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# The effect of handedness in tactile speech perception

**Julia Z. Sarant, BSc, DipAud; Robert S.C. Cowan, PhD, DipAud; Peter J. Blamey, PhD; Karyn L. Galvin, BSc, DipAud; Graeme M. Clark, PhD, FRACS**
*Department of Otolaryngology, University of Melbourne, The Royal Victorian Eye and Ear Hospital, East Melbourne, Victoria 3002, Australia*

**Abstract**—This study examined differential performance of normally hearing subjects using a tactile device on the dominant versus non-dominant hand. The study evaluated whether tactual sensitivity for non-speech stimuli was greater for the dominant hand as compared with the non-dominant hand, and secondly, whether there was an advantage for speech presented tactually to the dominant hand, resulting from a preferential pathway to the language processing area in the left cerebral hemisphere. Evaluations of threshold pulse width, dynamic ranges, paired electrode identification, and a closed-set tactual pattern discrimination test battery showed no difference in tactual sensitivity measures between the two hands. Speech perception was assessed with closed sets of vowels and consonants and with open-set Harvey Gardner (HG) words and Arthur Boothroyd (AB) words. Group mean scores were higher in each of the tactually aided conditions as compared with the unaided conditions for speech tests, with the exception of AB words in the tactile plus lip-reading plus audition/lip-reading plus audition condition on the right hand. Overall mean scores on the closed-set vowel test and on open-set HG and AB words were significantly higher for the tactually aided condition as compared with the unaided condition. Comparison of performance between the dominant and non-dominant hand showed a significant advantage for the dominant hand on the closed-set vowel test only. No significant differences between hands in either tactually aided or unaided conditions were evident for any of the other speech perception tests. Factors influencing this result could have been variations in degree of difficulty of the tests, the amount of training subjects received, or the training strategy employed. Although an advantage to presenting speech through the dominant hand may exist, it is unlikely to be great enough to outweigh possible restrictions on everyday use.

Address all correspondence and requests for reprints to: J.Z. Sarant, Department of Otolaryngology, University of Melbourne, The Royal Victorian Eye and Ear Hospital, 32 Gisborne Street, East Melbourne, Victoria 3002, Australia.

**Key words:** *lip-reading, multichannel electrotactile speech processor (Tickle Talker), normally hearing subjects, speech perception.*

## INTRODUCTION

The use of tactile devices as a means of improving speech perception for the hearing impaired was pioneered by Gault (1). A history of tactile devices can be found in recent reviews (2,3,4,5). It has been shown that tactile devices can provide both prosodic (6,7,8) and spectral speech information (9,10,11). For the severely-to-profoundly and profoundly hearing impaired who may gain varying degrees of benefit from hearing aids, tactual devices can provide additional speech information. This information, when combined with aided residual hearing and visual information from lip-reading, has been shown to improve discrimination of phonemes and words on both closed- and open-set speech tests (8,12,13).

In the development of tactile devices, a variety of methods of stimulation (piezoelectric, vibrotactile, and electrotactile), points of stimulation (back, forearm, abdomen, wrist, and fingertips), and number of channels of stimulation (10,14,15) have been used in efforts to tailor the tactile signal to the receptive characteristics of the tactual modality. Studies of the Tadoma method of tactile communication developed for deaf-blind users (16,17) and the reading of Braille characters by the blind (18,19) demonstrate that the skin of the hands has considerable information-processing capabilities. A question of particular concern in the development of tactile devices is whether these processing capabilities exist only in the hands or are generalized to other parts of the body.

It has been shown that the hands have both structural and functional advantages over other parts of the body. Geldard (20) noted that the glabrous skin on the hands is different from that on other parts of the body in several ways. It is smooth, hairless, and contains several types of specialized receptor cells important for detecting and discriminating stimuli of different types (21). Furthermore, the proportion of cortical sensory and motor area devoted to the hands in relation to the rest of the body is very large (22), and the absolute sensitivity and spatial acuity of the hands is among the highest in the body (23). Finally, a study conducted by Spens (24) of seven different tactile systems, each sited in a different body position, found that the fingers were the optimal receptor sites for tactile stimulation.

Given this study showing an advantage in using the hands as a site for tactile stimulation, a question arises as to whether there is an advantage in using one hand as opposed to the other. Studies of learned motor skills have shown that motor abilities are, in general, superior on the dominant hand as compared with the non-dominant hand (25). Given this finding, it may also be possible that tactual sensitivity would be greater for the dominant hand. In addition, for the majority of the population, the language processing center of the brain is found in the left cerebral hemisphere, whereas certain nonverbal functions are represented more strongly in the right hemisphere (26). In terms of language processing, dichotic listening and reading studies have shown both a right ear and right eye advantage for 75–87 percent of right-handed (right-dominant) people (26,27,28,29). In addition, it has been found that for right-hand-dominant readers of braille, the right forefinger reads two-thirds of the text in the same time it takes for the left to read one-third (18). It would seem reasonable that the advantage gained by presenting language to the right side, either visually, auditorily, or tactually, might be related to the time required for the information to travel to the processing center. Studies have shown that information presented to the right side would travel directly to the left hemisphere, while that presented to the left side would go first to the right hemisphere, and then cross to the language area in the left hemisphere (30). Given that modern multichannel tactile devices act as real-time speech encoders, the total time required for information to reach the processing center may be critical for language tasks. Therefore, it may be that there is an advantage, in terms of processing language, in use of the dominant hand.

A previous study (31) has investigated whether tactile pattern recognition skills learned with the transducers in one location transferred to other transducer locations. The researchers found that this did indeed occur for stimuli presented to the right and left thighs of subjects. The present study is somewhat different in emphasis, looking for differences in speech perception between the right and left hands after training for equal time with both hands. The point under investigation is not transfer of learned skills, but an inherent advantage for the perception of linguistic information for the dominant hand.

## PURPOSE

The aim of this study was to examine the differential performance of subjects using a tactile device on the dominant versus the non-dominant hand. Two issues were investigated: 1) is tactual sensitivity for non-speech stimuli greater for the dominant hand as compared with the non-dominant hand? and, 2) is there an advantage, on speech perception tests, to presenting tactual information to the dominant hand?

## METHODS

### The Electrotactile Speech Processor

The Tickle Talker, a tactile device that uses the fingers as a site of stimulation, was used to explore these questions. Previous results demonstrated that use of this device could provide speech perception benefits in children and adults (6,12,32); and it can be modified for use on either hand.

The wearable multiple-channel electrotactile speech processor used in the study has been described in detail by Blamey and Clark (14,15) and, more recently, in Cowan, et al., 1989 (32) and Cowan, et al., 1990 (12). The device, dubbed the "Tickle Talker," consists of a handset that is usually worn on the fingers of the non-dominant hand and a speech processor that uses a speech coding strategy similar to that of the 22-channel cochlear implant developed by the University of Melbourne and Cochlear Pty. Ltd. (33). Speech is received through a lapel microphone and passed to the speech processor, which extracts estimates of second formant frequency (EF2), fundamental frequency (EF0), and speech amplitude envelope (EA) and encodes them as electrode position, stimulus pulse rate, and stimulus pulse width, respectively. Stimuli are presented through eight stainless steel finger electrodes positioned directly over the digital nerve bundles on each side of the four fingers. This is an important feature of the device, as stimulation of nerve bundles in contrast to nerve endings provides a more pleasant tactual sensation than electrical stimulation at other body sites (15). A common ground electrode is located at the wrist. Electrotactile stimuli are constant current biphasic pulses of 1.5 mA with equal charge in each phase. The two phases are separated by a 100 $\mu$s gap, in which there is no current flow. Pulse widths vary within the range 10–1000 $\mu$s per phase. Pulse rate is a scaled function of fundamental frequency. In the current device, a 4000–10,000 Hz filter is included, the average output of which is encoded as pulse width for electrode number 8 (on the outer side of the little finger), to signal the presence or absence of high frequency fricative energy.

**Subjects**

Six normally hearing adults, three males and three females, participated in the study. Hearing-impaired users of the Tickle Talker (the majority of whom wear the device on their non-dominant hand) were not used, because they had received substantial amounts of training on only one hand. As a result of this asymmetrical training, the factors influencing their results would have been difficult to determine. All subjects were university students and were paid for their participation. Subject #6 withdrew from the study after the first phase of the experimental procedure because of educational commitments.

Subjects were tested with the Edinburgh Handedness Inventory, a preference measure that is stable across sex and over a test-retest interval (26), to determine their degree of laterality. This test gives a measure of the degree of handedness preference, as this varies between individuals in a continuous rather than dichotomous fashion (34). It was important that subjects were strongly right-handed to avoid confusion with the interpretation of results. This is because most right-handed people (75–87 percent) have language represented predominantly in the left hemisphere of the brain, whereas for left-handed people the language processing center may be in either hemisphere (26). All subjects were shown to be extremely right-handed on this measure.

**Training Program**

Prior to speech perception evaluations, each subject participated in an ordered program of training, which included speech feature discrimination and word identification exercises and a connected discourse tracking task. Training was live-voice, using one female and one male trainer. Individual subjects were trained and evaluated by the same trainer throughout the study. Subjects attended twice weekly sessions, of 1.5 hours each, over a period of 9 weeks. They were evaluated psychophysically prior to training, and were evaluated with language tests after they had received a total of 15 hours training, 7.5 hours on each hand. The stimulated hand was alternated between training sessions and was balanced across subjects throughout the training period.

During training, subjects were isolated in a sound-attenuating chamber providing 45 dB, A-weighted sound level attenuation. Visual input was provided through a double-glazed window in the wall of the sound chamber. The speaker's face was 1 m from the subject and was well lit from both sides. Tactile input was provided via a Sony model ECM-16T omnidirectional electret condenser microphone which was directly connected to the external input socket of the electrotactile speech processor. Auditory information was provided via a Sennheiser MD431 microphone, connected to an audio mixer and digital low-pass elliptical filter with a cutoff frequency of 300 Hz and a rejection slope in excess of 70 dB/octave. Both microphones were located approximately 40 cm from the speaker's lips. Pre-

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sentation level was monitored at 70 dBA by a Quest Model 215 sound-level meter. The filtered signal was then amplified and mixed with 60 dB SPL of speech-shaped masking noise. It was presented to the subject binaurally through Telephonics TDH39 headphones. The masking noise was presented at a level designed to achieve a 10 dB signal-to-noise ratio, and ensured that the trainer's voice would not be audible to the subject via transmission through the sound chamber wall. A low-pass filter cutoff frequency of 300 Hz was chosen to approximate the auditory information potentially available to a profoundly hearing-impaired person.

Training of speech feature discrimination was conducted in the tactile plus auditory (TTA) and the tactile alone (TT) conditions. Subjects were trained in the recognition of vowel duration, intensity, and second formant frequency as well as consonant manner and voicing distinctions.

Connected discourse tracking was conducted in the tactile plus lip-reading (TTL) and lip-reading alone (L) conditions and used the procedure devised by De Filippo and Scott (35). The speechtracking text was the adult-level biography, "A Fortunate Life" by A.B. Facey (36).

**Evaluations**

Two different types of evaluations were included: 1) psychophysical tests designed to determine whether one hand showed greater tactual sensitivity than the other, administered prior to training; and, 2) speech perception tests to evaluate the possibility of a right-hand advantage for language perception, administered after training.

The stimulated hand was alternated between evaluation sessions and was balanced across subjects throughout the training and evaluation procedures. No repeats or feedback on the correctness of response were given for any of the tests. Testing conditions were the same as for the training program, with the additions of the TTLA (tactile plus lip-reading plus audition), LA (lip-reading plus audition), and A (audition alone) conditions.

**Psychophysical Tests**

*(i) Absolute Thresholds and Dynamic Range*

Subjects set thresholds and comfortable levels for each electrode on both hands. Threshold was defined as the pulse width at which stimulation was first felt on a given electrode, whereas comfortable level was defined as maximum pulse width that subjects would find acceptable for continuous stimulation. Tactual threshold (T) and comfortable (C) pulse widths were measured over time, to determine whether either hand showed an advantage in terms of greater dynamic range, this being calculated by the following formula:

$$\text{Range in dB} = 20\text{Log}_{10}C/T.$$

*(ii) Paired Electrode Identification*

This test has been used in a previous study (37), in which it was shown that naive subjects could achieve significant scores, but that these scores were not so high as to result in a ceiling effect.

The six subjects were presented with a set of tactile stimuli, consisting of pairs of electrodes. The set consisted of five random-order repetitions of each possible stimulus combination (i.e., 5×28 possible pairs). Presentation of the stimuli was controlled by a computer program using the multichannel electrotactile speech processor. Subjects were told that the stimuli would consist of pairs, and were asked to identify the electrode positions (numbers 1–8) which had been presented in each stimulus. Subject responses were scored as correct only if both electrode positions in the stimulus were correctly identified.

The duration of each stimulus was 0.5 sec. Although the stimuli were perceived by subjects as being simultaneous, stimulus pulses were interleaved sequentially so that only one electrode was activated at a given moment. A 100 $\mu$s gap was present between pulses on the two electrodes, which represented the time taken for the encoder program controlling the stimulus pulses to recycle to a new stimulus command. The order of presentation within the electrode pairs was arbitrarily selected to be from lowest electrode position to highest position. All stimuli were presented at comfortable levels. Prior to testing, threshold and comfortable levels for the eight electrodes were balanced to be at similar subjective intensities.

*(iii) Closed-Set Tactual ABX Test Battery*

This study used a closed-set test battery, conducted prior to training with language material, as a test of differences in tactual pattern perception between the dominant hand and non-dominant hand. This test battery, developed and recorded by Plant (38), has been used to evaluate discrimination of specific speech contrasts presented through various tactile devices. The test included 12 subtests, presented as two-alternative forced-choice tasks in ABX format (e.g., cat, bat: cat), with the exception of subtest number 12 which used 3 alternatives in an ABCX format. The ABX format of the test does not require recognition of the stimuli, only discrimination. A previous study using the Tickle Talker demonstrated that subjects can perform very well on this test, and did not show a significant difference in scores between naive and experienced users of the device (6). Given these findings, and the fact that subjects need only discriminate, not interpret, the tactile stimuli, it is appropriate to include this test as a psychophysical measure of possible differences in tactual perception between the hands, rather than a speech test per se.

The subtests contained representative phonemes from various contrast groups, although not all phonemes were contrasted. Contrasts included combinations of voiced and unvoiced nasals, stops, fricatives, affricates, and blends. Vowel items were presented in a /cVc/ format. Consonant items were presented in a /vCv/ format. The test utilized only initial position contrasts for all consonant subtests. The contrasts were perceived tactually as small variations in pattern of stimulation. For example, tactual cues for speech features could be presence or absence of frication, duration, and formant frequency (i.e., electrode place) information (9).

Tests were prerecorded on audiocassette by a male native speaker of Australian English and were presented via a Phillips FC444 cassette deck. The tape output was directly coupled to the external input of the speech processor. Prior to commencing testing, a segment of the Rainbow Passage (39) was played while the aid sensitivity control was adjusted to a comfortable setting for each subject. The tests were presented in the tactile alone (TT) condition, and no auditory input was given.

Subtests were presented consecutively, and no repeats of test items were given. Subjects were given printed response forms giving the response alternatives and were instructed to circle the word that was repeated. Each word in any subject pair was the stimulus for an equal number of presentations.

### Speech Perception Tests

Each of the speech tests used was selected on the basis of its proven sensitivity to variations in speech recognition (6,32). This allowed an analysis of differences in speech perception when a tactual device was used between the dominant and nondominant hands.

Lip-reading and audition were added to the conditions in which subjects were tested, as the device has been designed to be used in conjunction with lip-reading and residual hearing, not in the tactile alone condition. In addition, the tests used were too difficult to be done in the tactile alone condition, especially after only a relatively small amount of training.

*(i) Vowel and Consonant Tests*

Two closed-sets of vowels and consonants were used. The vowel test included 11 vowels presented in /hVd/ format, forming the words "heed, hid, head, hoard, hod, who'd, hood, hud, hard, had, heard." The consonant test comprised 12 consonants (/p, b, m, t, d, n, f, v, k, g, s, z/) presented in /aCa/ format. Lists of 44 vowels and 48 consonants were given in each condition, each item being presented four times in random order. Evaluations were conducted in TTLA, LA, TTL, L, TTA, and A conditions for each hand, so that for each hand there were six lists. The tests were prerecorded on videotape using an unfamiliar Australian male speaker. Visual information was presented via a 38-cm color monitor located 1.5 m from the subject. The filtered audio output of the videotape recorder replaced the amplified microphone signal as the sound source. The unfiltered audio output was directly coupled to the external input of the electrotactile speech processor to provide tactile information.

*(ii) High Frequency Consonant Identification Test*

Harvey Gardner (HG) high-frequency words (40) were also used in the evaluation, as results from a study using low-pass filtered speech showed that this test was sensitive to the amount of high frequency auditory information available (41). The test has been used in previous studies with the Tickle Talker, and subjects have shown a significant difference in the tactually aided versus unaided conditions (6,32,42). Since this was an identification test, the involvement of the language center was implied, and the test was therefore used to investigate the possibility of a right-hand advantage for speech recognition based on information presented through a tactile device.

The lists comprise seven voiceless consonants[1] used in words with the vowel /I/. There were 25 words per list. Evaluations were conducted in the TTLA, LA, TTL, L, TTA, and A conditions. Test lists were prerecorded on videotape using an unfamiliar Australian female speaker. Auditory, visual, and tactile input were provided exactly as described for the closed-set vowel and consonant tests. The test lists were scored by the number of consonants or consonant blends correct.

*(iii) Monosyllabic AB Words*

Speech discrimination differences between the dominant and non-dominant hand were evaluated at word level with Arthur Boothroyd (AB) words (43). This test was used because of the high interlist reliability. The word lists are phonemically balanced and presented in a /CVC/ format. Each list comprises 10 words, containing 10 vowels and 20 consonants, scored phonemically. Evaluations were conducted in the TTLA, LA, TTL, L, TTA, and A conditions. Test lists were prerecorded on videotape using an unfamiliar Australian male speaker. Auditory, visual, and tactile input were provided exactly as described for the previous speech tests.

### Statistical Analysis

All speech test results were analyzed using paired *t*-tests in order to remove the effects of large intersubject variability that were present. The following analyses were carried out:

a) paired *t*-test ($TT_B - U_B$) to determine whether the tactually aided (TT) scores, for both hands (B) combined, were significantly better than unaided (U) scores.
b) paired *t*-test $(TT_R) - (TT_L)$ to determine whether the scores in the tactually aided conditions were significantly greater for the right hand (R) than the left hand (L).
c) paired *t*-test $(U_R) - (U_L)$ as a control, to ensure that there were no spurious differences between the hands in the unaided conditions.

Although the number of *t*-tests carried out was quite large, a significance level of 0.05 was adopted rather than a stricter criterion to reduce the possibility of a type II error. In practical terms, acceptance of the null hypothesis that there was no difference between the hands when actually there was a strong right hand advantage would lead to poorer clinical performance with the device. We wished to avoid this outcome.

[1] Contact author for consonants used.

## RESULTS

### Psychophysical Tests

*(i) Absolute T Values and Dynamic Range*

Individual subject mean T pulse widths for the eight electrodes are shown in **Table 1**. In addition, the mean dynamic ranges for the eight electrodes at the final session for each hand are also shown in **Table 1**. Although there was reasonable intrasubject consistency between hands, inter-subject differences were large, for both mean T pulse widths and dynamic range. This resulted in a large range of values for both these measures. Overall, mean T pulse widths were 103.2 μs for the left hand and 115.1 μs for the right hand. Overall mean dynamic ranges for both hands were very similar, these being 7.8 dB for the left hand and 7.6 dB for the right hand. Dynamic range is a function of the differences between T and C pulse widths, as explained in the Methods section. A paired *t*-test on the difference in mean dynamic ranges between the two hands indicated that this was not significant ($t=0.351$, $df=4$, NS, $p>0.05$). In addition, a *t*-test on the difference in mean T pulse widths was not significant ($t=0.706$, $df=4$, NS, $p>0.05$).

*(ii) Paired Electrode Identification*

Individual and mean scores for paired electrode identification on both hands for the six subjects are shown in **Table 2**. Mean scores were 44.9 percent

**Table 1.**
Mean threshold pulse widths (μs) and dynamic range (dB) for eight electrodes measured for five subjects on two hands.

| Subject | Mean T Pulse Widths (μs) Left Hand | Mean T Pulse Widths (μs) Right Hand | Dynamic Range (dB) Left Hand | Dynamic Range (dB) Right Hand |
|---|---|---|---|---|
| #1 | 164.6 | 117.6 | 8.4 | 7.9 |
| #2 | 73.4 | 85.5 | 2.6 | 3.1 |
| #3 | 52.8 | 64.8 | 8.8 | 9.5 |
| #4 | 82.8 | 139.6 | 17.4 | 14.6 |
| #5 | 142.5 | 168.0 | 2.0 | 2.9 |
| Overall Mean | 103.2 | 115.1 | 7.8 | 7.6 |

**Table 2.**
Mean scores on a paired electrode identification test for six subjects on two hands.

| Subject | Paired Electrode Scores (%) Left Hand | Right Hand |
|---|---|---|
| #1 | 65.7 | 62.9 |
| #2 | 29.3 | 32.9 |
| #3 | 20.0 | 45.0 |
| #4 | 77.0 | 82.0 |
| #5 | 26.4 | 34.3 |
| #6 | 50.7 | 38.6 |
| Mean Score | 44.9 | 49.3 |

and 49.3 percent for the left and right hands respectively. A paired *t*-test showed no significant difference between mean scores for the two hands on identification of electrode pairs ($t = -0.880$, $df = 5$, NS, $p > 0.05$). The actual number of electrode positions correctly identified in contrast to pairs correct was calculated for the highest scoring subject (subject 4) for both hands to determine if there was a significant difference in this score between hands. This was not found to be the case, with scores of 88 percent on the left hand and 90 percent correct on the right hand.

*(iii) Closed Set Tactual ABX Test Battery*

**Table 3** shows the mean scores (from a total of 24) for the six subjects on the closed set tactual ABX test battery subtests. Overall mean scores for the combined subtests were 16 and 15.9 for the left and right hands respectively. Results showed that 36 mean scores for the 12 subtests were significant above chance (i.e., a score of 17 or greater on subtests 1–11, and 14 or greater on subtest 12) on the left hand, as compared with a total of 35 for the right hand. A paired *t*-test did not show a significant difference in tactual pattern perception between the dominant and non-dominant hands ($t = 0.118$, $df = 11$, NS, $p > 0.05$).

**Table 3.**
Mean scores for six subjects on closed-set tactual ABX test battery.

| Subtest | Feature | Left Hand[1] | Right Hand[1] |
|---|---|---|---|
| #1 | syllable number | 17.0 | 17.3 |
| #2 | syllable number | 16.0 | 15.2 |
| #3 | vowel length | 15.0 | 16.2 |
| #4 | vowel length | 17.2 | 16.0 |
| #5 | vowel formants | 18.5 | 18.5 |
| #6 | vowel formants | 18.0 | 17.0 |
| #7 | consonant voicing | 14.8 | 12.8 |
| #8 | consonant manner | 15.3 | 15.2 |
| #9 | consonant manner | 18.5 | 18.0 |
| #10 | consonant manner | 14.7 | 15.8 |
| #11 | consonant manner | 14.3 | 16.0 |
| #12 | consonant manner | 12.5 | 13.3 |
| Overall Mean Score (for hands) | | 16.0 | 15.9 |

[1]Number correct for 6 subjects across 12 subtests.

## Speech Perception Tests

*(i) Vowel and Consonant Tests*

**Table 4** shows identification scores for five subjects on the closed-set vowel test. The group means in each tactually aided condition were higher than in the respective unaided conditions for both hands. As shown, the overall mean scores for the subjects across all tactually aided conditions were 54.4 percent for the left hand and 58.8 percent for the right hand. In the unaided conditions there was less difference between the hands, the left hand scoring 49.4 percent and the right hand scoring 50.7 percent. **Table 5** shows the analysis of difference in scores for all subjects on this test. A paired *t*-test comparing difference in mean scores in tactually aided versus unaided conditions across both hands showed that subjects scored significantly better in the aided as compared with the unaided conditions ($t = 4.23$, $df = 29$, $p < 0.05$). A paired *t*-test comparing difference in mean scores between the right and left hands in the tactually-aided conditions showed that the right hand scores were significantly higher than for the left hand ($t = 2.21$, $df = 14$, $p < 0.05$). A paired *t*-test comparing difference in mean scores on the two hands in the unaided conditions showed this was not significant ($t = 0.50$, $df = 14$, NS, $p > 0.05$).

**Table 6** shows identification scores for all subjects on the closed-set consonant test. Similarly to the vowels, group mean scores for the five subjects were higher in each of the tactually aided conditions as compared with the corresponding unaided conditions for both hands. Overall mean

**Table 4.**
Percentage correct identification scores for five subjects on closed-set vowel test.

| Hand | Condition | Group Mean (%) (n = 5) | Subject Score (%) #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|---|---|
| **Left Hand** | TTLA | 75.0 | 70 | 82 | 89 | 89 | 45 |
| | LA | 71.2 | 77 | 73 | 77 | 84 | 45 |
| | TTL | 66.8 | 66 | 70 | 84 | 84 | 30 |
| | L | 56.2 | 64 | 61 | 61 | 59 | 36 |
| | TTA | 21.4 | 23 | 11 | 32 | 18 | 23 |
| | A | 20.8 | 11 | 25 | 27 | 18 | 23 |
| **Right Hand** | TTLA | 81.0 | 77 | 84 | 96 | 100 | 48 |
| | LA | 74.8 | 68 | 84 | 86 | 91 | 45 |
| | TTL | 66.8 | 70 | 70 | 82 | 89 | 23 |
| | L | 58.4 | 52 | 61 | 77 | 77 | 25 |
| | TTA | 28.6 | 23 | 32 | 34 | 36 | 18 |
| | A | 18.8 | 16 | 16 | 23 | 23 | 16 |

| **Overall Mean Scores** | **Tactually Aided** | **Unaided** |
|---|---|---|
| Left Hand | 54.4 | 49.4 |
| Right Hand | 58.8 | 50.7 |

scores in the tactually aided conditions were 48.9 percent for the left hand and 53.3 percent for the right hand. In the unaided conditions, mean scores were 47.6 percent for the left hand and 48.5 percent for the right hand. **Table 7** shows the analysis of difference in mean scores for all subjects on this test. A paired *t*-test showed no significant differences between consonant scores for the two hands in tactually aided versus unaided conditions ($t = 1.63$, $df = 30$, NS, $p > 0.05$). Consonant scores for the right hand were not shown to be significantly higher than for the left in the tactually aided conditions ($t = 1.17$, $df = 15$, NS, $p > 0.05$). In addition, there was no significant difference in consonant scores

**Table 5.**
Analysis of differences in mean for five subjects on closed-set vowel test.

| Condition | Difference Score | Standard Deviation | $t$ | $df$ | $p$[1] |
|---|---|---|---|---|---|
| $(TT_B - U_B)$ | 6.57 | 8.35 | 4.23 | 29 | 0.05 |
| $(TT_R) - (TT_L)$ | 4.40 | 7.44 | 2.21 | 14 | 0.05 |
| $(U_R) - (U_L)$ | 1.27 | 9.48 | 0.50 | 14 | NS[2] |

[1]Level of significance on paired *t*-test comparing difference in mean scores.
[2]Not significant, $p > 0.05$.

**Table 6.**
Percentage correct identification scores for five subjects on closed-set consonant test.

| Hand | Condition | Group Mean (%) (n = 5) | Subject Scores (%) #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|---|---|
| **Left Hand** | TTLA | 84.2 | 85 | 65 | 96 | 98 | 77 |
| | LA | 82.6 | 92 | 79 | 79 | 94 | 71 |
| | TTL | 36.2 | 44 | 35 | 33 | 48 | 21 |
| | L | 34.4 | 40 | 23 | 40 | 38 | 31 |
| | TTA | 26.4 | 27 | 19 | 27 | 40 | 19 |
| | A | 25.9 | 25 | 31 | 27 | 21 | 21 |
| **Right Hand** | TTLA | 85.2 | 88 | 88 | 92 | 100 | 58 |
| | LA | 78.6 | 85 | 79 | 79 | 90 | 60 |
| | TTL | 42.8 | 33 | 33 | 69 | 58 | 21 |
| | L | 37.6 | 38 | 21 | 50 | 48 | 31 |
| | TTA | 32.0 | 31 | 35 | 44 | 25 | 25 |
| | A | 29.4 | 25 | 29 | 33 | 31 | 29 |

| **Overall Mean Scores** | **Tactually Aided** | **Unaided** |
|---|---|---|
| Left Hand | 48.9 | 47.6 |
| Right Hand | 53.3 | 48.5 |

**Table 7.**
Analysis of differences in mean scores for five subjects on closed-set consonant identification test.

| Condition | Difference Score | Standard Deviation | $t$ | $df$ | $p$[1] |
|---|---|---|---|---|---|
| $(TT_B - U_B)$ | 2.83 | 9.35 | 1.63 | 30 | NS[2] |
| $(TT_R) - (TT_L)$ | 4.40 | 14.08 | 1.17 | 15 | NS[2] |
| $(U_R) - (U_L)$ | 0.47 | 6.89 | 0.25 | 15 | NS[2] |

[1]Level of significance on paired *t*-test comparing difference in mean scores.
[2]Not significant, $p > 0.05$.

between the hands in the unaided conditions ($t = 0.25$, $df = 14$, NS, $p > 0.05$).

*(ii) High Frequency Consonant Identification Test*

**Table 8** shows phoneme identification scores for five subjects on the HG word test. Again, mean scores for the five subjects were higher in each of the tactually aided conditions as compared with the respective unaided conditions for both hands. Overall mean scores in the tactually aided conditions were 47.2 percent for the left hand and 48.6 percent for the right hand. Overall mean unaided scores were 42.8 percent for the left hand and 42.5 percent for the right hand. **Table 9** shows the analysis of difference scores for all subjects on this test. A paired $t$-test showed that for all subjects, scores on HG words for both the right and left hands combined were significantly higher in the tactually aided conditions as compared with the unaided conditions. However, a paired $t$-test showed that in tactually aided conditions, mean scores for the right hand were not significantly higher than for the left hand ($t = 1.20$, $df = 14$, NS, $p > 0.05$). Similarly, a paired $t$-test showed that there was no significant difference in mean scores between the hands in the unaided conditions ($t = -0.29$, $df = 14$, NS, $p > 0.05$).

**Table 8.**
Percentage correct identification scores for five subjects on Harvey Gardner word test.

| Hand | Condition | Group Mean (%) (n = 5) | Subject Scores (%) #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|---|---|
| **Left Hand** | TTLA | 66.4 | 73 | 67 | 68 | 77 | 47 |
| | LA | 62.6 | 67 | 71 | 57 | 74 | 51 |
| | TTL | 46.7 | 40 | 43 | 46 | 61 | 31 |
| | L | 44.7 | 48 | 36 | 40 | 58 | 37 |
| | TTA | 28.6 | 30 | 21 | 34 | 34 | 24 |
| | A | 21.2 | 21 | 22 | 13 | 28 | 25 |
| **Right Hand** | TTLA | 68.0 | 77 | 67 | 72 | 84 | 40 |
| | LA | 61.4 | 76 | 62 | 60 | 58 | 51 |
| | TTL | 49.2 | 57 | 42 | 53 | 68 | 26 |
| | L | 45.6 | 53 | 49 | 41 | 64 | 21 |
| | TTA | 28.6 | 26 | 27 | 30 | 44 | 16 |
| | A | 20.6 | 22 | 27 | 16 | 24 | 14 |

| Overall Mean Scores | Tactually Aided | Unaided |
|---|---|---|
| Left Hand | 47.2 | 42.8 |
| Right Hand | 48.6 | 42.5 |

**Table 9.**
Analysis of differences in mean scores for five subjects on Harvey Gardner word test.

| Condition | Difference Score | Standard Deviation | $t$ | $df$ | $p$[1] |
|---|---|---|---|---|---|
| $(TT_B - U_B)$ | 4.63 | 8.45 | 2.95 | 29 | 0.05 |
| $(TT_R) - (TT_L)$ | 2.20 | 6.84 | 1.20 | 14 | NS[2] |
| $(U_R) - (U_L)$ | −0.67 | 8.48 | −0.29 | 14 | NS[2] |

[1]Level of significance on paired $t$-test comparing difference in mean scores.
[2]Not significant, $p > 0.05$.

*(iii) Monosyllabic AB Words*

**Table 10** shows phoneme identification scores for five subjects on AB words. Group mean scores in tactually aided conditions were higher, except for TTLA/LA in the right hand. Overall mean phoneme scores in the tactually aided conditions were 45.0 percent for the left hand and 41.8 percent for the right hand. Unaided mean scores were 38.7 percent for the left hand and 35.4 percent for the right hand. **Table 11** shows analyses of differences in mean scores for all subjects on this test. Paired $t$-tests showed that mean scores on AB words (for the right and left hands combined) were significantly higher in the tactually aided conditions as compared with the unaided conditions ($t = 3.13$, $df = 29$, $p < 0.05$). However, mean scores for the right hand were not significantly higher than those for the left hand in the tactually aided conditions ($t = -0.69$, $df = 14$, NS, $p > 0.05$). In the unaided conditions, a paired $t$-test showed no difference in mean scores between the two hands ($t = -3.20$, $df = 14$, NS, $p > 0.05$).

## DISCUSSION

No significant differences between right and left hands were found for threshold pulse width levels, dynamic range, multiple electrode identification or the ABX feature discrimination battery. These results suggest that the tactual sensitivity of the hands

**Table 10.**
Percentage correct phoneme identification scores for five subjects on monosyllabic AB words.

| Hand | Group Condition | Mean (%) (n = 5) | Subject Scores (%) #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|---|---|
| **Left Hand** | TTLA | 67.2 | 70 | 70 | 83 | 70 | 43 |
| | LA | 62.0 | 57 | 77 | 70 | 63 | 43 |
| | TTL | 48.6 | 53 | 63 | 53 | 47 | 27 |
| | L | 40.2 | 30 | 63 | 40 | 50 | 17 |
| | TTA | 19.2 | 23 | 13 | 23 | 20 | 17 |
| | A | 13.8 | 13 | 10 | 23 | 13 | 10 |
| **Right Hand** | TTLA | 64.2 | 53 | 77 | 87 | 87 | 17 |
| | LA | 66.4 | 63 | 70 | 93 | 73 | 33 |
| | TTL | 47.2 | 33 | 33 | 73 | 80 | 17 |
| | L | 31.8 | 10 | 43 | 43 | 53 | 10 |
| | TTA | 14.0 | 13 | 3 | 17 | 30 | 7 |
| | A | 8.0 | 0 | 0 | 17 | 13 | 10 |

| **Overall Mean Scores** | **Tactually Aided** | **Unaided** |
|---|---|---|
| Left Hand | 45.0 | 38.7 |
| Right Hand | 41.8 | 35.4 |

for electrotactile stimuli does not differ to a large degree between the dominant and non-dominant hands. Although inter-subject differences were large, intra-subject scores for all three psychophysical tests were very consistent, which lends support to this conclusion. Similarly, large inter-subject differences were reported for thresholds and dynamic ranges by Blamey and Clark (15) and for

**Table 11.**
Analysis of differences in mean scores for five subjects on monosyllabic AB words.

| Condition | Difference Score | Standard Deviation | $t$ | $df$ | $p$[1] |
|---|---|---|---|---|---|
| $(TT_B - U_B)$ | 6.40 | 11.02 | 3.13 | 29 | 0.05 |
| $(TT_R) - (TT_L)$ | −3.20 | 17.30 | −0.69 | 14 | NS[2] |
| $(U_R) - (U_L)$ | −3.20 | 11.05 | −1.08 | 14 | NS[2] |

[1]Level of significance on paired $t$-test comparing difference in mean scores.
[2]Not significant, $p > 0.05$.

electrode pair recognition in Cowan, et al. (44) after longer periods of experience with the device. Results for the language tests were not as clear as for the psychophysical tests.

Results for the closed-set vowel test demonstrated that subjects were gaining significant benefit, in terms of speech perception, from using the tactile aid. In aided conditions, a significant difference between vowel scores for the two hands was found in favor of the right hand. This suggests that there is an advantage, in terms of processing language, to presenting tactile information to the right hand. **Table 4** shows that for conditions TTA and TLA there was a difference between right and left hands, but for TTL and A this was not the case. This raises the possibility that the asymmetry results from an interaction between the tactile and auditory information in the left hemisphere of the brain, rather than from the processing of tactile or auditory information in isolation. Nevertheless, the clinical relevance of these results is unchanged because the Tickle Talker is normally used together with residual hearing. The fact that no significant difference between the hands was found in unaided conditions lends further support to this result.

Although group means in each of the tactually aided conditions for the closed-set consonant test were higher than in unaided conditions, no significant difference was found between overall mean scores for the two hands in any condition. This is not surprising, since this test is significantly harder than the vowel test. Many acoustically different consonants look the same for lip-reading. In addition, many consonants cannot be perceived through audition by a profoundly hearing-impaired person, as they contain little or no low frequency information, and sensorineural hearing losses tend to show greater deficits in the higher frequencies. Subject scores for this test in most conditions were low. This result would seem to indicate that subjects had received insufficient training with the device to benefit greatly from using it in this test. As shown in **Table 12**, subjects score more highly on this test with extended training (32,42).

Tactually aided group mean scores for HG words were higher than unaided scores for each set of conditions. In addition, overall mean scores were significantly higher in the tactually aided conditions. No significant difference between the hands was shown in either the aided or unaided conditions.

Once again, this test is extremely difficult, even more so than the consonant test, as it includes blends of consonants and the subject does not have a written response set to refer to. It seems possible, therefore, that the amount of training given was again insufficient for the device to aid subjects enough in this task to show a difference between hands.

Tactually aided overall mean scores for AB words were also significantly higher than unaided results for the two hands. However, similarly to HG words, no significant differences in overall mean scores between the two hands were shown in either tactually aided or unaided conditions. This test is also far more difficult than the vowel test, as it is an open-set test, and it seems likely once more that lack of training did not allow a difference between hands to be shown.

As shown in **Table 12**, it can be seen in previous studies (32,37) that subjects who have received more training achieve much higher scores on the same tests used in this study. Although there were, for three of the four language tests used in this study, significant differences between tactually aided and unaided conditions, in all of these cases the device effect was not large, and in the absence of this, it is perhaps unreasonable to expect a significant difference between left and right hands.

A contributing factor to the absence of a large device effect could have been the training strategy used in this study, whereby subjects were trained on alternating hands twice weekly. It has been suggested that to obtain optimal levels of performance with tactile devices, subjects should be trained in repeated daily sessions (45).

Despite the fact that there was no difference found in the psychophysical tactual sensitivity measures between the two hands, there was a small but significant difference in performance between the hands on the easiest of the speech perception tests used in this study, the vowel test. This suggests that an advantage may exist, in terms of processing language, to presenting speech information through a tactile device worn on the dominant hand. However, these results also suggest that if this advantage exists, it may not be overwhelmingly large. Further studies, subsequent to longer periods of training with both hands would be required to completely evaluate the existence of a language advantage.

**Table 12.**
Comparative results for four speech perception tests from three studies. Subjects in the first two studies (1989, 1991) received 45 hours training, as compared with 15 hours training in the present study.

| | Mean Scores (%) | | | |
|---|---|---|---|---|
| | Study 1 | Study 2 | Study 3 | |
| Speech Tests | | | Left Hand | Right Hand |
| **Vowels** | | | | |
| Tactually Aided | 98 | 89 | 54 | 59 |
| Unaided | 85 | 69 | 49 | 51 |
| **Consonants** | | | | |
| Tactually Aided | 92 | 70 | 49 | 53 |
| Unaided | 52 | 51 | 48 | 49 |
| **HG Words** | | | | |
| Tactually Aided | 52 | 75 | 45 | 42 |
| Unaided | 51 | 54 | 39 | 35 |
| **AB Words** | | | | |
| Tactually Aided | NA | 65 | 47 | 49 |
| Unaided | NA | 35 | 43 | 43 |

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