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 over the past year has focused on two projects: (1) perceptual interactions of near-threshold stimuli in the tactual and auditory sensory modalities, and (2) development of a new system for vibrotactile transduction of speech for use in speechreading aids for the deaf.

Current Studies

Perceptual Studies of the Integration of Auditory and Tactile Stimulation

Our previous research on auditory-tactile perceptual interaction provides evidence for the perceptual integration of auditory (A) and tactile (T) sinusoidal stimuli presented at near-threshold levels of presentation in both modalities (Wilson et al., 2007a, 2007b, 2007c, 2009). In Wilson et al. (2009), we demonstrated that certain combinations of auditory and tactile signals result in a significant increase in detectability above the levels when either A or T stimuli were presented in isolation. This is not due to changes in response bias (e.g., Yarrow et al., 2008), as indicated by a detection theory analysis. Specifically, for 500-msec, 250-Hz signals we have shown significant increases in detectability that are independent of relative auditory-tactile phase when the auditory and tactile stimuli are presented simultaneously, suggesting that the envelopes, and not the fine structure, of the two signals interact in a facilitative manner. Additionally, we have also shown asymmetric changes in detectability when the two signals are presented with temporal asynchrony: when the auditory signal is presented first, detectability is not significantly greater than in A-alone or T-alone conditions, but when the tactile signal is presented first, detectability is significantly greater for almost all values of SOA employed. These differences are consistent with the neural mechanics of auditory-on-auditory masking (e.g., Plack and Oxenham, 1997) and tactile-on-tactile masking (e.g., Gescheider and Migel, 1995).

Our results were compared with three models of integration: Optimal Signal Channel Model (OSCM), Pythogorean Sum Model (PSM), and Alegebraic Sum Model (ASM). While it is not always possible to differentiate among the models on the basis of a single experimental outcome, the models sort themselves out if one combines results across sessions and/or observers. If one assumes that all observers use a single model in all experiments, then the PSM gives a better fit to the data than the OSM or the ASM. This result suggests that the two independent pathways (A and T) are integrated only after being processed first by its own sensory system.

Over the past year, we have continued this research through a study of the effects of frequency of stimulation within the A and T modalities on perceptual integration (Wilson et al., 2008a, 2008b). Three experiments were conducted in which (1) the frequency of the auditory stimulus was varied while holding the tactile frequency constant ($A_V T_C$); (2) the frequency of the tactile signal was varied while holding the auditory frequency constant ($T_V A_C$); and (3) the frequencies of both the auditory and tactile stimuli were equal to one another while being systematically varied (($A_V T_V$). Our hypothesis states that if the auditory and tactile systems do integrate into a common neural pathway when the frequencies are equal, then the detectability of the combined A+T stimuli will decrease as the frequency separation between the auditory and tactile stimulus increases. Measurements of d' (and %-Correct) were obtained for auditory-alone, tactile-alone, and combined auditory-tactile presentations. The observed performance in the combined condition was then compared to predictions of multi-modal performance derived from observed measures of detectability within each of the two separate sensory modalities.

Basic Experimental Design and Methods

Subjects: Eight subjects (age range of 18 to 45 years) participated in these experiments. They were screened for normal hearing using an audiometric-threshold criterion of 20 dB HL or better at the seven octave frequencies in the range of 125 to 8000 Hz.

Stimuli and Block Diagram: The auditory stimuli were pure tones presented bilaterally over headphones in a background of white noise whose level was 50 dB SPL. The tactile stimuli were sinusoidal vibrations at 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. In A+T conditions, the auditory and tactile signals were presented with a starting phase of 0 degrees and equal onset and offset times. A basic block diagram for the presentation of the auditory and tactile signals is provided in Figure 1, showing an example of 250-Hz sinusoids for both A and T.

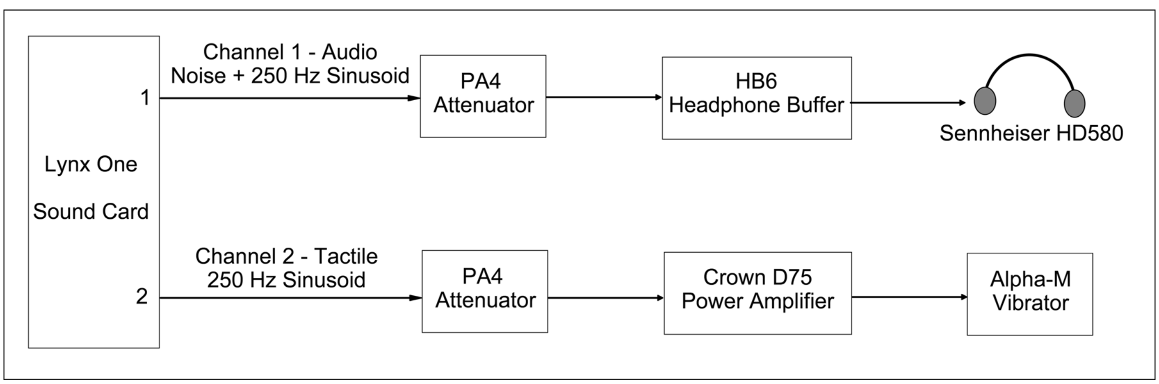

FIG 1: Block Diagram for Delivery of Auditory and Tactile Stimuli (demonstrating use of 250-Hz sinusoid in both modalities).

Test 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. Absolute-detection thresholds for the signals in each of the two unisensory modalities were first approximated using an adaptive 3-interval, 3-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) with the goal of obtaining performance in the range of 63-77%-correct performance. If the Auditory-Alone or Tactile-alone score fell outside this range, then the stimulus level was adjusted accordingly until this criterion was met. Once satisfactory A and T levels were obtained, performance was measured on the combined A+T conditions to be tested in a given experimental session using the fixed-level procedure. Measurements of %-correct and d' were obtained from individual 75-trial runs conducted for Auditory (A) Alone, Tactile (T) Alone, and Auditory plus Tactile (A+T) conditions (always with simultaneous in-phase onset of auditory and tactile stimuli with 500-ms durations).

Signal Levels Established from Single-Modality Threshold Tests:

<u>Levels for Auditory-Alone Conditions.</u> The mean signal levels in dB SPL established for performance in the range of 63 to 77%-Correct for pure tones in 50-dB SPL broadband noise are shown in the upper panel of Fig. 2. Frequencies measured in these experiments included 50, 125, 250, 400, 500, 1000 and 2000 Hz. Mean levels of the tones in dB SPL are plotted for each individual subject in each of the tone conditions for the three auditory-tactile experiments. Each data point depicted in the plot is based on an average of at least 4 and as many as 11 measurements per frequency in the fixed-level 2-I, 2-AFC procedure (each of which yielded performance in the range of 63%- to 77%-Correct). Averaged across subjects and experiments, the mean threshold levels for each of the masked pure tones were 50 Hz: 45.75 dB SPL; 125 Hz: 26.2 dB SPL; 250 Hz: 24 dB SPL; 400 Hz: 26.1 dB SPL; 500 Hz: 24.3 dB SPL; 1000 Hz: 25.4 dB SPL; 2000 Hz: 27.1 dB SPL. Within a given subject, tonal levels for all frequencies tested were highly stable for measurements made within a given experiment and across experiments. Values of ± 2 SEM (accounting for 96% of the measurements) ranged from 0.0 to 1.92 (one subject at 5.4) dB across subjects and experiments. These results are consistent with those obtained in previous studies of tonal detection in broadband noise (Hawkins and Stevens, 1950).

<u>Levels for Tactile-Alone Conditions</u>. The mean signal levels established for performance in the range of 63%- to 77%-Correct for a sinusoidal vibration to the left middle fingertip are shown in the lower panel of Fig. 2. Frequencies used in these experiments were 50, 125, 250 and 400 Hz. All threshold measurements were obtained in the presence of a binaural 50 dB SPL broadband noise presented over headphones. Signal levels are plotted in dB re: 1 μm peak displacement for individual subjects who participated in each of the three experiments. Each mean level is based on 4 to 20 measurements per frequency across individual subjects and experiments. Average signal levels employed for each frequency were 50 Hz: 0.14 dB re: 1 μm peak; 125 Hz: -24 dB re: 1 μm peak ; 250 Hz: -24 dB re: 1 μm peak ; 400 Hz: -11.3 dB re: 1 μm peak. Within-subject values of ± 2 SEM (accounting for 96% of the measurements) ranged from 0 to 2.2 dB across subjects and experiments.

The signal levels employed for the tactile-alone conditions are generally consistent with previous results in the literature for vibrotactile thresholds at these frequencies obtained using vibrators with contactor areas similar to that of the device employed in the present study (roughly 80 mm^2). Investigators using contactor areas in the range of 28 to 150 mm^2 have reported mean thresholds in the range of -21 to -32 dB re: 1 μm peak for 250 Hz stimuli (Gescheider et al., 2002; Verillo et al., 1983; Lamore et al., 1986; Rabinowitz et al., 1986; Verrillo, 1963). The threshold data for the other three frequencies tested were also consistent with previous measurements using similar contactor areas and signal durations (Verrillo, 1963).

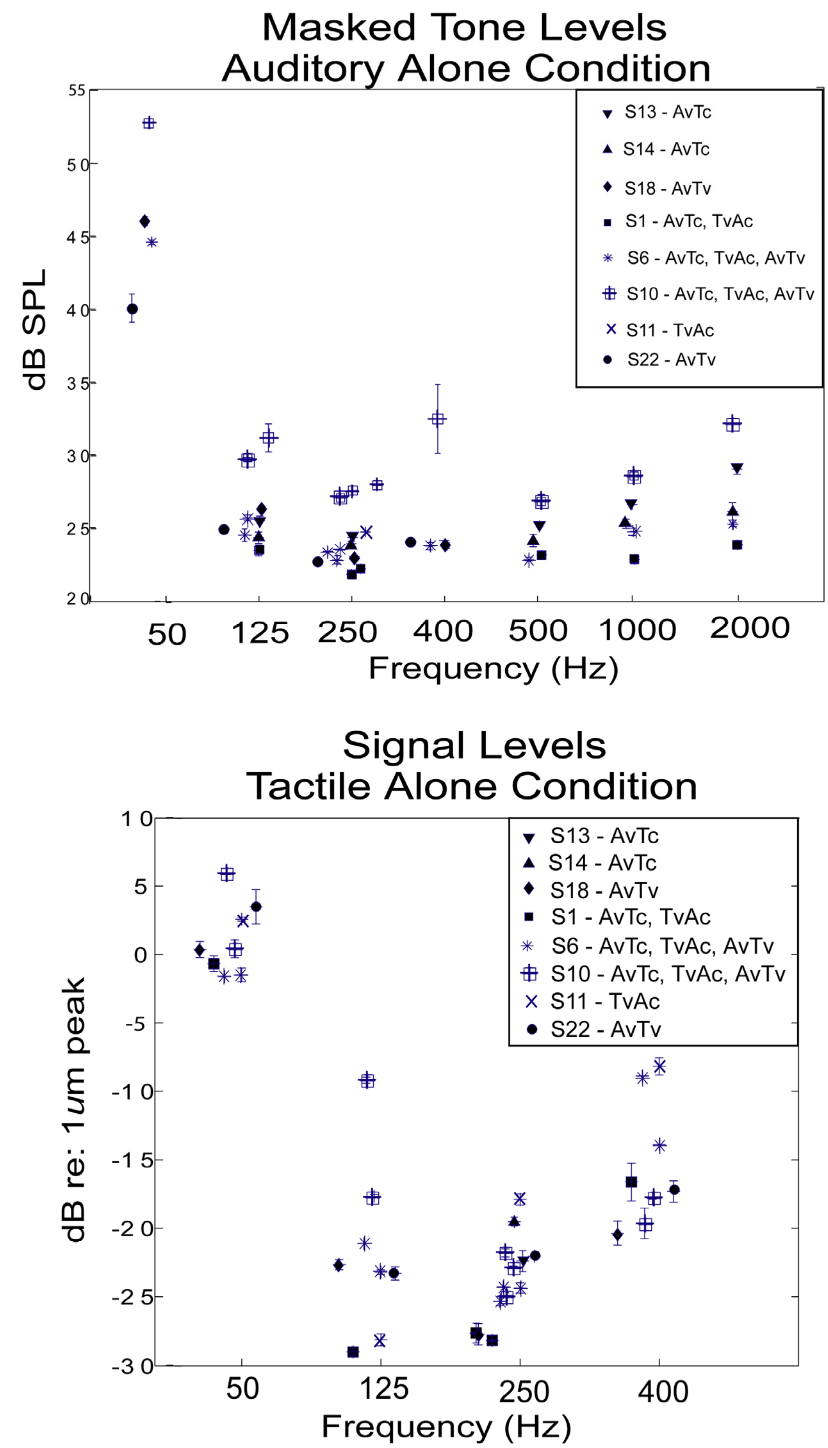

FIG 2: Single-modality signal levels employed for individual subjects. Auditory levels (top panel) are for detection of pure tones in 50 dB SPL broadband noise. Tactile levels (bottom panel) are for detection of sinusoidal vibrations presented to the left middle fingertip. Error bars are 2 SEM.

Baseline Condition: All subjects were tested on a Baseline Condition in which A and T were both set to 250 Hz. Results from the Baseline Condition are shown for individual subjects in Experiments 1, 2, and 3 in the four panels of Figure 1. The mean percent-correct scores (with error bars representing ∀1 SEM) 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 within each experiment, the results indicate that scores for the two unimodal conditions were similar (at roughly 70-73%-correct) and significantly lower than the scores in the A+T condition (which ranged roughly 87%-correct). These baseline results are consistent with those reported for an identical condition tested by Wilson et al. (2009).

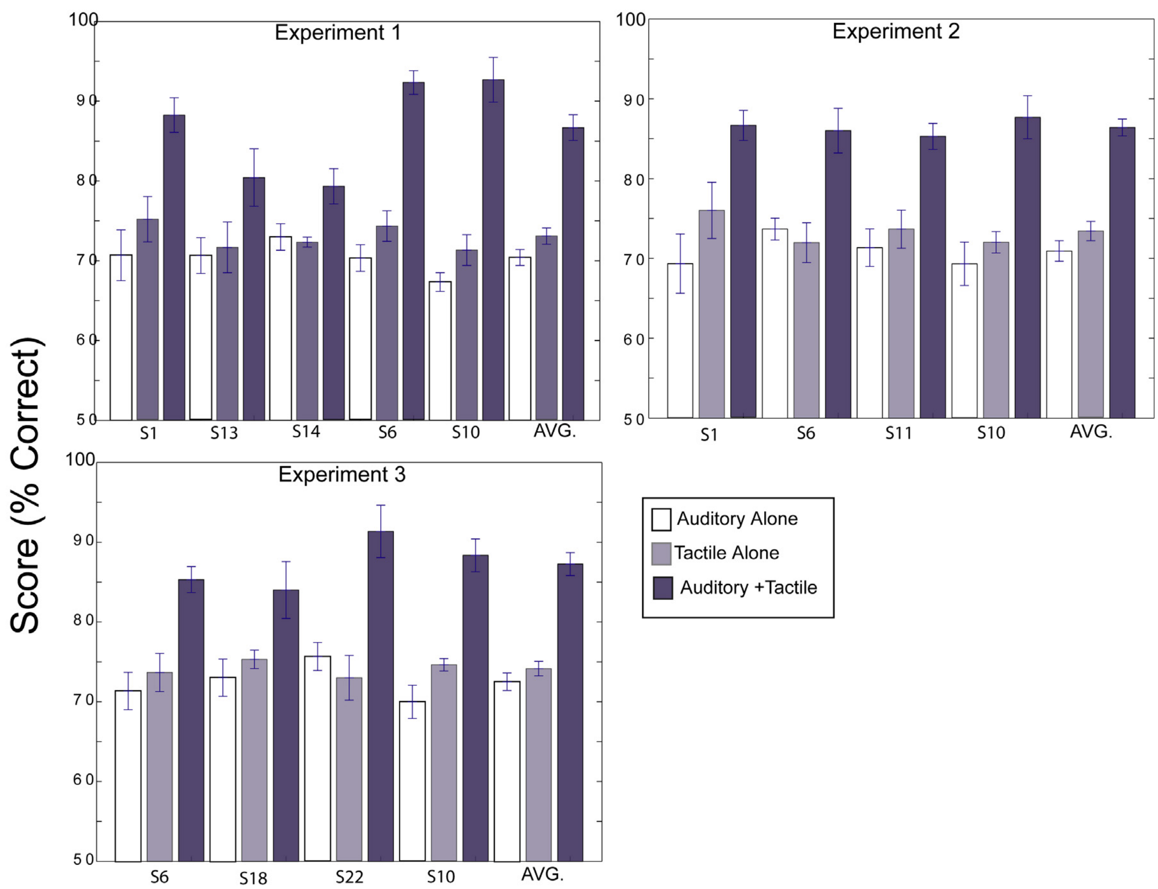

FIG 3: Summary of individual-subject results for baseline experimental condition (A=T=250 Hz).

Experiment 1: In Experiment 1 (A_VT_C), the frequency of the tactile vibratory stimulus was always 250 Hz, while the auditory signal took on five different frequency values of 125, 250, 500, 1000, and 2000 Hz. For each of the five resulting A+T conditions, performance was measured for A-alone and T-alone and then for the combined A+T stimulus. This experiment was conducted on five subjects, each of whom completed six repetitions of each condition. The results of Experiment 1 are shown in Fig. 4 (upper left panel). Percent-correct scores averaged across 5 subjects and 6 repetitions per condition are shown for each of the five experimental conditions: A-alone, T-alone, and combined A+T with five different values for the frequency of the auditory stimulus (125, 250, 500, 1000 and 2000 Hz) while the frequency of the tactile stimulus remained constant at 250 Hz. Average scores for T-alone were 71.8 %-Correct and the A-alone scores ranged from 69.3 %-Correct (1000 Hz) to 71.6 %-Correct (125 Hz). Variability in terms of ±2 SEM was small and ranged from 1.2 (Tactile 250 Hz) to 2.2 (Auditory 1000 Hz) percentage points across all single modality conditions. Average scores for the A+T conditions changed as a function of auditory stimulus frequency, with auditory frequency = 250 Hz having the highest score at 86.7%-Correct while other auditory frequencies had lower scores: 125 Hz = 81.8%-Correct; 500 Hz: 81.1%-Correct; 1000 Hz = 76.4 %-Correct; and 2000 Hz = 80.2%-Correct. Variability was small, with ±2 SEM values ranging from 5.2 (A = 1000 Hz) to 3.0 (A = 125 Hz) percentage points.

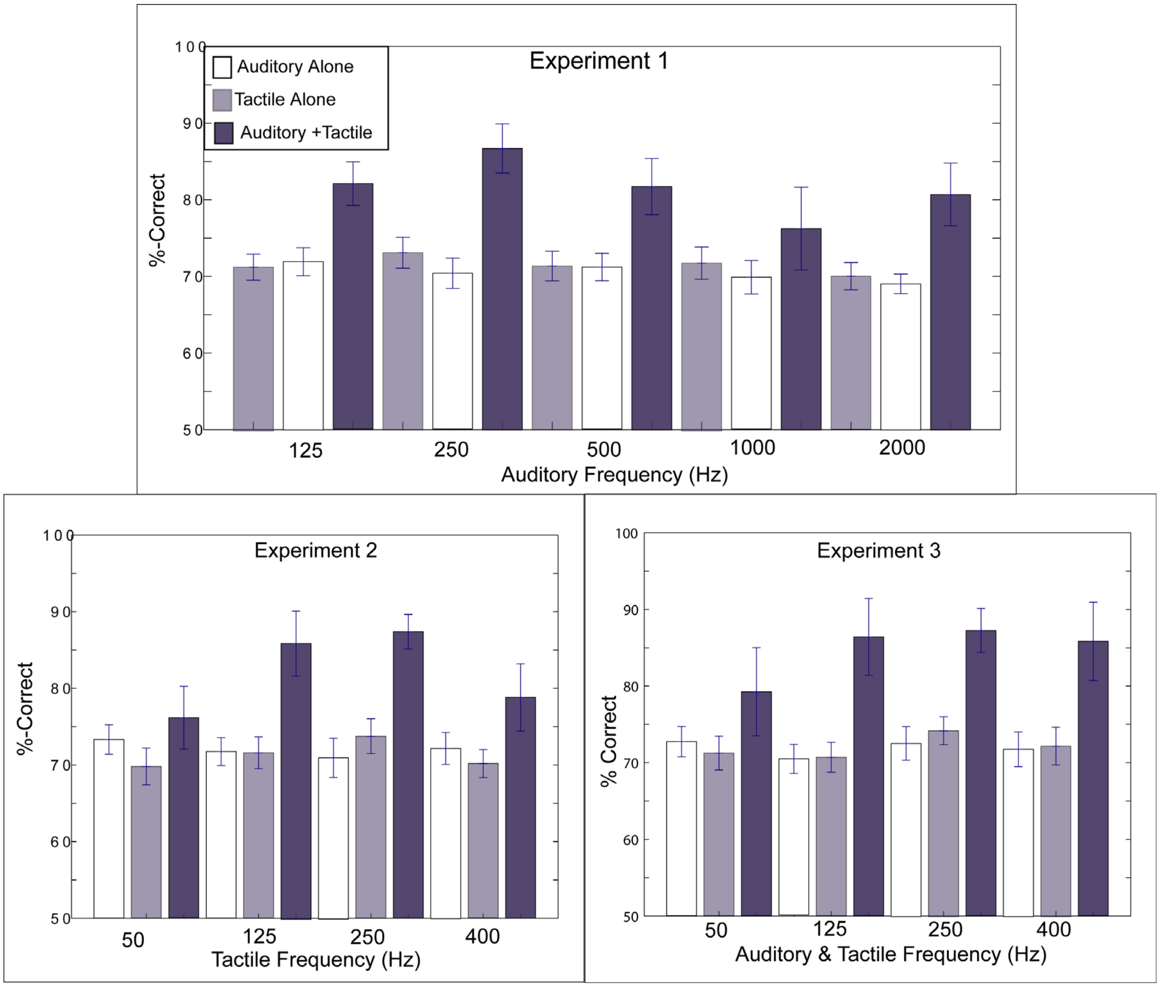

FIG. 4: Results of Experiment 1 ((A_VT_C): Tactile Frequency Constant at 250 Hz and Auditory Frequency Varying), Experiment 2 ((T_VA_C): Auditory Frequency Constant at 250 Hz and Tactile Frequency Varying) and Experiment 3 ((A_VT_V): Auditory Frequency = Tactile Frequency). Mean %-correct sores are plotted for Auditory Alone (unfilled bars), Tactile Alone (shaded bars), and Auditory Plus Tactile (dark bars) conditions. Error bars are plus/minus two SEM.

Experiment 2: In Experiment 2 (T_VA_C), the frequency of the auditory stimulus was held constant at 250 Hz, while the frequency of the tactile vibratory stimulus took on four values of 50, 100, 250, and 400 Hz. For each of the four resulting A+T conditions, performance was measured for A-alone and T-alone and then for the combined A+T stimulus. This experiment was conducted on four subjects, each of whom completed four repetitions of each condition. The results of this experiment are shown in Fig. 4 (top right panel). Average scores for A-alone were 71.3 %-Correct and the T-alone scores ranged from 69.8 %-Correct (50 Hz) to 73.4 %-Correct (250 Hz). Variability in terms of ±2 SEM was small and ranged from 1.6 (Auditory 250 Hz) to 2.4 (Tactile 250 Hz) percentage points across all single modality conditions. Average scores for the A+T conditions changed as a function of tactile stimulus frequency, with tactile frequency = 250 Hz having the highest score at 86.4 %-Correct while other tactile frequencies had lower scores: 50 Hz = 76.2 %-Correct; 125 Hz = 85.8 %-Correct; 400 Hz = 78.8 %-Correct. Variability was small, with ±2 SEM values ranging from 2.1 (T = 250 Hz) to 4.4 (T = 400 Hz) percentage points.

Experiment 3: In Experiment 3 ($A_V T_V$), the frequency of the auditory and tactile signals was always identical and took on four values of 50, 125, 250, and 400 Hz. This experiment was conducted on four subjects, each of whom completed four repetitions of each condition. The results of this experiment are shown in the bottom left panel of Fig. 4. Average scores for A-alone ranged from 70.5 %-Correct (125 Hz) to 72.5 %-Correct (50 and 250 Hz) and the T-alone scores ranged from 70.6 %-Correct (50 Hz) to 74.1 %-Correct (250 Hz). Variability in terms of ± 2 SEM was small and ranged from 1.9 (Auditory 50 Hz) to 2.4 (Tactile 50 Hz) percentage points across all single modality conditions. Average scores for the A+T conditions changed as a function of auditory and tactile stimulus frequency, with auditory-tactile frequencies = 125, 250 and 400 Hz having the highest scores at 86.4, 87.25 and 85.8 %-Correct, respectively while the 50 Hz auditory-tactile frequency had the lowest average score at 78.3 %-Correct. Variability was smallest on the 250 Hz condition, with a ± 2 SEM value of 2.8 percentage points, while other frequencies ranged from 5 (125 Hz) to 5.6 (50 Hz) percentage points.

Summary

The highest scores on the combined A+T conditions were observed in cases where 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. Preliminary results of fits of these data to different models of auditory-tactile integration indicate that an Algebraic Sum Model provides a better fit to the data when frequencies of stimulation are close together, and that a Pythogorean Sum Model provides a better fit when frequencies are farther apart. 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, 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. Second, studies are currently underway 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.

Development of Vibrotactile Speech-Reception Aids for the Deaf

Work over the past year (Moallem, 2009) has extended a previously developed tactile display of consonant voicing information, which effectively supports discrimination of isolated CVC nonsense syllables (Yuan et al., 2005b). In its original form, the transduction scheme involves separation of an acoustic speech signal into two channels. One channel is high-pass filtered with a cutoff frequency of 3000 Hz, and the other channel is low-pass filtered with a cutoff frequency of 350 Hz. The envelopes of these signals are extracted by rectification and low-pass filtering at 25 Hz, and then used to modulate sinusoidal carrier signals driving two tactual stimulators. The envelope of the low-pass filtered signal modulates the amplitude of a 50-Hz vibrotactile signal delivered to the user's left thumb and the envelope of the high-pass filtered signal modulates the amplitude of a 250-Hz vibrotactile signal delivered to the left index finger. The combined inputs allow the trained user to decipher acoustic cues for consonant voicing, which are conveyed in the relative onset and offset timings of the two vibrotactile inputs (Yuan et al., 2004a, 2004b, 2005b; Yuan and Reed, 2005).

A major drawback of this approach is that it discards low frequency modulations inherent to speech, most notably the fundamental frequency (F0) of voicing. The output of the low- frequency channel of the current system reflects voicing, but provides no information about the F0 contour, and does not enable the user to distinguish voicing from other, aperiodic speech and environmental sounds. Variations in F0 contribute substantially to prosodic structure, phonetic discrimination, and stream segregation, all of which take on increasing significance as the acoustic signal-to-noise ratio decreases. In particular, F0 facilitates speech discrimination in the presence of multiple talkers or speech-like noise (Brokx and Nooteboom, 1982; Bird and Darwin, 1998; Assmann, 1999). Prosodic cues, consisting largely of variations in voicing frequency and amplitude, contribute substantially to speech comprehension even at high SNRs, but they are often exaggerated further as background noise levels increase. In fact, much information can be communicated through stresses and intonation patterns alone, or in combination with highly degraded or modified phonetic cues (Blesser, 1969).

During voicing, F0 is present across the frequency spectrum — not only is it reflected in the harmonic content of the signal, but the amplitude of each harmonic component is modulated at the F0 frequency. The ability of the auditory system to follow variations in voicing F0 is robust to low-frequency noise or the removal of low-frequency content from a speech signal. The spectrum-wide contribution of voicing to an incoming acoustic signal can be identified on the basis of F0 amplitude modulations. Moreover, the frequencies over which these modulations vary fall within the range of tactual sensitivity.

With these considerations in mind, we have implemented a vibrotactile transduction scheme that conveys the time-varying amplitude of each frequency-filtered audio signal, while retaining voicing F0 and other low-frequency modulations and preserving the cross-channel timing information required for consonant voicing discriminations. A flowchart illustrating the proposed speech transduction strategy is shown in Fig. 5. The digitized speech signal is split into three streams, each of which is band-pass filtered (4th order Butterworth) with one of three sets of cutoff frequencies: 50-500 Hz, 800-2200 Hz, and 3000-8000 Hz.

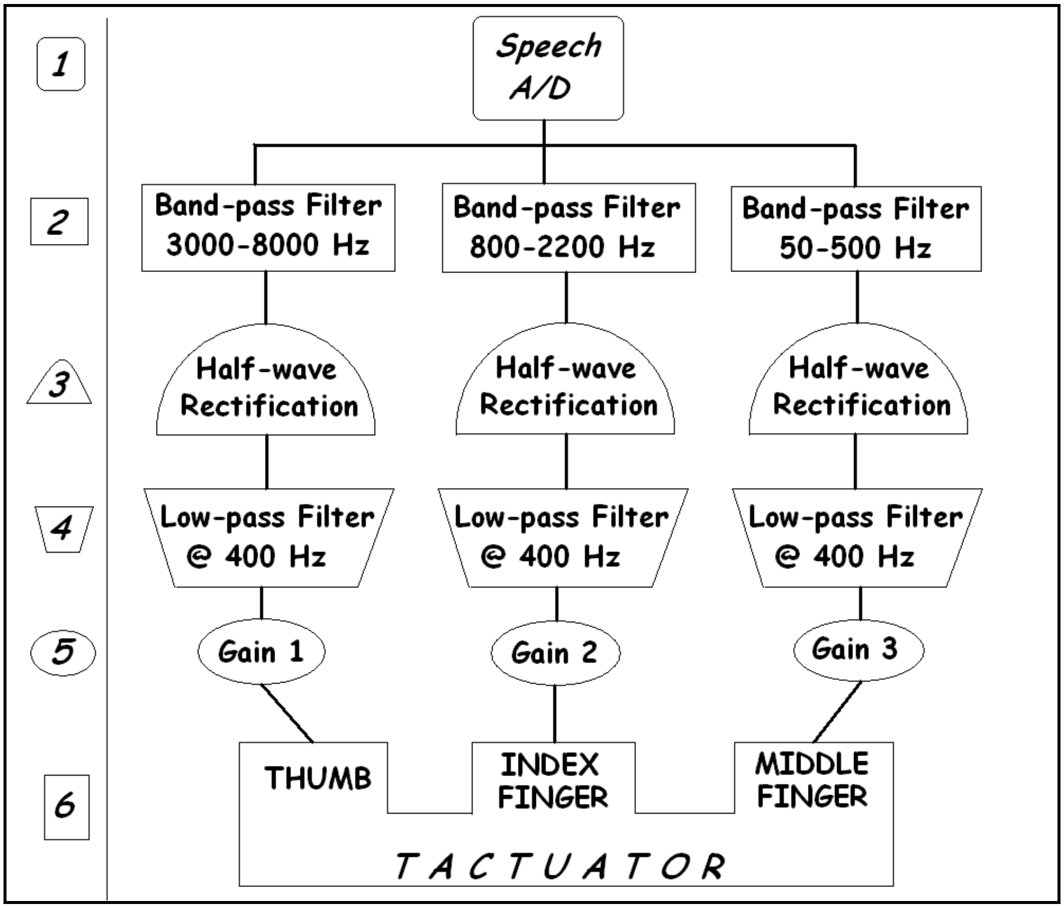

FIG 5: A flowchart illustration of the proposed vibrotactile speech transduction scheme. Stage 1: Speech signal from microphone (or other audio source) enters soundcard as low-latency (ASIO) input for analog-to-digital conversion. Stage 2: Input signal is split into three separate streams, each of which is band-pass filtered to attenuate signal content outside of the specified frequency band. Stage 3: Each signal is half-wave rectified, one effect of which is to introduce low-frequency content that directly reflects its time-varying amplitude. Stage 4: All three signals are low-pass filtered at 400 Hz, in order to restrict frequency content primarily to the range of tactual sensitivity. Stage 5: The gain is adjusted on each channel independently, in order to equalize the maximum output amplitudes. Stage 6: The three output waveforms serve as control signals for the three vibrotactile stimulators of the Tactuator device, each of which is configured to contact a different finger of the subject's left hand.

Figure 6 shows the frequency response characteristics of these filters. The filtered signals are then half-wave rectified — i.e., either positive or negative values of the digitized waveforms on each channel are changed to zero. Regardless of the frequency content of each signal prior to rectification, the spectrum of each half-wave rectified signal reflects all low frequency amplitude variations as actual low-frequency content. Thus, F0 modulations in all regions of the speech signal spectrum are now reflected within the frequency range of tactual sensitivity. Following rectification, all three signals are low-pass filtered at 400 Hz, primarily to reduce high frequency content, which is not tactually salient, but is well within the range of audible frequencies. Finally, the amplitudes of the three signals are adjusted to comparable levels (in general, higher frequency bands require more gain).

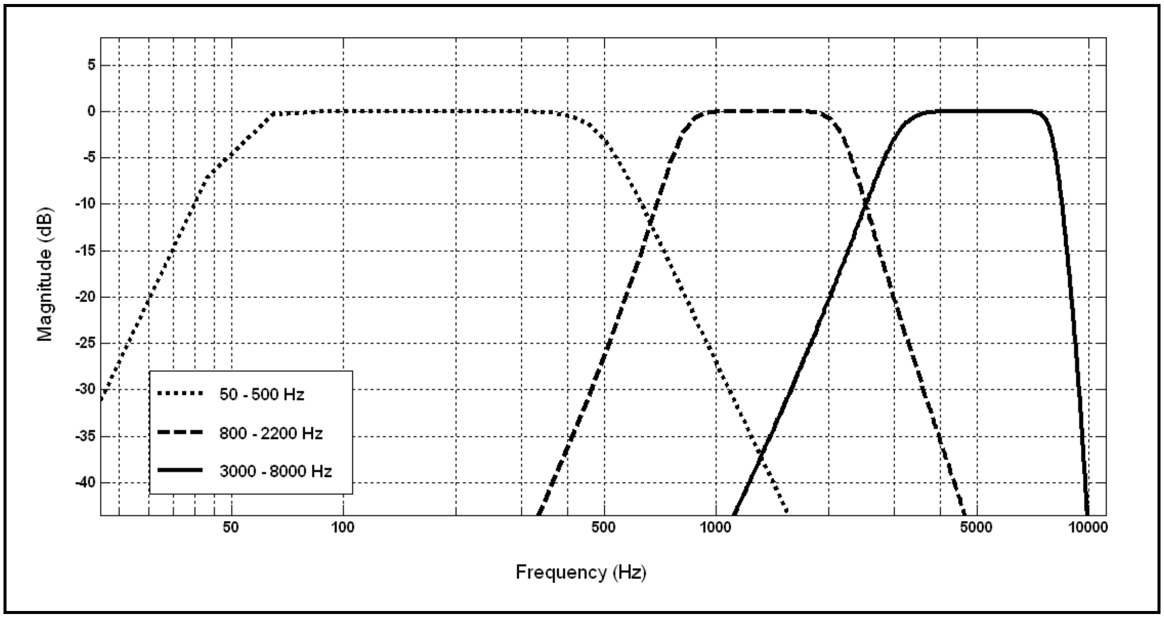

FIG 6: Frequency response plots of fourth-order Butterworth filters used in the first stage of the proposed tactual transduction scheme (legend indicates low and high cutoff frequencies).

Figure 7 presents the three-channel vibrotactile waveforms corresponding to segments of the vowels /i/, /u/, and /a/. The fundamental frequency of voicing is clearly reflected in the time waveforms of all three channels. The high-, mid-, and low-frequency band signals are used to drive vibrotactile stimulators at the left thumb, index finger, and middle finger, respectively. The peaks in corresponding F0 periods reveal a relative time shift of about 1-3 ms among the three waveforms, depending on the phase characteristics of each filter and the frequency content of the original speech signal.

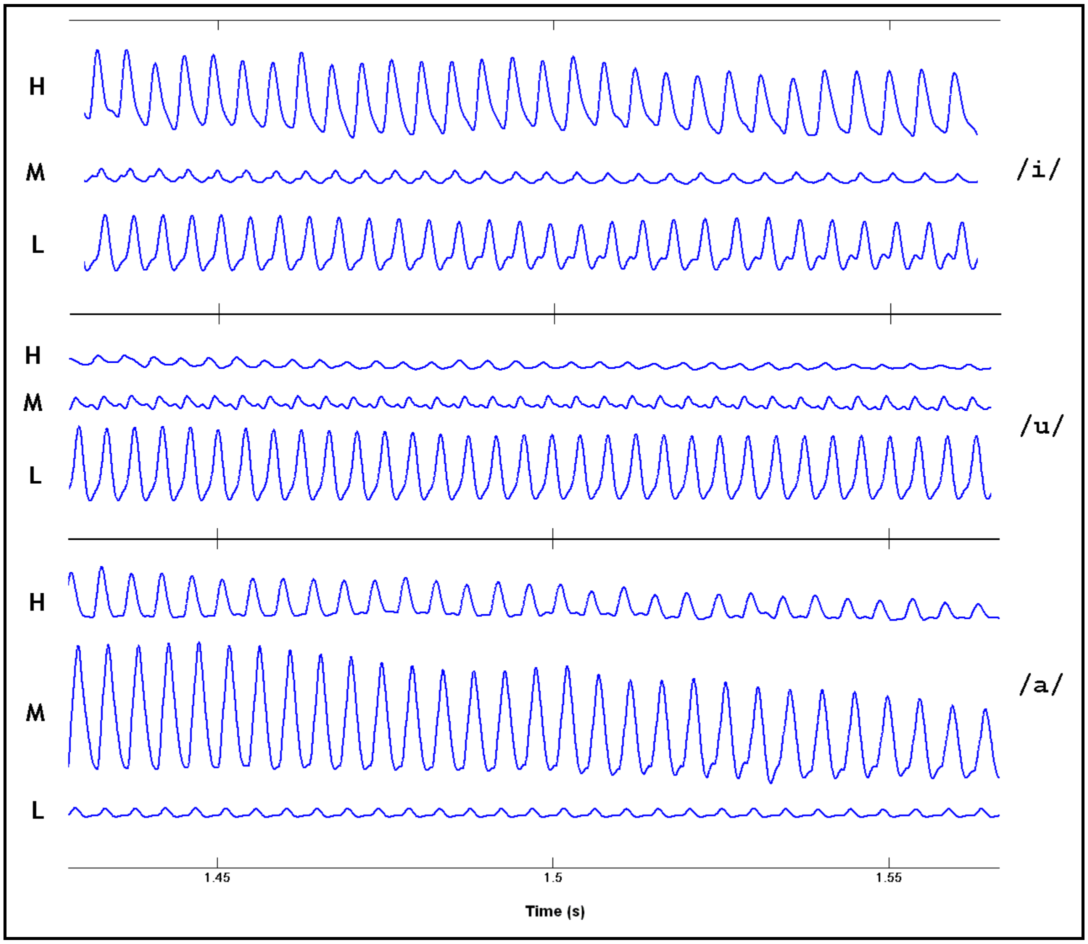

FIG 7. Three-channel vibrotactile signals corresponding to brief segments of the vowels /i/ in "beed"(top), /u/ in "zood" (middle), and /a/ in "gahd" (bottom). Traces corresponding to the 50-500 Hz, 800-2200 Hz, and 3000-8000 Hz channels are labeled "L", "M", and "H", respectively.

Figure 8 presents the three-channel vibrotactile waveforms corresponding to six CVC utterances. The three CVCs on the left side of the figure, "peet" (/p i t/), "sahp" (/s a p/), and "kees" (/k i s/), have unvoiced consonants in both initial and final positions. By contrast, the CVCs on the right, "beed" (/b i d/), "zahb" (/z a b/), and "geez" (/g i z/), have voiced consonants in both initial and final positions. Horizontally adjacent CVC pairs share all articulatory features other than consonant voicing --- thus, they would appear virtually identical through lipreading alone. However, comparison of the time-varying signal patterns across the three vibrotactile channels allows one to discriminate both initial and final consonant voicing quite easily. Note in particular the relative onsets and offsets of the high and low channels (labeled "H" and "L", respectively) for each CVC utterance. For example, in the utterance "peet" (top left of Fig. 8), the "H" signal onset precedes the "L" signal onset by well over 100 ms, reflecting the fact that the initial consonant (/p/) is unvoiced. By contrast, in the utterance "beed" (top right of Fig. 8), the "H" and "L" signal onsets are approximately simultaneous, characteristic of a voiced initial consonant (/b/). Similarly, the final offset of the "H" signal for the utterance "peet" extends about 200 ms beyond the offset of the "L" signal, as is commonly observed for unvoiced consonants in the final position (in this case, the short burst of noise combined with a large, slow displacement on the "H" channel is quite characteristic of a well-enunciated consonant /t/). The nearly simultaneous offsets of the "H" and "L" signals for the utterance "beed" reflect the voicing of the final consonant (/d/). Preliminary testing suggests that this transduction strategy provides an experienced user with substantially more information about articulatory manner than the envelope extraction scheme used by Yuan et al. (2005b).

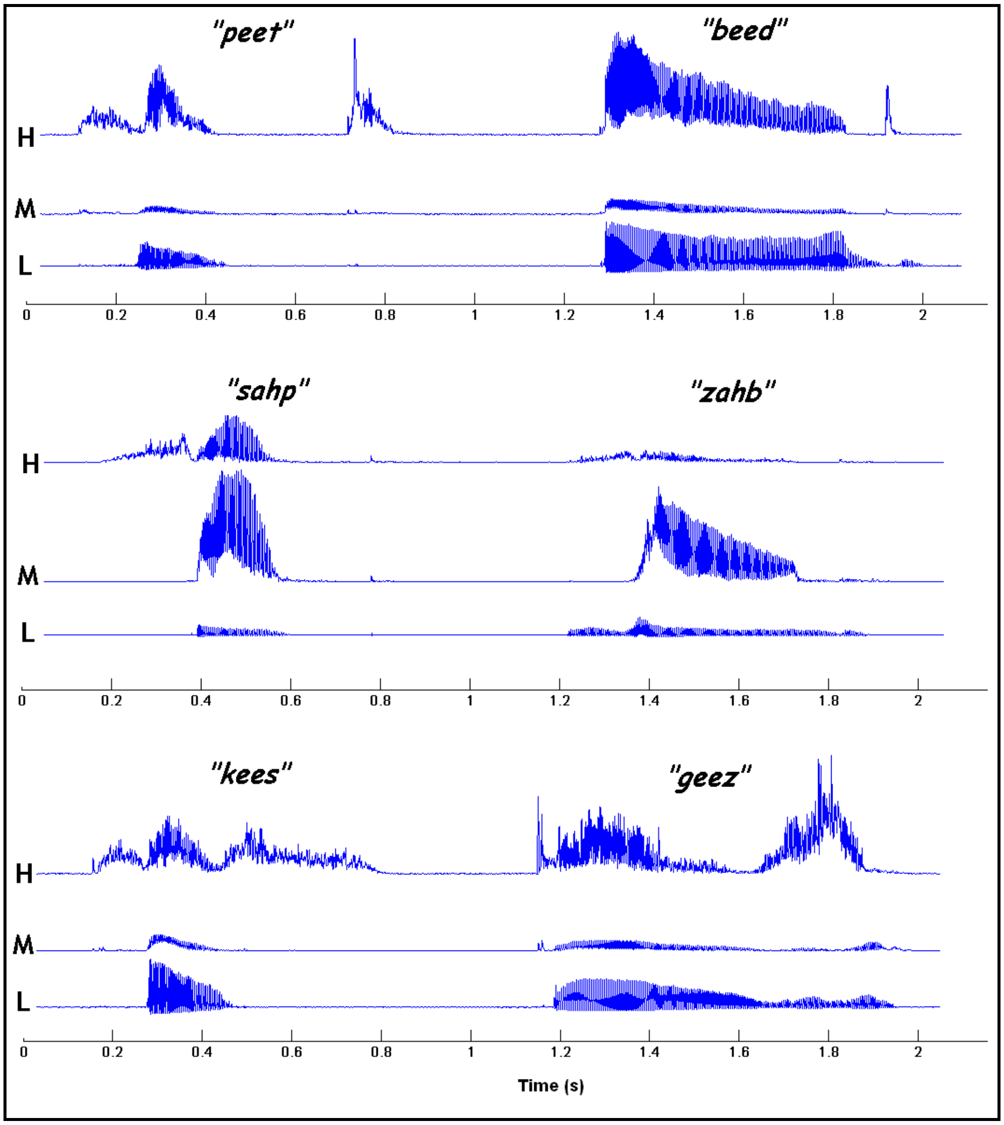

FIG 8. Three-channel vibrotactile signals, produced from audio recordings of six CVC syllables using the proposed speech transduction scheme. Traces corresponding to the 50-500 Hz, 800-2200 Hz, and 3000-8000 Hz channels are labeled "L", "M", and "H", respectively. The three CVCs on the left, "peet" (/p i t/), "sahp" (/s a p/), and "kees" (/k i s/), have unvoiced consonants in both initial and final positions. By contrast, the CVCs on the right, "beed" (/b i d/), "zahb" (/z a b/), and "geez" (/g i z/), have voiced consonants in both initial and final positions. Horizontally adjacent CVC pairs share all articulatory features other than consonant voicing and, as a result, they appear virtually identical through lipreading alone. However, both initial and final consonant voicing are readily discernible from the time-varying signal pattern on the three vibrotactile channels.

Future Work

Experimental work will be conducted to evaluate the ability of deaf and normal-hearing subjects to discriminate and identify speech signals presented through the vibrotactile display described above. Perceptual studies will include pair-wise discrimination of pairs of English consonants that differ only in the voicing feature, as well as consonant pairs that contrast features of manner or place of articulation. Tests will be conducted both through the vibrotactile display alone and in conjunction with speechreading. Stimuli will include isolated nonsense syllables as well as syllables that are embedded in running speech. Training protocols will incorporate vocal imitation of speech stimuli to guide performance.

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Meeting Papers, Presented

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