A REVIEW OF THE BIOLOGICAL, PSYCHOPHYSICAL, AND SPEECH PROCESSING PRINCIPLES USED TO DESIGN THE TICKLE TALKER

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The Tickle Talker is a wearable electrotactile speech processor, designed to be used by profoundly hearing-impaired children and adults in conjunction with lipreading and residual hearing. The effectiveness of such a device is affected by an interaction between biological, human engineering, psychophysical, and speech processing considerations. The requirements, the design principles, and the performance of the Tickle Talker in each of these areas will be discussed. Electrical stimulation of the nerve bundles lying along the sides of the fingers was chosen to provide safe, comfortable, energy-efficient stimulation of a well-organised and sensitive part of the tactile sensory system. This is achieved at a small cost to the appearance and mobility of one hand when using the Tickle Talker. The biphasic pulse waveform used to stimulate the nerve bundles has been chosen to ensure a biologically safe stimulus. The electrical parameters (pulse duration, pulse rate, and electrode position) that are used to encode speech information are varied within ranges that are matched to the characteristics of the tactile sense. The usable ranges and information-carrying potential of each of these parameters have been assessed in psychophysical experiments. A comparison of these results with similar experimental data for cochlear implant and hearing aid users is instructive in assessing the possible limitations of tactile and auditory speech processors. The results discussed will include the discrimination and identification of stimuli differing in intensity, duration and pulse rate; the identification of different spatial patterns of stimulation, and the detection of gaps in stimuli. In most respects, the tactile results are similar to the corresponding auditory measures. The resolution of temporal differences such as pulse rate discrimination or gap detection are generally not as good as in the auditory case, but may be as good or better than the corresponding results for some profoundly hearing-impaired individuals. The speech processor used in the Tickle Talker is a "feature extraction" device that explicitly estimates the second formant frequency, amplitude envelope, and fundamental frequency of the voice and encodes them in terms of electrode position, pulse width and pulse rate of the electrical stimulation pattern. Consideration of the psychophysical results and the speech information available from these parameters allows optimization of the Tickle Talker's operation and a broad estimation of its potential performance in speech discrimination. The perception of duration and place of articulation (front/back) of vowels, and the manner and voicing of consonants are expected to be improved by the Tickle Talker. Prosodic variations conveyed by pulse rate are expected to be perceived by some users, but not all. High frequency consonants such as: /s/,/z/,/ʃ/, and /tʃ/ are encoded in a particularly salient manner by the Tickle Talker.

Developmental work on the Tickle Talker began in the Department of Otolaryngology in 1984, when cochlear implant studies with children were initially planned. The cochlear implant was to be compared with the best alternative sensory device in a single-subject design. One of the original selection criteria for implantation was that children obtained no significant benefit from hearing aids, which left tactile devices as the only alternative. However, it was felt that single and dual-channel devices commercially available at that time were extremely limited, and for this reason, the University of Melbourne commenced a program to design a multichannel tactile device. Since that time, the Tickle Talker development has received support from the Department of Industry, Technology and Commerce of the Australian Commonwealth, and Cochlear Pty. Ltd. Potential users of the device include severely and profoundly hearing-impaired children and adults, who are not suitable for cochlear implantation. This may also include a substantial number of hearing aid users (Cowan *et al* 1989).

Design Requirements

The initial design requirements were for the Tickle Talker to be wearable, safe, and effective.

(i) Wearability
The most difficult requirement of these three is wearability, as emphasized in the review of Sherrick (1984). Initial studies with vibrotactile stimulation failed to produce a wearable device which could be hand-worn, and for this reason, subsequent devices have used electrotactile stimulation. The current processor runs for 10 hours on a single AA-cell, weighs 200gm and can be worn on the belt or carried in a pocket. The comfort and convenience is such that children and adults have accepted and used

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the device as an everyday communication aid for periods now reaching two years.

(ii) Biomedical Safety

Extensive studies were included in the development plan to ensure biomedical safety (Cowan et al, in press). Electrical current levels used in the Tickle Talker are similar to intracochlear current levels used in the 22-channel cochlear implant, and current densities at the electrode surface are much lower than maximum densities recommended for electrical stimulation within the body. Although slight cooling of the fingers was detected in some subjects, acute and chronic studies of finger and blood flow, mean arterial pressure, and heart rate have shown no pathological changes in circulation in the hand or fingers, nor effects of electrical stimulation on sympathetic efferent activity. Acute and chronic studies of EEG activity have shown no change from normal patterns which might be associated with development of epileptic foci. Chronic studies have shown no change to physiological thresholds or discrimination for tactile stimuli subsequent to use of the Tickle Talker. Finally, careful design of circuits and packaging has minimized risk of accidental electrical stimulation. This is particularly important for electro- and vibrotactile devices which may require high voltage or currents to produce strong tactual stimuli.

(iii) Effectiveness

Effectiveness requirements were similar to those recommended by Spens (1980), based on his comparison of tactile devices. Multiple transducers are used to provide a spatial pattern of stimulation. The fingers are used as the site of stimulation, since they possess the most sensitive and highly developed tactile sensory capabilities. The speech signal is highly processed to take advantage of the psychophysical capacities of the tactile senses. In addition, individual programming of the electrodes is used to achieve comfort and ensure a good dynamic range of stimulation for each electrode (Blamey and Clark 1985).

Description of the Tickle Talker

The prototype device, shown as worn by a child in Figure 1, has 3 main components:

(i) the microphone, worn behind-the-ear or on the lapel
(ii) the pocket-sized speech processor
(iii) the electrode handset.

The electrodes are held against the sides of the fingers by metal rings that allow independent movement of the fingers. The handset and cabling do not restrict normal movements of the fingers and hand in any way. Eight finger electrodes are located one on either side of the proximal phalanx of the four fingers of the non-dominant hand. A larger, common return electrode is located at the wrist (this has been eliminated in the newest prototype device). One of the novel features of the Tickle Talker was positioning of the electrodes on the sides of the fingers, such that activation of the electrode resulted in stimulation of the digital nerve bundles. Stimulation of nerve bundles has been found to produce a more pleasant and comfortable sensation than electrical stimulation of skin nerve endings. In addition, the electrode positioning accesses a well-ordered spatial array of nerve bundles, providing distinct electrode position sensations, while minimizing restrictions on finger movement. Electric current flows between a single selected finger eletrode and the wrist electrode at any given moment. No sensation is felt at the wrist, due to the much lower current densities as compared with under the active finger electrode.

FIG. 1. The current prototype Tickle Talker.

The stimulus waveform utilizes a constant current of 1.5mA to overcome variations in skin/electrode impedance. Biphasic constant current pulses were chosen for safety reasons, minimizing irreversible electrochemical reactions at the electrodes. The strength of the stimulus is varied by changing the pulse width of each phase of the biphasic pulses. The two phases are separated by a short gap in which there is no current flow. Pulse rate is controlled by the speech processor.

The processing and coding of speech for the Tickle Talker use the wearable speech processor developed for the 22-channel cochlear implant. The Tickle Talker encoding strategy is similar to that employed in earlier models of the cochlear prosthesis (Clark et al 1984), which encloded fundamental frequency as electric pulse rate, second formant frequency as electrode position in the cochlea and amplitude as electric current level. The application of this speech processing approach has produced a device which is fundamentally different from other tactile devices which function as either band-pass vocoders or concentrate on a single-parameter such as fundamental frequency or amplitude.

Psychophysical Results

In order for speech information to be conveyed to the user, the electrical parameters must produce recognizable tactile sensations. Recognition of electrode position is easily done even by naive users of the device. Pulse rate differences are recognized by users as alterations in the quality of sensation, with lower pulse rates feeling rougher. Pulse width differences are recognized by subjects as changes in the strength of the stimulus.

(i) Identification of Pulse Rate

A set of 7 stimuli, with pulse rates ranging from 25-200pps, were numbered from 1 to 7, and presented in random order to 7 subjects wearing the Tickle Talker. Subjects were asked to identify each stimulus by number. A confusion matrix was calculated from the responses, and summarized using the d' statistic (the d' value for two stimuli being the mean difference in response divided by the standard deviation of the response distribution). A high d' value indicates good recognition, for example: a d' of 3 corresponds to 93% correct recognition of two stimuli, while a d' value of 1 corresponds to 69% correct for two stimuli. Figure 2 shows cumulative d' scores for the seven subjects. As shown, there was a wide variation between subjects, with the best subject scoring 75%, as compared to the poorest subject who scored only 30% correct. Results flattened out at high rates, indicating that discrimination of pulse rate was poorer for the higher rates of stimulation. For this reason, voice fundamental frequency (F0) is divided by two in the current Tickle Talker encoding strategy, and this scaled F0 value is used to control pulse rate. Given the range of psychophysical results, it is also expected that some subjects will be better able to utilize F0 information conveying cues to prosodic and segmental consonant features.

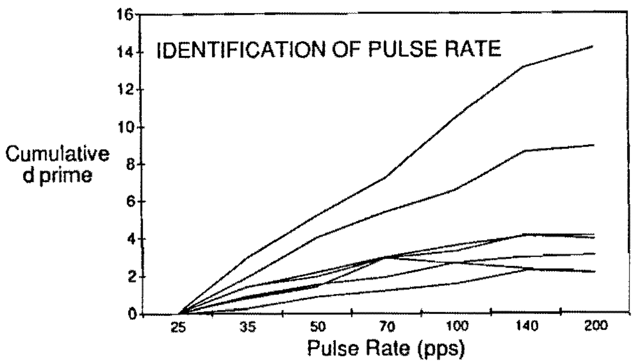

FIG. 2. Identification of pulse rate for seven Tickle Talker subjects.

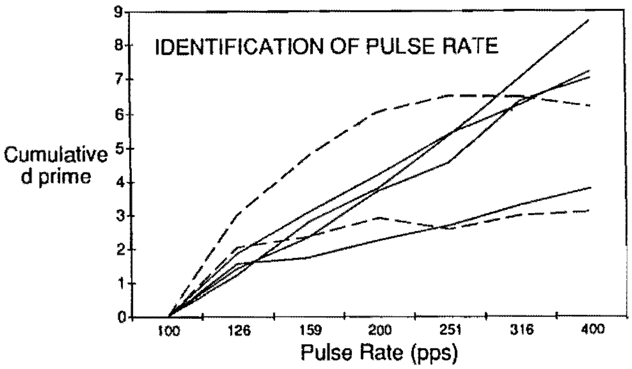

FIG. 3. Identification of pulse rate in the range 100-400pps for 2 tactile subjects (dashed lines) and four cochlear implant patients (solid lines).

Figure 3 shows results from a similar experiment conducted over a higher pulse rate range for the best two Tickle Talker subjects, compared with results for four multichannel cochlear implant patients. As shown, the flattening of the curves for the Tickle Talker users is quite pronounced as compared with implant users.

(ii) Stimulus Duration Identification

The amplitude envelope conveys information about duration of sections of the speech waveform. Figure 4 shows results for recognition of seven stimuli varying in

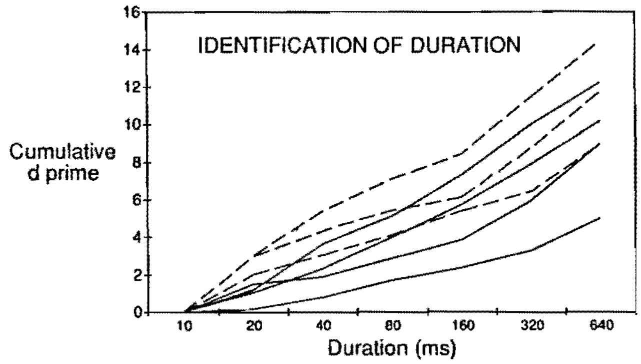

FIG. 4. Identification of stimulus duration for three tactile subjects (dashed lines) and four cochlear implant patients (solid lines).

duration from 10-640ms. Recognition was very good for all tactile subjects over the full range. The difference in curves between Tickle Talker scores and cochlear implant scores may reflect different integration times for the auditory and tactile senses (Blamey et al 1990).

(iii) Electrode Position Identification

Figure 5 shows results from a study of electrode identification. Subjects were presented with sets of stimuli containing either single electrodes, pairs of electrodes, three electrodes, or combinations of single and paired electrodes. Identification scores reached 98% for single electrodes (as used in the current encoding strategy). Results were poorer for paired and three electrode stimuli. Although percent correct scores dropped for the more complex stimuli, Figure 6 shows the information transmitted was similar for single, two and three electrode stimuli. Information transmission scores were increased for the combined single and paired electrode patterns (Cowan et al 1991). Modified versions of this strategy are currently being tested to assess whether better encoding of consonant voicing and/or provision of F1 formant frequency may be achieved with multiple electrode stimulation patterns, and in addition, whether this will result in improved speech perception.

Speech Feature Perception

(i) Prosodic Features

Figure 7 shows results on the Minimal Auditory Capabilities (MAC) Battery for 7 normally-hearing adults (NH) who received 70 hours of training with the Tickle Talker, and 4 hearing-impaired adults (HI) who received 35 hours tactile training prior to evaluation (Cowan et al 1988). Results for 13 postlinguistically deaf cochlear implant patients (CI), (using an F0F2 speech processing strategy) are shown for comparison (Blamey et al 1987a). All three groups were able to recognize syllable number at high levels, consistent with good recognition of amplitude envelope time/duration information. Spondee same/different was good for the NH and CI groups. However, lower scores were recorded for the HI Tickle Talker group. Possible reasons for this are insufficient training, or the fact that 3 of this group were congenitally hearing-impaired adults with below-average language skills. No group was able to score well on the question/statement test which requires

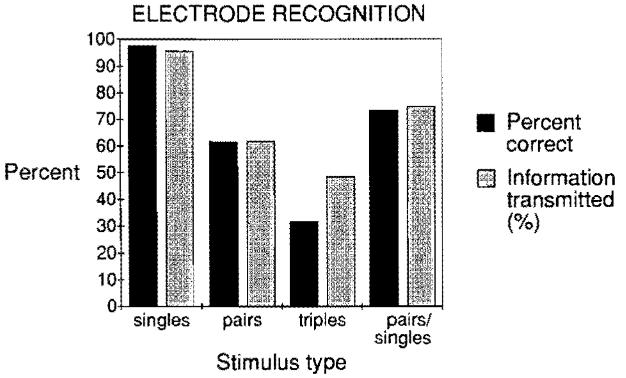

FIG. 5. Electrode identification scores in percent correct and percentage of information transmitted.

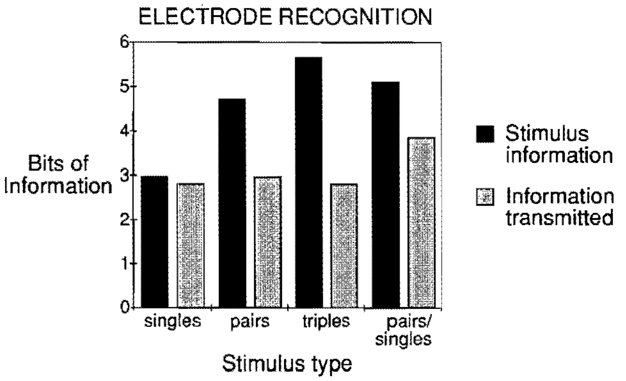

FIG. 6. Total information transmitted in the electrode identification study.

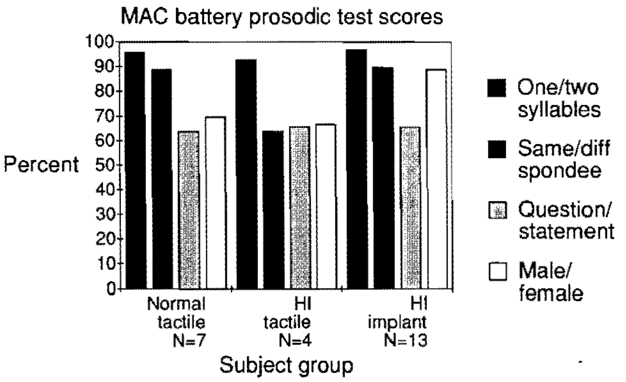

FIG. 7. MAC Battery scores for Tickle Talker and cochlear implant.

recognition of dynamic changes in fundamental frequency. Only the implant group scored well on the male/female speaker test. This result may be due to inferior recognition of pulse rate differences by some tactile subjects, observed in the psychophysical testing.

(ii) Closed-set Vowels

Recognition of a closed set of eleven vowels presented in h/V/d format are shown in Figure 8. Scores were well above chance in the tactile-alone condition, and significant improvements were shown when the Tickle Talker was used as a supplement to lipreading. The normally-hearing subjects using the Tickle Talker had received considerably more training on the task prior to evaluation than either the HI or CI groups, and this may explain the better

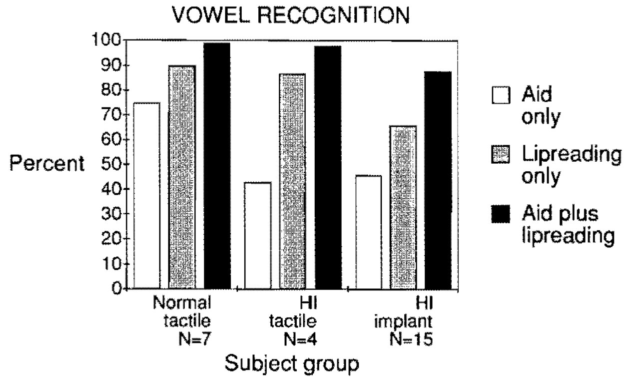

FIG. 8. Vowel recognition for Tickle Talker and cochlear implant.

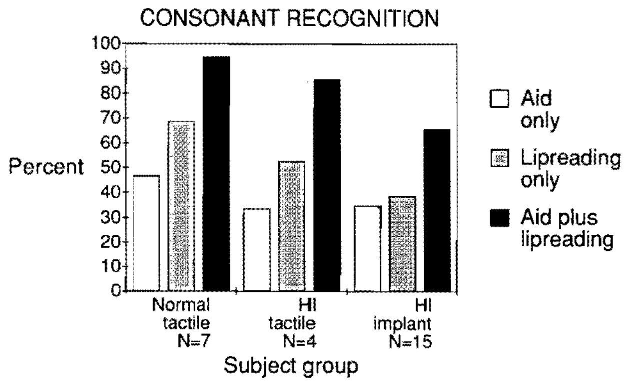

FIG. 9. Consonant recognition for Tickle Talker and cochlear implant.

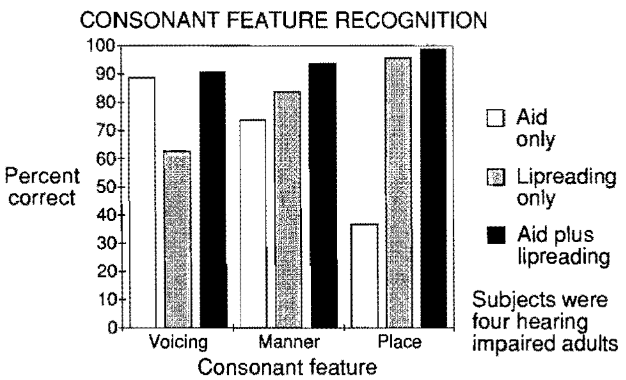

FIG. 10. Consonant feature recognition for Tickle Talker users.

performance. Alternatively, the difference between NH scores and CI scores may be due to the good electrode recognition with the Tickle Talker. Cochlear implant vowel and consonant results are from Blamey et al (1987b).

(iii) Closed-set Consonants

Recognition scores for a closed set of twelve consonants presented in a/C/a format are shown as Figure 9. Results are similar to those for vowel recognition. While aid-alone scores are lower than those shown on vowels, improvements over lipreading alone scores are larger for the combined device plus lipreading conditions. Figure 10 shows results for the four hearing-impaired Tickle Talker users in more detail. Recognition of voicing and manner features were better than place for the Tickle Talker, while the reverse was true for lipreading alone. Combined modality scores were high for all three features.

(iv) Speech Pattern Contrast (SPAC) Results

The Tickle Talker has also been evaluated with the SPAC Battery (Boothroyd 1984). Figure 11 shows the average scores for seven normally-hearing adults using the Tickle Talker without lipreading. The number in brackets after each subtest shows the number of subjects scoring better than chance at the 95% confidence level. The vowel height test overestimates the amount of first formant information available from the Tickle Talker, since the items in this American test have marked durational differences when spoken by Australian speakers. The consonant subtests indicate poorer performance than in the closed-set consonant test, especially for consonants in the initial position. Future speech processing research will focus on improvements in consonant perception.

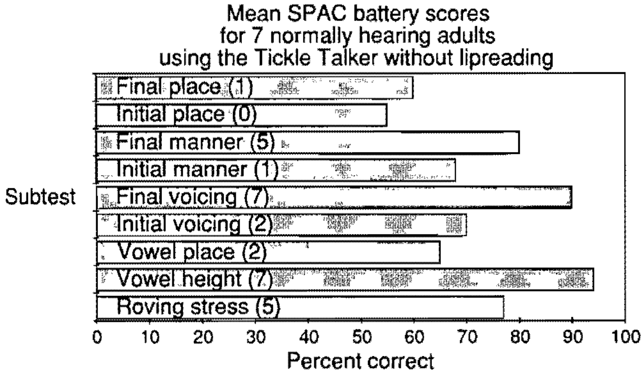

FIG. 11. SPAC Battery Test scores for normally hearing Tickle Talker subjects. The numbers in brackets indicate the number of subjects scoring significantly above chance ($p > 0.05$).

Summary

In summary, the Tickle Talker has been demonstrated to be wearable, biomedically safe, and an efficient mechanism for providing speech information as recognizable tactual patterns which can be utilized by hearing-impaired subjects either in isolation or in combination with other sensory modalities to improve speech perception. However, to achieve successful development of a device, several other elements are vitally important, including: an effective training program in the use of the device, sufficient time and experience (measured in years) for users to become fluent in device usage, and lastly, a team of skilled, patient and caring trainers to work with both adults and children using the device. Each of these four elements is essential if a tactual device development programme is to be successful.

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