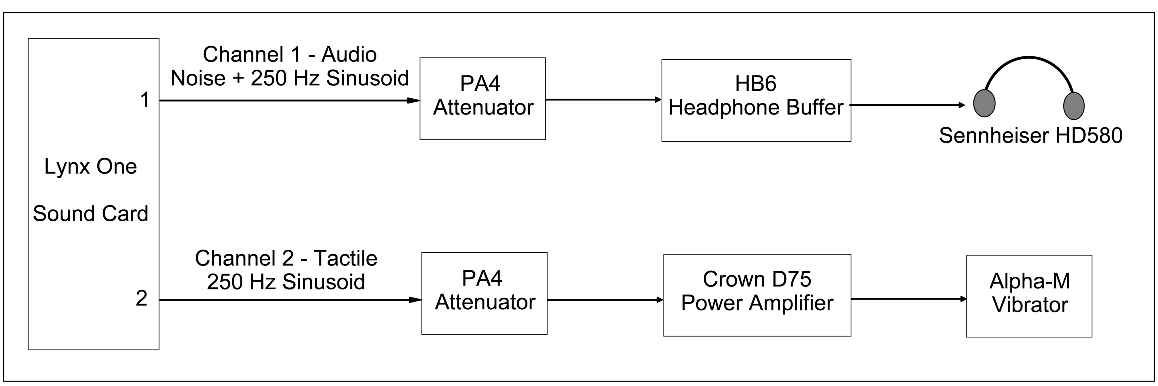

FIG 9: Block Diagram for Delivery of Auditory and Tactile Stimuli.

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

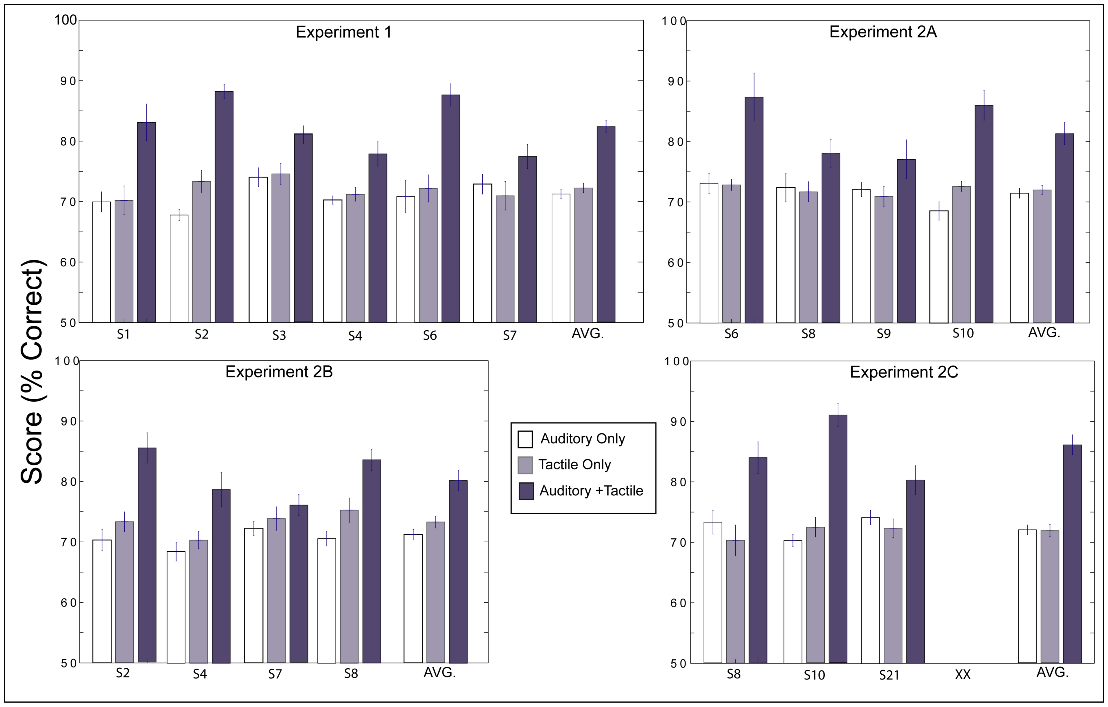

FIG 10: Summary of individual-subject results of baseline experimental conditions from four experiments: Expt. 1, 2A, 2B, and 2C.

correct-answer feedback. Measurements of d' were obtained from individual 75-trial runs conducted for Auditory (A) Alone, Tactile (T) Alone, and Auditory plus Tactile (A+T) conditions (with simultaneous in-phase onset of auditory and tactile stimuli). 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.

Experimental Conditions: Two experiments have been completed examining auditory-tactile interactions for combined A+T conditions as a function of relative phase of a 250-Hz sinusoidal signal presented simultaneously to both modalities (Experiment 1); and as a function of stimulus onset asynchrony between the auditory pure tone and the vibrotactile sinusoidal signal (Experiments 2A, 2B, and 2C). In addition, preliminary results are reported concerning the frequency of the auditory stimulus relative to the tactile stimulating frequency (Experiment 3).

Baseline Results: Results from the Baseline experiment are shown for individual subjects in Experiments 1 and 2 (2A, 2B, and 2C) in the four panels of Figure 10. The mean percent-correct scores (with error bars representing ∀1 s.e.m.) are plotted for the three conditions of A-alone, T-alone, and A+T for individual subjects within each experiment. Averages across subjects are provided at the right of each panel. These data show a substantial increase in the percent-correct score when the auditory and tactile stimuli are presented simultaneously compared with the A-alone and T-alone conditions. Averaged over subjects, the results indicate that scores for the two unimodal conditions were similar (at roughly 70%-correct) and significantly lower than the scores in the A+T condition (which ranged from roughly 80 to 84%-correct).

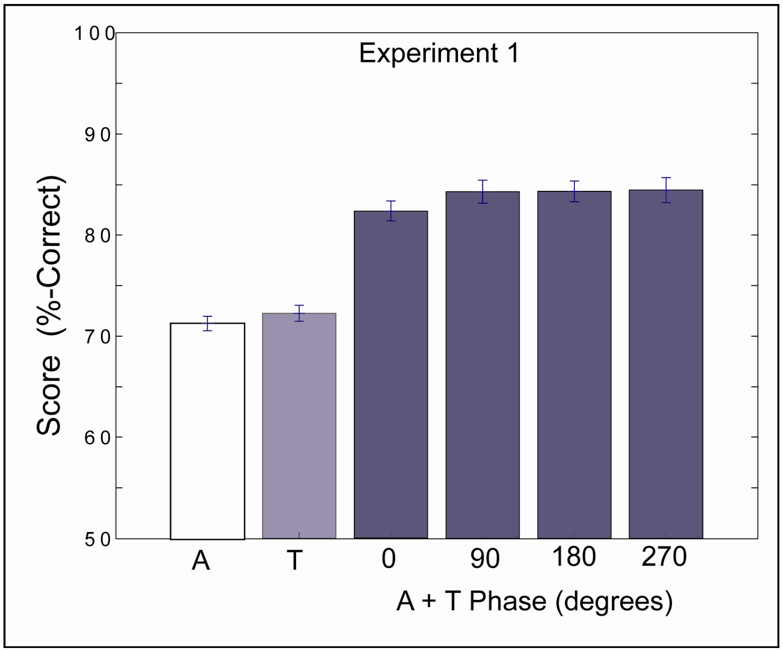

FIG 11: Results of Experiment 1 averaged over subjects, showing performance on Auditory Alone, Tactile Alone, and four Auditory plus Tactile conditions as a function of phase (in degrees).

Experiment 1: Effects of Phase

This experiment examined the effects of the relative phases of the auditory and tactile stimuli on performance in the combined A+T conditions. These results are summarized in Figure 11. Percent-correct scores averaged over data from six subjects are shown for each of the six experimental conditions: A-alone, T-alone, and combined A+T with four different values of the starting phase of the tactual stimulus relative to that of the auditory stimulus (0, 90, 180, and 270 degrees). Average scores on the unimodal conditions A-alone and T-alone averaged roughly 70%-correct and were significantly lower than scores on each of the combined A+T conditions (which ranged from 83 to 85%-correct across the four combined A+T conditions). No significant differences were observed among the four A+T conditions. These results suggest that the interactions observed here are likely to occur at an envelope, rather than fine-structure, level.

Experiment 2: Effects of Stimulus-Onset Asynchrony

This experiment explored the effect of Stimulus-Onset Asynchrony (SOA), defined as SOA=Onset Time $_{\text{Tactile}}$ - Onset Time $_{\text{Auditory}}$. By this definition, the SOA is positive when the auditory stimulus precedes the tactile stimulus, 0 when the two stimuli have simultaneous onsets, and negative when the tactile stimulus precedes the auditory stimulus. The starting phase of the auditory and tactile signals was always 0 degrees throughout the conditions of Experiment 2.

In Experiment 2A, the auditory stimulus preceded the tactile stimulus with six values of SOA in the range of 0 to 750 msec. Results (shown in upper left panel of Figure 12) indicate average A-alone and T-alone scores of 70% and 74%-correct, respectively. For the combined A+T conditions, average scores ranged from 82% (SOA = 600 msec) to 75% (SOA=750 msec). Only one combined condition (SOA=0) produced a score that was significantly greater than that observed in the unimodal conditions. Thus, no significant perceptual interactions were observed when there was no overlap between the auditory and tactual stimuli.

In Experiments 2B and 2C, the tactile stimulus preceded the auditory stimulus. In Experiment 2B, seven values of SOA in the range of -500 to -750 msec were studied. Experiment 2C included these seven values plus a condition of -250 msec which examined the effect of temporal overlap between the two stimuli. In Experiment 2B (Figure 12, upper right panel), average scores for the A-alone and T-alone conditions averaged 70% and 73%-correct, respectively. For the combined A+T conditions, the average scores ranged from 82% (SOA = -600 msec) to 75%-correct (SOA= -750 msec). Scores on the combined A+T conditions with SOA values of 0,-500, -550, and -600 msec were significantly greater than scores on the A- and T-alone conditions. Scores on the combined A+T conditions with SOA values of -650, -700, and -750 msec, on the other hand, were not significantly different from A-alone and T-alone scores. The results of Experiment 2C (Figure 12, lower left panel) indicated that the scores in the combined A+T conditions for every value of SOA were significantly higher than sores on the A-alone and T-alone conditions. Thus, the summation effect of a preceding tactile stimulus appears to persist beyond the offset of the stimulus itself.

A composite summary across the subsets of Experiment 2 is shown in the lower right panel of Figure 12, where it is clear that different effects are observed when the auditory precedes the tactile stimulus (positive values of SOA) than for the case when the tactile precedes the auditory stimulus (negative values of SOA). When the tactile stimulus is presented first, performance on all combined A+T conditions is similar in magnitude to that obtained in the simultaneous multisensory condition (SOA=0), indicating possible continued integration of stimuli from the two modalities. On the other hand, when the auditory stimulus is presented first, scores for all cases where SOA>0 were equivalent to unimodal performance. These 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).

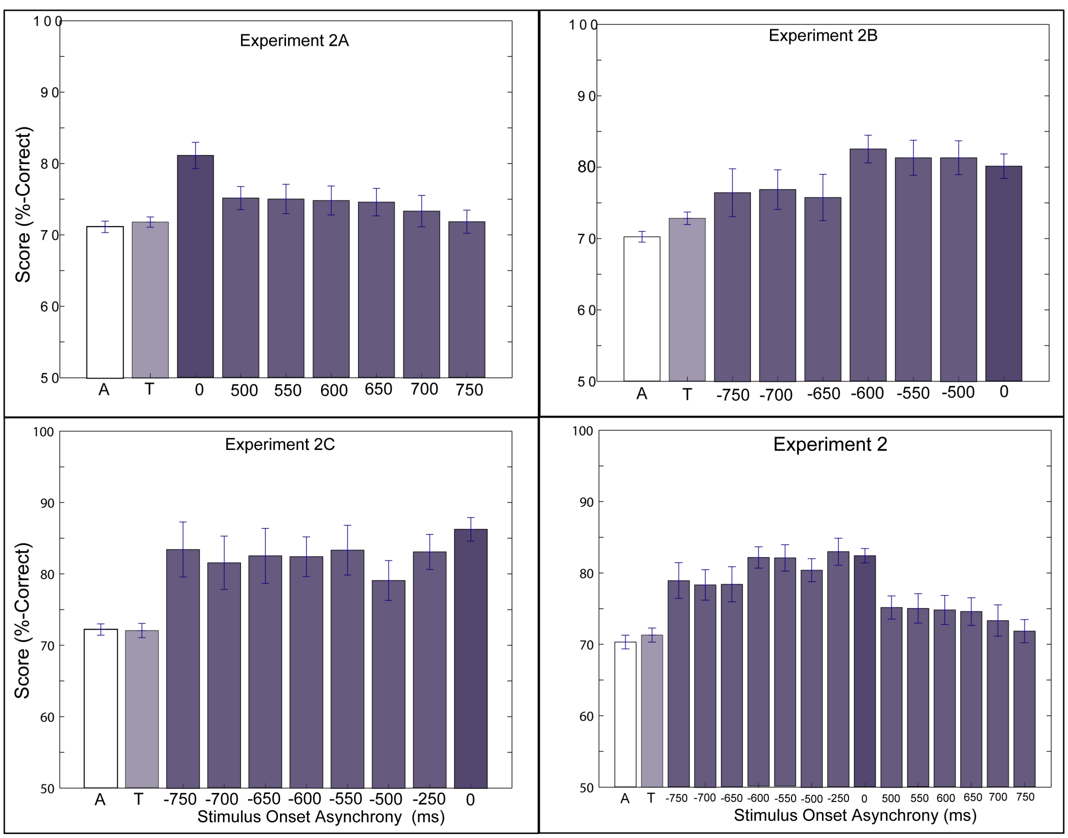

FIG 12: Summary of results across subjects in Expts. 2A, 2B, 2C, and composite data.

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

Preliminary data have been obtained on three topics concerned with the role of spectral properties in the perceptual interactions between auditory and tactual stimulation. In all three studies, the stimuli are 500 msec in duration, have SOA=0, and are presented with the same starting phase of 0 degrees.

In Experiment 3A, the frequency of the auditory tone was always 250 Hz, while A+T conditions were created using different vibratory frequency values of 50, 125, 250, and 400 Hz. For all frequency values of the vibrotactile stimulus, the percent-correct scores in the A+T conditions (77 to 87%-correct) were significantly greater than the unimodal scores (which averaged roughly 70%-correct).

In Experiment 3B, the frequency of the vibrotactile stimulus was always 250 Hz and different A+T conditions were created using auditory pure-tone frequencies of 125, 250, 500, 1000, and 2000 Hz. For auditory frequencies 125, 250, 500, and 2000 Hz, scores in the combined A+T conditions were significantly greater than scores for the A-alone and T-alone conditions.

In Experiment 3C, the effects of frequency were examined for cases where the frequency of stimulation was the same in both modalities and took on values of 50, 125, 250, and 400 Hz. For all auditory and tactile frequency pairs, the percent-correct scores for the combined A+T conditions were significantly higher than scores for the A-alone and T-alone conditions.

Taken together, the results of Experiment 3 can be interpreted in terms of filtering in that greater summation is observed when the auditory and tactile frequencies are close to one another. The largest scores on the combined A+T conditions are always observed when stimulating

frequencies are equal in the two modalities. When different frequencies are employed across modalities, the combined-condition scores are never greater than when the same frequency is used in both modalities. For equal-frequency conditions, scores were somewhat lower at 50 Hz than at the three higher frequencies studied. One interpretation of these results is that a 50-Hz tactile stimulus elicits different percepts than the three higher frequencies corresponding to the engagement of different components of the tactual sensory system. Non-Pacinian receptors operate in the frequency range of <1 Hz to approximately 50 Hz, whereas Pacinian receptors are active in the range above 40 Hz. It is possible that the differences seen in the combined A+T scores result from differences in the sensory systems engaged.

Future Work

Ongoing research is being conducted on several topics in this area. First, the experimental data reported here are being compared to the predictions of two distinct models of auditory-tactile integration (models of linear and Pythagorean summation). Second, we are quantifying auditory-tactile interaction effects as a function of signal-to-noise ratio by measuring different points along the psychometric functions for detection of the auditory and tactile signals. Third, studies are being performed to examine the perceived loudness of various combinations of auditory and tactile stimuli presented at supra-threshold levels. Finally, in addition to examining such effects in subjects with normal hearing, we also plan to investigate auditory-tactile interactions in persons with hearing impairment.

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