Tactile Communication of Speech

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Project Staff

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Goals and Significance

This research is aimed at increasing our understanding of the basic perceptual properties of the tactual system and developing improved strategies for encoding and displaying speech and other sounds that will lead to improved tactual communication devices. Research was conducted in four general areas:

(1) Basic studies of hand stimulation and active touch.
(2) Evaluations of children and adults with wearable tactile aids.
(3) Development of improved tactual displays.
(4) Study of the reception of environmental sounds through tactual displays.

The long-term goal of this research is to develop tactual aids for the deaf and deaf-blind that can serve as substitutes for hearing in the communication of speech and environmental sounds. This research plays a significant role in helping such individuals to achieve improved speech reception, speech production, language competence, and awareness of environmental sounds. At a more basic scientific level, this research contributes to increased knowledge about speech communication, environmental-sound reception, tactual perception, manual sensing, display design, and sensory substitution.

Studies and Results

1. Basic Studies of Hand Stimulation and Active Touch

Our research in this area is focused on the perceptual properties of both the kinesthetic and tactile sensory systems of the fingers, and in determining how information from these two components can be best combined to create an effective communication system. This research includes the design and construction of a multi-finger tactual display for delivery of multi-component stimuli that evoke sensations along the entire tactual continuum from the kinesthetic to the tactile. Previous artificial tactile displays have been limited primarily to homogeneous arrays of relatively small vibrators that provide only low-amplitude, high-frequency stimulation of the tactual system. Perceptual studies conducted with our new tactual display include exploration of information transfer (IT) and IT rates for large sets of multi-dimensional stimuli, effects of backward and forward masking on IT and IT rates, and the use of roving-parameter techniques to predict IT for multi-dimensional signals. In addition, our research on the identification of large stimulus sets has led to an empirically derived method for estimating IT from percent-correct scores. Finally, our work on basic studies of human touch includes research directed towards understanding the roles of kinesthetic and tactile information in the perception of object thickness (in the context of pinch grasping). Progress in each of these areas is summarized below.

1-a. Development of a Tactual-Stimulating Device

Work was completed on the development of a multi-finger tactual display for use in studies of communication through the kinesthetic and vibrotactile components of the tactual sensory system of the hand (Tan, 1996; Tan and Rabinowitz, 1996). The display consists of three independent single contact-point actuators interfaced individually with the fingerpads of the thumb, index finger, and middle finger. Each actuator utilizes a disk-drive head-positioning motor augmented with angular position feedback from a precision rotary variable differential transformer. A floating-point DSP system provides real-time positional control using a digital PID controller. Stimuli from threshold to roughly 50 dB SL can be delivered throughout the frequency range from near DC to above 300 Hz, thereby encompassing the perceptual range from gross motion to vibration. The operating characteristics of the device are such that it exhibits low distortion, system noise, and inter-channel crosstalk, and it permits accurate following of a wide variety of drive waveforms. Behavioral measurements of absolute threshold are in good agreement with values previously reported in the literature.

1-b. Studies of Information Transmission with the Multi-Finger Tactual Display

Multi-dimensional stimulus sets were created for use in experiments measuring the information-transmission capacity of the tactual sense with the multi-finger display (Tan, 1996; Tan, Durlach, Rabinowitz, and Reed, 1997; Tan, Durlach, Reed, and Rabinowitz, 1999). Specifically, stimulus sets were designed at each of three signal durations (125, 250, and 500 msec) by combining salient attributes such as frequency, amplitude, finger location, and direction of motion. The 500-msec and 250-msec stimulus sets consisted of 30 waveforms (each of which could be presented at each of four finger locations–thumb, index finger, middle finger, or all three fingers combined): eight single-frequency signals, sixteen double-frequency signals, and six triple-frequency signals. The size of the 125-msec stimulus set was reduced to 19 waveforms: six single-frequency signals, nine double-frequency signals, and four triple-frequency signals (each of which could be presented to any of the four finger locations).

Experiments were conducted to measure information transmission (IT) for the stimulus sets at each of the three durations (Tan, 1996; Tan, Durlach, Rabinowitz, and Reed, 1996, 1997; Tan, Durlach, Reed, and Rabinowitz, 1999). These studies employed a one-interval forced-choice procedure in which one of the 30 (for 500- and 250-msec stimulus sets) or 19 (125-msec stimulus set) waveforms was presented at one of the four possible finger locations, and the subject's task was to decide which of the possible alternatives had been presented on each trial by choosing a waveform and a finger location. The total number of alternatives was 120 (30 waveforms at each of four finger locations) for the 500- and 250-msec stimulus sets and 76 (19 waveforms at each of four finger locations) for the 125-msec set. Subjects received training with each stimulus set in the form of trial-by-trial correct-answer feedback. Once a criterion level of performance was achieved, subjects were tested without feedback. Stimulus-response confusion matrices constructed from the identification test results were used to derive estimates of IT. The results are summarized in the table below.

Stimulus Set	No. of Alternatives (K)	Stimulus Uncertainty in bits ($\log_2 K$)	Static IT (bits)	Equiv. No. of Perfectly Identified Items
500 msec	120	6.91	6.5	90
250 msec	120	6.91	6.4	84
125 msec	76	6.25	5.6	50

The identification experiments described above demonstrate high levels of IT for *static* stimulus presentation; however, if such a display is to be used for the transfer of streams of signals that change rapidly as a function of time (such as speech), then it is important to demonstrate that acceptable *rates* of IT can be achieved through the display. The IT rate (in bits/sec) is defined as the product of IT per presentation (in bits/item) and presentation rate (in items/sec). Ideally such an assessment would involve the presentation of sequences of stimuli at rates approximating those that occur in speech and the repetition of the sequence by the subject.

The training requirements for such a task, however, are enormous. In order to estimate IT rates within a reasonable time frame, we used a greatly simplified task in which the subject identified the middle stimulus in a sequence of three stimuli presented at various signal durations and inter-stimulus intervals. This method allowed us to estimate IT per presentation as well as presentation rate (across a range of different rates), thus leading to estimates of IT rates in bits/sec. The experiments were conducted using an AXB identification paradigm in which the subject's task was to identify the target stimulus X, which was preceded and followed by maskers A and B. The maskers and the target were selected randomly from all the alternatives within each stimulus set. For each of the three stimulus sets, the duration of the target X and the two maskers (A and B) was identical, as was each inter-stimulus interval (ISI). Six values of ISI, ranging from 20 to 500 msec, were employed at each signal duration. Estimates of IT rate (in bits/sec) for each combination of signal duration and ISI were calculated by dividing estimated IT by the time between stimulus onsets (i.e., signal duration plus ISI, referred to as stimulus-onset asynchrony, SOA). Results indicated that performance was dependent on SOA, or equivalently, stimulus presentation rate, but not on the ISI alone. Maximum values of IT rate were observed for SOA values in the range of 350-500 msec, corresponding to presentation rates of 2 to 3 items/sec and consistent with Garner's (1962) estimates. The maximum estimated IT rate averaged over three subjects was 12 bits/sec. These estimates fall within the range of estimates of maximal IT rates for natural methods of tactual communication (see Reed and Durlach, 1998) which range from roughly 8 bits/sec (for tactual reception of fingerspelling) to roughly 22 bits/sec (for the Tadoma method of communication and for tactual reception of sign language).

Additional studies have been conducted to investigate further the effects of various types of masking on the identification of multidimensional signals presented tactually (Farel, 1996; Tan, Wan, and Reed, 1998). Farel (1996) studied IT for a set of thirty signals presented to the index finger in the presence of either a forward masker (presented prior to the target signal that was to be identified by the subject) or a backward masker (presented after the target signal). The results of the study indicate a different time course of masking for the forward and backward maskers: backward-masking effects were greater than forward-masking effects at short values of SOA; however, the effects of forward masking persisted for a longer period of time. The backward masking effects observed here were similar to those observed by Tan (1996) using the AXB paradigm. Tan, Wan, and Reed (1998) studied masking effects for tactual stimuli that differed in their spectral contents. This study employed a set of seven signals at two different durations (125 or 250 msec) presented to the index finger of the left hand. The stimuli consisted of three single-frequency waveforms (a low, middle, and high frequency), three double-frequency waveforms (resulting from all possible combinations of the three single waveforms), and one triple-frequency waveform (resulting from the combination of the three single frequency waveforms). Three masking paradigms were used: forward and backward masking as well as the AXB masking paradigm described above. Errors made on identification were processed to measure the percentage of (1) masker response (i.e., response = masker); (2) composite response (i.e., response = target + masker); and (3) component response (i.e., response = target + a component present only in the masker (see Evans, 1987). Partial results from three subjects indicated that (1) roughly 20-35% of all errors arose as a result of using the masker as the response; (2) there was no evidence of composite response under any condition; and (3) while there was little evidence of component response from low frequencies, there was statistically significant mid-frequency component response at the 125 ms duration, and statistically significant high-frequency component response at the 250 ms duration. The results of the current studies differ somewhat from those reported in previous tactile recognition masking studies (e.g., Evans and Craig, 1986; Evans, 1987) using very brief line patterns presented to the index finger. While our results are similar to theirs in showing greater effects of backward compared to forward masking at short values of stimulus-onset asynchrony, the effects of forward masking appear to persist for a longer period of time in our experiments. Additionally, the "composite response" observed by Craig and Evans was not found in the present data.

1-c. Development of a Method for Estimating IT from Percent-Correct Scores

This research was addressed to the problem of deriving unbiased estimates of IT in identification studies employing large stimulus sets, where the number of trials required for such estimates is approximated by $5k^2$ (where k is the number of stimuli). This rule of thumb would require a prohibitively large number of trials for the stimulus sets with sizes (57-120) employed by Tan (1996). Our research has led to the empirical demonstration that, for low error rates (i.e., an error rate of 5 percentage points or fewer), the quantity IT lies in the interval IS(1-2e). IT. IS(1-e), where e is overall error rate and IS is the information in the stimulus set. The lower bound can be shown to provide a good approximation of IT under the “worst-case” assumption that all incorrect responses are distributed randomly throughout the off-diagonal cells of the stimulus-response confusion matrix, while the upper bound holds for the case in which incorrect responses are distributed such that all the errors for a given stimulus are located in the same off-diagonal cell, and a different off-diagonal cell is employed for the error responses to each stimulus. This formulation provides a means of bounding and estimating IT from the percent-correct score when it is impractical to collect the number of trials necessary for directly calculating unbiased estimates of IT (see Tan, 1996; Tan et al., 1999; Reed and Durlach, 1998).

1-d. Use of Roving-Parameter Techniques to Predict IT for Multidimensional Signals

In addition to being supported by two earlier studies (Tan, Rabinowitz, & Durlach, 1989; Campbell, 1993), the general additivity law of Durlach et al. (1989b) was also confirmed by experiments measuring static one-dimensional and two-dimensional information transfers with tactile stimulation (Denesvich, 1995). The stimuli, varying in frequency (F, 100 to 300 Hz) and amplitude (A, 12 to 40 dB SL), were delivered to the left index fingerpad using the multi-finger tactual display. Estimated values of IT from F-identification experiments (with fixed A values) and from A-identification experiments (with fixed F values) were 0.74 and 1.25 bits, respectively, giving a sum of 1.99 bits. Estimated values of IT from F- and A-identification experiments with the other parameter roving as the background were 0.38 and 0.88, respectively, giving a sum of 1.26 bits. The latter estimate provides a much better prediction of the two-dimensional IT, which was estimated from empirical results to be roughly 1.29 bits.

1-e. Discrimination of Thickness

Our previous work in this area (Gajaweera, 1994) was extended both through additional measurements of the human tactual ability to discriminate thickness and through the application of a finite-element model of plate deformation to the psychophysical data (Ho, 1996). Experiments were conducted using a two-interval, two-alternative, forced-choice procedure in which subjects were asked to discriminate pairs of plates in which one was a reference plate and the other was a thicker comparison plate. To investigate the role of plate stiffness on discriminability, plastic (less stiff) and steel (more stiff) plates were used. The thickness of the reference plates ranged from 0.25 to 10 mm for plastic and from 0.05 to 0.5 mm for steel. For both materials, the size of the jnd increased with the thickness of the reference plate, up to a critical thickness beyond which the jnd remained constant at roughly 0.4 ± 0.1 mm. The critical thickness was roughly 0.5-1.0 mm for plastic plates and 0.1-0.25 mm for steel plates. Analysis of plate deformation using a finite-element procedure indicated that, under the typical forces applied by the subjects, this critical thickness represented the boundary thickness between bendable and unbendable plates. For effectively unbendable plates, the only reliable cue for discrimination arises from kinesthetic sensations and leads to a constant value of jnd independent of reference thickness. For bendable plates, the tactile sensation of change in plate curvature introduces an additional cue for discrimination, leading to a decrease in jnd. After calculating the curvature of the deformed plates within the region of contact, it was found that the data for both plastic and steel, across the five subjects, could be explained by postulating a jnd for plate curvature of roughly 60 ± 20%. The size of the jnd for unbendable plates is consistent with measurements of the discriminability of joint-angle position (Tan et al., 1994), thus supporting our conclusion that kinesthetic sensations are the source of the cues used in discriminating thickness when curvature is eliminated. In addition, our current understanding of the two processes involved in the discrimination of thickness provides an explanation for the results obtained both by John et al. (1989) for studies with very thin plates and by Durlach et al. (1989a) for length discrimination.

2. Evaluation of children and adults with wearable tactile aids

Research in this area includes studies of the effects of training on the speech-production and speech-perception abilities of children and adults, as well as the development of training programs for use with tactile aids and assessment tools for evaluating the effects of training. This research was generally conducted in the context of the development of rehabilitation techniques for tactile aids and the application of these techniques in individualized training sessions. Although the results indicate various benefits achieved through tactile aids, these studies have generally not included systematic comparisons with alternative approaches to rehabilitation. While we do not have plans to continue this line of work in the current proposal, this research (including case and field studies) may be proposed under a separate application. In view of space considerations, we provide only a brief summary of progress in this area. Further descriptions of this work are available in two items of the Appendix (Plant, Horan, and Reed, 1997 and Plant, 1998b) as well as in other published articles (Plant, 1995; Plant, 1999) and training manuals (Plant, 1996; Plant, 1998a).

In the area of *speech production,* this research includes a case study of a young deaf adult whose speech intelligibility was evaluated following training sessions conducted with tactile aids (Plant, Horan, and Reed, 1997; Plant, 1999). The results of this study indicate improvements in the intelligibility of the subject's segmental and connected-speech productions. Individual speech-training sessions using tactile aids have also been conducted with a group of profoundly deaf children at the Rhode Island School for the Deaf who use sign as their primary means of communication. Assessments of the children's ability to produce target consonants and vowels in syllables, words, and short meaningful phrases indicate improvements over the course of the training.

In the area of *speech perception*, this research includes a case study demonstrating improvements in the perception of high-frequency sounds by a deaf high-school student using hearing aids and tactile aids. A second case study in this area examined the segmental speech-reception ability of a young deaf male using a modification of the Danish Hand-Mouth System (Plant, submitted). This research, which is in agreement with results reported by Delhorne et al. (1999) for the tactual presentation of the manual cues of Cornett's Cued Speech system, suggests that tactual cues based on phonemic properties of speech can be successfully integrated with speechreading. Finally, training in the use of the Tactaid 7 over an 18-month period was provided to an adult subject with sudden profound deafness (Plant, 1998b). The magnitude of the improvements observed over speechreading alone with this subject's use of the Tactaid 7 are consistent with results reported by Reed and Delhorne (1995) for a group of adult users of this device.

In the area of *development of training programs and assessment tools*, work has been conducted on the development of a variety of different materials for use in training programs with tactile aids and for use in assessing the speech-perception and speech-production skills of deaf children and adults. These materials include a speech-training program and assessment materials for use by teachers and speech therapists working with young deaf children (Plant, 1998a) as well as an adult training program for the Tactaid 7 (Plant, 1996). Other ongoing work in this area includes the development of a video program aimed at home use for adults fitted with sensory aids and work on the development of training and testing programs using materials that are representative of everyday communication.

3. Development of Improved Tactual Supplements to Speechreading

Research in this area is focused on developing a more complete understanding of the limitations of current tactile aids in providing supplemental information to speechreading and on developing improved tactual displays for this purpose. Studies in this area include an analysis of the segmental reception of speech through several existing tactile aids, a study of the integration of auditory, visual, and tactual information in the reception of speech, and work on the implementation of our multifinger display for the display of encoded speech signals.

3-a. Segmental Speech Reception through Existing Tactile Aids

Data on the identification of small sets of consonants and vowels have been collected on seven profoundly deaf adults who are subjects in our field study of tactile aids. Testing was conducted primarily for the conditions of lipreading alone and lipreading combined with the Tactaid 7 device. For a set of ten vowels, the size of the improvement over lipreading alone through the use of the Tactaid 7 ranged from roughly 0 to 8 percentage points across the 6 subjects tested. For a set of twelve consonants, the size of the improvement over lipreading alone through the use of the Tactaid 7 ranged from roughly -4 to 20 percentage points across the 6 subjects tested. Feature analyses did not show any strong effects for the aided condition for any of the vowel or consonant features.

Additional studies of segmental reception have been conducted with normal-hearing laboratory subjects using a wearable electro-tactile device (the “Tickle Talker”) developed at the University of Melbourne (Blamey et al., 1992). The Tickle Talker consists of an eight-channel array of electrodes worn on four fingers of the hand which are used to encode information about F0, F2, and speech amplitude through the electrical parameters of pulse rate, electrode position, and charge per pulse, respectively. Segmental discrimination data were obtained using recorded test materials and procedures similar to those employed in our previous studies with vibrotactile displays. These results indicate that discriminability performance through the Tickle Talker is roughly comparable to that obtained in similar tests with the Tactaid 7 device for consonants and vowels (Reed et al., 1992b). In comparing electrocutaneous to vibrotactile devices, it is worth noting that electrocutaneous devices are more difficult to use in that threshold sensitivity is dependent on placement of the device and may vary from day to day; thus, a setting that was comfortable one day may not be so the next. In addition, the subjects reported that the sensations could be unpleasant. Thus, to this point we have not observed any significant advantages for the Tickle Talker over traditional vibrotactile devices.

3-b. Integration of auditory, tactile, and visual information

The ability to integrate visual, auditory, and tactual information in the reception of speech was studied in a subject with profound bilateral hearing loss who has been using a Tactaid 7 device in addition to wearing a hearing aid in her better ear (Delhorne and Reed, 1996). The audiometric thresholds in her better ear are characteristic of a “corner” loss with hearing levels ranging from 80 dB at 250 Hz to >110 dB at 4000 Hz. This subject has used a hearing aid for most of her life and has had roughly 6 years experience with a tactile aid. The subject was tested on her ability to receive consonants in CV syllables, vowels in /h/-V-/d/ syllables, CUNY and IEEE sentences, and connected discourse under a variety of conditions, including lipreading alone (L) and in combination with the hearing aid (L+HA), the tactile aid (L+TA), and both devices simultaneously (L+HA+TA). For both types of sentences and for connected-discourse tracking, performance followed the general pattern L < L+TA = L+HA < L+TA+HA, indicating that the size of the benefit provided by each of the aids was similar and that the use of both aids together provided greater benefit than either aid used separately. For consonants, scores followed the pattern of L < L+TA < L+HA = L+TA+HA, indicating that the tactile aid did not provide further benefit to that derived from the hearing aid. The improvements with the tactile aid were related primarily to reception of manner features, while the hearing aid improved performance both on manner and voicing. For vowels, the subject’s lipreading alone performance of 90% left little room for improvement with the aids. The largest effects were observed for the following materials and conditions: consonant recognition scores increased from 49% for L to roughly 77% for L+HA and L+HA+TA; and IEEE key-word reception increased from 49% correct for L to 67% for L+T to 73% for L+HA to 78% for L+TA+HA.

3-c. Work on Delivering Speech Signals through the Multi-Finger Tactual Display

Work has been conducted to implement the multi-finger tactual display developed by Tan (1996) for displaying speech signals. Software and hardware modifications have been developed such that the device is now capable of conveying amplitude-envelope signals that are derived from filtered bands of speech. In addition, software has been developed to control experiments employing audio-visual speech materials that have been recorded onto laserdiscs. A system is in place for creating multi-dimensional signals derived from speech for presentation on our multi-finger tactual display and for evaluating the contributions of these signals as an aid to speechreading. This system involves estimating the envelope signal of band-pass filtered regions of speech and using the amplitude of this envelope to modulate the amplitude of a sinusoid which is delivered to the tactual display. The system is currently capable of delivering two separate envelope signals and one low-pass-filtered speech signal to the tactual device.

4. **Reception of Environmental Sounds**

Research in this area is focused on assessing the reception of environmental sounds through tactile aids. This research includes the development of a test of environmental-sound reception and measurements of performance in both laboratory-trained subjects and experienced adult tactile-aid users from our field study. In addition, performance on the test was measured in a group of subjects with cochlear implants.

4-a. Development of a Test of Environmental-Sound Reception

To provide an assessment of environmental-sound reception under conditions that approximate those encountered in natural situations, a test was developed employing sets of ten sounds likely to occur in each of four different settings (office, outdoors, kitchen, and general home environments). The stimuli for the tests, which were obtained from a compact-disc recording, included a variety of different types and tokens of environmental sounds. Software was developed in MATLAB for presenting stimuli and recording responses using a one-interval, 10-alternative, forced-choice procedure, either with or without correct-answer feedback.

4-b. Results with Laboratory-Trained Subjects

Data were obtained from two normal-hearing laboratory subjects with the Tactaid 7 device (with direct input) worn on the forearm and with earplugs and earmuffs to eliminate any auditory cues. Signals were presented at a comfortable level of approximately 25 dB SL. For each of the four settings (office, outside, kitchen, general home), subjects received 600 trials with correct-answer feedback followed by an additional 300 trials without feedback. Post-training performance, across settings and subjects, averaged 57% correct (where chance performance is 10% correct). Performance improved by roughly 20 percentage points over the course of the training. A third subject received extensive training with both the Tactaid 7 and Tactaid 2 devices. Post-training scores indicated that performance was similar for the two devices, averaging 79% for the Tactaid 7 and 76% for the Tactaid 2. Thus, there does not appear to be a clear advantage for the more detailed spectral information provided by the Tactaid 7 in identifying the given small sets of environmental sounds.

4-c. Results with Deaf Adult Users of Tactile Aids

Three profoundly deaf subjects who are regular users of the Tactaid 7 device (and participated in the field study reported by Reed and Delhorne, 1995) were tested on their ability to recognize environmental sounds. Within each of the four environments, subjects were tested initially on 300 trials without correct-answer feedback to determine their ability to identify the sounds based solely on their own prior experience with their tactile aids. The subjects then received an additional 300 trials with the presentation of trial-by-trial correct-answer feedback to determine the effects of training on performance. Individual-subject results are summarized below for each test environment, with and without the use of correct-answer feedback. Performance expected on the basis of chance alone is 10% correct in each of the test environments.

Subject	Kitchen		General Home		Office		Outdoors	
	Feedback		Feedback		Feedback		Feedback	
	No	Yes	No	Yes	No	Yes	No	Yes
JL	49.3	68.7	41.3	61.3	50.0	70.0	43.0	61.7
MC	51.4	63.9	36.2	72.0	44.3	77.2	36.2	63.3
RS	14.0	45.0	18.7	42.0	30.0	47.0	19.3	33.7
Average	38.2	59.2	32.1	58.4	41.4	64.7	32.8	52.9

The results indicate that the performance of subjects JL and MC was similar and superior to that of subject RS; performance, which was similar across the four environments, averaged 36% correct for initial testing without feedback; and scores were increased by an average of 23 percentage points in the presence of correct-answer feedback. Subjects were able to identify closed sets of environmental sounds at greater than chance levels even without any specific training, and the use of correct-answer feedback led to substantial improvements in performance. These results imply that cues useful to the identification of non-speech environmental sounds are provided by the seven-channel formant-based display of the Tactaid 7 device. Additional results obtained with subject MC under conditions of hearing aid alone and hearing aid combined with tactile aid indicate that her scores for the combined condition are substantially higher than those obtained with either the hearing aid or tactile aid alone. These results suggest that the information derived from the tactile aid was to some extent independent of that derived from the hearing aid and that the information from the two sources was integrated in a positive manner.

4-d. Results with Adult Users of Cochlear Implants (But No Tactile Input)

The environmental-sound reception test was administered to a group of implant users who had participated in long-term evaluations of their speech-reception ability (see Rabinowitz et al., 1992; Delhorne, 1997). Data were collected initially without correct-answer feedback; however, depending on level of performance, additional data were collected for some subjects and some environmental settings using trial-by-trial correct-answer feedback. Of the 11 subjects tested by Delhorne and Reed (1998), performance averaged over the four environments was 90% correct or better for 5 subjects; 70-80% correct for 4 subjects; 60-70% for 1 subject; and less than 50% for 1 subject. Ability on this task appears to correlate well with the ability to identify monosyllabic words through the implant alone (i.e., without speechreading). Comparisons of the performance of the tactile-aid subjects with the implanted subjects on this task indicates that the scores of two of the three tactile-aid users (following training) were near the median level of performance of the implant users; the performance of the third tactile-aid subject was similar to that of the worst-performing implant user. Thus, while none of the tactile-aid users achieved scores as high as those of the best cochlear-implant users, their performance did fall into the range observed across the implanted subjects.

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