SENSORY AIDS FOR THE PROFOUNDLY HEARING-IMPAIRED: A COMPARISON

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Sensory Aids for the Profoundly Hearing-Impaired

The majority of hearing-impaired persons are fortunate enough to be able to perceive their own speech and that of others, auditorily, with the help of hearing aid amplification. However, there is a small segment of the population who are unable to benefit from such amplification, these are the profoundly hearing-impaired. These individuals are usually identified as having pure-tone thresholds above 95 db HL for 500, 1000, and 2000 Hz. However, Erber (1978) further states, "One cannot use any audiogram classification alone to define profound impairment because pure-tone thresholds obtained from very young children may be invalid." (p. 256).

In addition, it has been shown that thresholds obtained for many profoundly deaf individuals may not be hearing thresholds at all, but may be vibratory thresholds of the outer and middle ear. Nobler (1967), demonstrated, as in Figure 1, that the pure-tone thresholds obtained from the ears and hands of deaf children were nearly identical.

DeFilippo (1982) further indicates that a profoundly hearing-impaired person is not able to sense sound auditorily. She states that frequency discrimination and word identification tests will clarify whether the sensation thresholds obtained on the audiogram are indeed auditory or tactile detection thresholds.

The implications of such a profound impairment are reviewed rather extensively elsewhere (Erber, 1978). The following paper is
concerned with the devices and procedures that might prove useful to the profoundly hearing-impaired in overcoming the devastating affects that such a sensory loss has on language and communication. It is hoped that with these devices, these individuals will be able to improve their receptive ability of understanding the speech of others in a meaningful way for language learning and communication and the expressive ability of speech production.

It is important to understand that although powerful hearing aids have been used as sensory aids, they require high levels of sound to cause vibration in the ear, which may be occurring at the threshold of pain; furthermore, the sensitivity of the skin in the outer and middle ear may not be as sensitive to vibration as elsewhere (Defilippo, 1982). Consequently, the person using a hearing aid to compensate for a profound hearing loss may only detect high-intensity, low frequency sounds (Defilippo, 1982). For these reasons, the following paper will focus on the development of tactile aids and cochlear implants for profoundly hearing-impaired usage. It is hoped with these devices sound can be received in a meaningful way for this small segment of the hearing-impaired population. The following paper will discuss the history, development, current research, and rehabilitation measures for both the tactile aid and the cochlear implant.
Figure 1. Similar median thresholds obtained from the ears and hands of adult children. Each point represents the hearing thresholds for the right and left ears of 42 children; age range five to 16 years. Hands, right hands of 54 children; age range five to 15 years. The transducer used for these measurements was a Phonak 20 earphone with a 10-MHz amplifier, mounted in an AK-41 earphone with a 247-MHz UHF receiver (from Pitcher, 1967).
History of the Cochlear Implant

In the past century, interest has increased tremendously in finding a device that will enable a profoundly deaf person to hear. These devices ranged from powerful binaural hearing aids, tactile devices, speechreading strategy, to the newest device, the cochlear implant. To date unfortunately, none of these devices has successfully given understanding of speech to the profoundly deaf person. With the increased knowledge, though still not fully understood, of the physiology of the ear in the recent years and the advanced technology of electronics, enthusiasm has increased in the research of tactile devices and the cochlear implant was developed. The first reported experiment of electrically stimulating the auditory nerve in humans was by a French team, Djourno and Eyries (1957). Since then excitement has generated much research in this area. One of the leading researchers, William F. House, M.D., directed a research program beginning in 1960 at the House Ear Institute located in Los Angeles, California. Dr. House and Jack Urban, an engineer, designed and developed a single electrode induction coil cochlear implant which further influenced the development of a wearable stimulator unit in 1970. At the annual meeting of the American Speech-Language-Hearing Association, Eisenberg (1984) stated that in the United States, 370 profoundly deaf adults and 152 children had received this implant known at the 3M system.

The House Ear institute has also developed a clinical program
that includes pre-surgery evaluations concerning the medical, audiological and psychological constitutions of the perspective candidate. They have also developed a "Basic Guidance Program" for post-surgery rehabilitation and a guideline for follow-up evaluations that occur at regular intervals following surgery.

In 1969, the Food and Drug Administration approved a clinical trials program headed by Dr. House. This allowed House to direct several select otologists as co-investigators in extensive training of his cochlear implant, surgery and clinical program. In 1981, another milestone was reached when the FDA approved the 3M Cochlear Implant System for adult usage. Further, the FDA approved clinical study of this implant in children under the direction of the House Ear Institute.
Cochlear Implants

To date, there are many cochlear implant systems. These systems differ in the number of electrodes (monopolar or bipolar electrodes), placement of electrodes and the speech processing strategies. The basic device, as seen in Figure 2 (3M Cochlear Implant System by William F. House, M.D.), is composed of an omnidirectional microphone, cord, signal processor, external transmitter cord, external induction coil, internal induction coil (receiver) and electrodes. The block diagram of this implant can be seen in Figure 3.

Sound travels as an acoustic signal to the microphone where it is changed into electrical energy. This energy is then amplified by the speech processor and filtered according to the predesigned strategies. The speech processor has an intensity control that includes an erasable-programmable read-only memory (EPROM) that can be programmed to produce current levels between threshold and most comfortable listening levels for each electrode. The energy from the speech processor is sent to the external induction coil which is magnetically coupled to the skull by the internal induction coil; therefore, no wires are needed to connect the external and the internal coil. The signal is then passed by magnetic currents through the skin to the internal induction coil. This receiver, or coil, is implanted in the mastoid bone behind the ear. From the receiver, the signal is sent down a wire to an electrode that is either placed outside the round window or through the round window.
and implanted in the scala tympani (as seen with the 3M system). Another electrode is suspended in the middle ear as a grounding source for the electrical current. Perhaps the least complicated system is the extracochlear electrode, discussed by Douek et al. (1977). This device, also known as the promontory implant, was developed in London and involves a single electrode implanted in the middle ear, suspended near the round window or on the promontory. This single-channel system processes the speech characteristics of primarily voicing and timing (Douek et al., 1977). The 3M system, previously discussed, is also a single-channel, monopolar system, although implanted in the scala tympani. This implant, discussed in further detail later, provides intensity and rhythm patterns, duration cues and limited spectrum shape (House et al., 1983, Lins and Niemhuys, 1984, Midwest Ear Institute, 1984).

A team of investigators located in Melbourne, Australia, have developed the multiple-channel cochlear implant that has 22 bipolar electrodes, the largest number of electrodes implanted today. This multi-channel prosthesis was designed to utilize the fundamental frequency and second formant of the speech spectrum for processing speech.

As seen with the Melbourne implant, there may be several electrodes used in a system and these electrodes may be implanted through different holes in the medial wall or through the round window and aligned along the scala tympani. These electrodes may be bipolar, thus not requiring ground electrodes, or monopolar with common ground electrodes implanted in the middle ear, Eustachian tube
or the scala tympani (Miller et al., 1984). "Monopolar stimulation produces a broader distribution of current than bipolar stimulation at the same level," (Shannon, 1993, p. 3).

The reader is referred to Miller et al. (1984) for a more complete description of the different Cochlear implants that are available today.
Figure 2

Block diagram of the House-Blame implant and signal processing scheme.
Candidacy and Surgery for the Single-Channel Implant

The single-channel implant, unfortunately, is not for all hearing-impaired people. This aid, although giving an awareness of sound at speech-intensity ranges and frequencies (see Figure 4), does not produce sound similar to what is familiar to the hearing populations: furthermore, it is unlike any amplified sound that one might receive from a conventional hearing aid. The implant cannot at this time process speech so that it is intelligible to the listener and therefore should be considered a sensory aid because its basic benefit will be with supplementing speechreading. The sound from the single-channel implant has been described by implanted patients as "crackling," "static," "dusty," and even like "Donald Duck." The cochlear implant is for that segment of the hearing-impaired population designated as the profoundly deaf (95 dB HL or greater for frequencies of 500, 1000, and 2000 Hz). In addition, prospective implant patients must demonstrate that they cannot obtain a better performance using a hearing aid than the average performance seen with the cochlear implant patient.

![Figure 4](image-url)
To be considered for an implant, the candidate must participate in a battery of tests which include otologic, audiologic, vestibular, radiographic, psychological and general physical evaluations.

The otologic evaluation is performed to determine if an infection or other problem exists in the middle or inner ear that may complicate the surgery. Also, a full audiologic evaluation is required which includes a routine hearing test, the Monosyllable, Tracehe, Spondee (MTS) battery, and the HRP E (Hearing Rehabilitation Research Clinic, an affiliate of the House Ear Institute of Los Angeles) Environmental Sound Test. Each of these evaluations are made without hearing aid amplification and then with several in-stock powerful hearing aids and then the candidate's own hearing aid(s) if s/he is currently using one. If the candidate's results on these tests are poorer than what is expected with the implant, then s/he can continue with the following evaluations.

An Electronystagmography (ENG), a vestibular test, is taken to determine the balance nerve function and also a radiographic (x-ray) evaluation is given to determine the condition of the inner ear bone. Lastly, a basic physical and perhaps a psychological evaluation is given to ensure that the candidate is healthy for surgery and postoperative use of the implant.

Cochlear implant surgery is performed under general anesthesia and usually lasts about one and a half hours. The poorer-hearing ear of the two ears is selected for surgery. This ear is chosen because research has shown that only a minimum number of neural elements is necessary for a response (Linthicum and Bailey, 1993).
therefore, leaving the better ear for further amplification from a
hearing aid or for possibly a more advanced implant system.

During surgery the hair of the patient is shaved several inches
above and behind the ear and an incision is made, opening the
mastoid and the middle ear. A cell is imbedded under the skin
behind the ear and an active electrode is placed through the Round
window (SM system) and into the basal turn of the scala tympani. An
additional ground, or inactive electrode is placed on the bone in
the middle ear. (For further details concerning the surgery refer
to Clark et al., 1984).

Following surgery, the patient may experience a taste
disturbance, salt for sugar and sugar for salt, and mouth dryness
for a few days to a few weeks. Patients also usually experience a
numbness about the ear (ranging from a short period up to six
months) and a soreness or stiffness in the jaw, which usually lasts
only a few days.

The patient usually remains in the hospital two to five days
and then can return home by any means of transportation.

Rehabilitation with the implant then usually commences one to two
months following surgery. At that time, the external cell and
speech processor are attached and rehabilitation begins.

The HRPC staff has prepared a 300-page manual detailing all
aspects of the program, from the initial patient contact through the
medical, audiological and psychological evaluations, surgery and
follow-up. A second manual has also been prepared that describes
the settings and adjustments of the stimulator unit. There is also
a third manual that offers a guide to their plan for a
Single-Channel Cochlear Implants

"The single-channel cochlear implant has been demonstrated to be highly successful in reuniting the profoundly deaf adult with the world of sound," (Dent, 1982, p. 41). The implant has given the individual a means of monitoring and regulating her/his own voice, ability to follow the voice of someone speaking at normal conversation levels and offers additional cues to supplement speechreading. With the implant, the profoundly deaf person can hear sounds either for the first time or for the first time since her/his hearing loss, and because of this s/he may also experience a psychological uplifting (House et al., 1981). The implant has given the profoundly deaf a chance to interact more successfully with the hearing world, and consequently change her/his own world accordingly. House et al. (1981) notes however, that the prelingually deaf adults' world is not significantly altered like that of the postlingually deaf; because their world has long been established within the deaf population.

In a pilot study of 24 implanted patients by House et al. (1981), the patients indicated that with the implant they felt less isolated; they felt less concern about their safety; they felt more comfortable in social situations; they felt upset less often about being deaf; they found communication less difficult and less frustrating; they felt that the quality of their relationships with their families was more satisfying; and they felt less of a burden to their families (p. 467, 1981a). Eighty-six percent of the
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Patients also indicated that their implant has affected their life positively.

Functionally, the implantee can perceive mainly the prosodic elements of speech, the information of duration and intensity, with frequency discrimination being limited to frequencies below 300 Hz. (House and Berliner, 1984). Also conversational speech, as stated earlier, is easily within the implant's range and can be detected in a quiet room at distances of 15 to 20 feet (House and Berliner, 1984). An average audiogram of nine postlingually deaf adults can be seen in Figure 3 (Engelmann et al., 1971). This audiogram shows the improvement in threshold detection of the implant over the hearing aid and the unaided conditions.

The following is an excerpt from a diary of the first patient that was implanted with the House single electrode system in 1972:

A combination of anticipation and doubt preceded the field testing of a new electronic cochlea. Anxiety was gradually replaced by excitement as all kinds of new sounds were experienced.

Sound is so immediate, natural, conscious, etc., that it is a totally different experience from a highly amplified source from a regular hearing aid.

Saturday morning I heard a persistent sound that I could not identify. My son came out into the yard and said it was a mockingbird. I asked about a quieter noise and he said it was the cat and her kittens.

On a twenty-mile bike ride I felt that I had good audowarning for each overtaking vehicle, from motorcycles to large trucks. At
home, the opening and closing of doors, the TV playing in the next
room, dishes and silverware being moved, are all noticeable.
Sunday, in church, reciting the Lord’s Prayer in unison was
natural and easy. During the singing of the Doxology I just
naturally started singing a very familiar song and surprised my
wife, who heard me singing, and on Kev.

I notice that with concentration I can hear quieter or distant
sounds that would at first seem impossible. I can hear my pen
scratch on the paper as I write. Today I had a conversation with a
teacher for the first time in eight years that we worked in the same
school. He has a very strong accent and he told me he had given up
trying to talk to me. (House, 1978, p. 282).

This excerpt demonstrates the exciting possibilities that the
implant can have for prospective implantees.

The following discussion will concern some investigations that
have been published that have tried to evaluate the different kinds
of perceptual cues that are available through the single-channel
implant.

In a study by Edgerton et al. (1983), 12 postlingually deaf
cochlear implant (CI) patients, with at least one year of daily
experience with their implants, were tested using the Minimum
Auditory Capability (MAC) battery. Table I shows the subtests that
could be performed by the subjects and the means, standard
deviations and scores necessary for significance at the 0.05 level
of these subtests.
Figure 6 shows the results of the environmental sounds test, which demonstrates that only an average of 48% of the 15 environmental sounds were recognized. However, the individual performance varied greatly from 27 to 60%.

The Noise-Voice test, as seen in the table, was 78% correctly discriminated. Figure 7 shows the individual's performance. Interestingly, only two subjects could correctly classify noise above chance performance; however, all the subjects were able to correctly identify the voice stimuli above chance performance.

Concerning the Question-Statement subtest, on the average, performance was above chance level. Figure 8 provides the percentage of correct scores for each individual. This appears to be a slightly difficult task because it is highly dependent on the ability of the listener to discriminate small changes in the pitch contour which is difficult for some single-channel CI users (Edgerton et al., 1983). The Accent test also was a very difficult task for some subjects and performance overall was not significantly above chance (p>0.05). Figure 9 shows the extreme variability between subjects on this test.

Information about consonant identification was obtained by the initial consonant and final consonant subtests. The mean scores for both tests were significantly above chance level and the results can be seen in Table 2. In these tests, the features of voicing and nasality significantly contributed to identification. Also, the final consonants, particularly the stop feature, were more frequently identified than the initial consonants.
The subjects demonstrated an average improvement of 24% in the speechreading test with the implant over vision alone. Figure 10 shows the variability between subjects ranging from 7% to 45% improvement.

Lastly, a vowel test was administered. This was the most difficult closed response test that the subjects were given. The results can be seen in Figure 11 and the mean score was 29%, which is not significantly above chance levels. The difficulty experienced by the subjects may be due to the inability to resolve frequency cues in the first and second formant regions of the speech spectrum.

Dent (1982) also investigated the ability of the CI user to discriminate English vowels in a consonantal context. This experiment differs from the above vowel test of the MAC battery as the MAC battery was a closed set vowel identification task. From Dent's investigation, she noted that "there is evidence that the cochlear implant users can distinguish tense and lax syllable nuclei," (p. 45). The tense vowels, she noted, tended to have "a longer sound interval" and with "a greater sum of the deviation of their formants from the neutral position," compared to the lax vowels. Further, her data depicted that the single-channel implant can distinguish between monosyllables containing high back vowels and to a lesser extent high front vowels from monosyllables containing low vowels.

In another investigation by Engelman et al. (1981), nine postlingually deafened adults were tested using the Monosyllable, Trochee, Spondee (MTS) test, the HRRC Environmental Sounds Test, and
the CHABA lists to test speechreading skills.

The subjects were divided into two groups. Group 1 received 52 hours of training spanning a 2-month period where they practiced auditory skills, speechreading skills, and speech and voice. Group 2 received 25 hours over a 2-month period which also encompassed auditory training, speechreading and some voice therapy.

Figure 12 compares the mean scores of the NTS for Group 2 using the implant versus the hearing aid. The implant clearly proved to be greatly advantageous for both word recognition and stress recognition. The mean score on the word recognition test was 43.3% with the implant and 10% with the hearing aid and further, 83.3% on stress recognition with the implant and only 32.9% with the hearing aid. Individually, the subjects scores varied widely with their hearing aids. These ranged from 0 to 24% correct for word recognition and 0 to 61.9% for stress recognition. Figure 13 also shows a great improvement in recognizing environmental sounds using the implant over the hearing aid. Group 1 demonstrated a mean improvement of 31.1% (with a mean correct score of 76.7% with the CI) and Group 2 demonstrated a mean improvement of 53% (with a mean correct score of 67% with the CI).

Lastly, speechreading skills were also assessed. The scores can be seen in Figures 14 and 15. The overall mean improvement was 38.5% for Group 1 and 34% for Group 2. The figures also compare post-rehabilitation scores with and without the CI in which the results yielded a mean difference of 8% for Group 1 and 10% for Group 2. The investigators, however, noted that the overall improvement could be due to either the supplemented implant's
acoustic information or a learning effect on the ability to utilize visual information. They do report that "most of the patients reported either that they had not learned to speechread satisfactorily with previous instruction or that their skills had reached a plateau subsequent to previous instruction and lengthy experience," (p. 1928).

In a study by Edgerton and Brinacomb (1984), an investigation was made concerning the effects of changing the modulating signal level of the House 3M processor and how this affected consonant identification. They note that "it is important to recognize that the volume control does not influence the shape of the signal envelope. The volume control simply increases or decreases the level of a predetermined envelope within the dynamic range of the listener," (p. 115).

In this investigation, 8 postlingually deaf CI patients participated. The test stimuli consisted of stops /p,b,k,g,/, fricatives /f,v,x,s/, and sonorants /m,n,l,r/ in a /ka/ context. There were four conditions tested by manipulating the House 3M signal processor in a manner that achieved four distinct groups of consonant envelopes (four different compression ratios). This was achieved by setting the microphone input level to produce processed speech waveforms that were either just peaking (58 median dB SPL) or in three different stages of saturation (66, 71, 78 median dB SPL).

The results were scored as phoneme correct and category correct. The Phoneme correct score indicates the number of times the VCV was correctly identified and the category score was considered correct when one stop was confused with another stop.
fricative with a fricative, or a sonorant with a sonorant. Table 3 shows the results of these scores as a function of the condition. For both phoneme and category, mean scores were highest in condition four and lowest in condition one. Figure 16 and 17 plainly show the confusion of consonants for condition one and four respectively. In condition one, the patient only scored 18.9% on identification and 38.5% on categorization compared to condition four where there was improvement of 58.3% on correct identification and 89.8% on correct categorization. The high scores achieved in categorization indicates that the features stop, fricative, and sonorant were perceptually different to these subjects.

This investigation has shown that as the stimulus input level is increased, six of the eight subjects showed improvement in consonant discrimination. This is a result of increasing the amplitude of the consonant portion of the VCV as stimulus input level increased from 58 to 72 dB SPL, while the relatively unchanged amplitude of the vowel portion remained saturated in conditions two through four. This indicates that proper setting and adjustment of the signal processor is very important in receiving the full benefit of this aid.

Some comparisons of the single-channel cochlear implant should be made with the extracochlear implant (or preponatory implant) and with the multi-channel implant. The reader will recall that the preonatory implant is the least complex and least invasive type of electrical stimulation, where an electrode is placed in the round window and in contact with, but not penetrating the membrane, or on the preonatory. This implant is also capable of producing
discriminable changes in the frequencies well within the range of fundamental frequencies in the normal speaking voice and can therefore be of communicative use to the speechreader (Douek et al., 1977). Furthermore, insertion of the electrode is essentially a standard middle-ear surgical technique and therefore much freer from complications than the cochlear procedures (Douek et al., 1977). However, this implant requires extremely high voltages for stimulation.

Edgerton et al. (1982) reported an experiment on a man who had a promontory implant and then had revision surgery where the promontory electrode was replaced with the cochlear implant. This man was a postlingually deaf 76-year-old individual. In this study, the investigators compared the average thresholds and uncomfortable loudness levels between the promontory electrode (PE) and the cochlear implant (CI). These results can be seen in Table 4.

<table>
<thead>
<tr>
<th>Condition</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>6000</th>
<th>8000</th>
<th>STD</th>
<th>ULL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Unilateral</td>
<td>NR</td>
<td>114</td>
<td>107</td>
<td>97</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>PE (R)</td>
<td>70</td>
<td>67</td>
<td>67</td>
<td>66</td>
<td>65</td>
<td>67</td>
<td>70</td>
<td>74</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>CI (R)</td>
<td>85</td>
<td>70</td>
<td>66</td>
<td>56</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>46</td>
<td>45</td>
</tr>
</tbody>
</table>

As can be seen in the table, the CI has consistently lower thresholds for all frequencies compared to the PE thresholds. The investigators also administered the MTS test, the HRRC Rhyme test and the HRRC Environmental Sounds test (Table 5).
TABLE 5  AVERAGED SPEECH AND SOUND DISCRIMINATION TEST SCORES AND SCORE BANCES FOR FOUR CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>MTS Word Discern (mean%)</th>
<th>MTS Stress (mean%)</th>
<th>HARC Rhyme Test (mean%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>17</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>CI</td>
<td>30</td>
<td>76</td>
<td>40</td>
</tr>
<tr>
<td>NA</td>
<td>79</td>
<td>93</td>
<td>77</td>
</tr>
<tr>
<td>CI/NA</td>
<td>74</td>
<td>99</td>
<td>74</td>
</tr>
</tbody>
</table>

Here again, the CI gave much better performance in all the tests except the Environmental Sounds test. These tests clearly indicate the superiority of the CI over the PE implant.

In a study undertaken by the Cochlear Implant Program at the University of Iowa (Tyler et al., 1984), comparisons were made between the Los Angeles (LA) single-channel implant (House and Urban, 1973), the intracochlear Vienna (V) implant (Mochmud-Oslovery et al., 1980), and the 21-channel Melbourne (M) device (Tang et al., 1981). The subjects included four patients with the (LA) device; three patients with the (V) device; and two patients with the (M) device. All the subjects were postlingually deaf adults who had worn their implants for at least three months prior to testing.

Many different tests were administered and a few of these will be cited here, for a full review of the experiment the reader is referred to Tyler et al., 1984). The HARC Accent test was administered and the results can be seen in Figure 16. With this type of test, the client should be able to pick the accented word if the device can reliably code voicing frequency. The results show that the implant does seem to provide some voicing frequency information; however, the investigators expected the patients to
perform better. As can be seen, all the patients scored around 40-50% correct, except V3, who scored 75% correct. The MAC Noise/Voice test was also administered where the subjects had to decide whether the stimulus was noise (whose amplitude was modulated by the speech waveform) or a voice. It can be seen in Figure 19, that two patients with the LA device could not distinguish the difference, but two (M) patients scored 80% correct.

In another test, the subjects had to discriminate whether a sentence was produced by the same or different speakers (of the same sex). The first task was the same sentence stimuli (see Figure 20). The performance on this task was very good; however, when the task involved two different sentences, the scores fell considerably (see Figure 21). This task was much more difficult because the subjects could no longer compare words or phonemes, but had to rely on finer quality differences.

Speech reading with and without implant sound was also compared with word and sentence tests that the investigators developed. They studied two conditions where in one condition, context clues were available (a picture of one of the words in the sentence was presented before each sentence) and in the other condition, no context clues were given. The results can be seen in Figures 22 and 23. As would be expected, the performance on the test with context clues was much better than without.

As seen in the results of the above tests, the multi-channel aid seemed to provide more information in speechreading and in the Noise/Voice test. However, in the Accent test and the
Same/Difference test the results were comparable to the single-channel aids.

To investigate the comparison further of the single-channel versus the multi-channel aid, the investigators designed a procedure of testing a postlingually, profoundly deaf patient (MB). This patient had recently been implanted with the Melbourne multi-channel cochlear implant. The researchers compared the test results of the patient using all 21 channels and then using only one channel. The channel with the largest dynamic range, channel 15, was chosen for the one-channel aid because it provided voicing and amplitude information. The test they devised was a 19-choice nonsyllable consonant confusion test which was presented in three conditions: sound alone, vision alone and sound plus vision. The consonant stimuli were /b, d, f, g, j, k, m, n, p, s, t, v, z/ and presented in a /kog/ context. The client was tested on three separate occasions to note learning effects. The results show that her scores were quite similar for the one-channel aid and the 21-channel aid in the first two testing situations. However, by the third testing date (19 days later from test 1), she scored 42% correct on the sound-plus-vision with the one-channel aid and 56% correct on the sound-plus-vision with the 21-channel aid. These results can be seen in Figures 24 and 25. Figure 26 is also included to show the results of vision alone tested on the first day. The researchers also computed an information transfer analysis. Figure 27, which interestingly shows that the one-channel aid processed slightly more voicing and nasality information than
the 21-channel system. The researchers felt the reason the
one-channel aid performed better was that perhaps the multi-channel
aid produced more potentially confusable cues than the one-channel.
The results from their experiment do suggest that with experience,
the multi-channel scheme may provide more valuable information.

House and Edgerton (1982) also investigated a
multiple-electrode cochlear implant that consisted of three
intracochlear and four extracochlear electrodes. They concluded
from their experiment that “the results of speech and environmental
tests did not reveal performance to be superior with the
multiple-electrode, multiple-channel system as compared to a
single-channel broad-band system,” (p. 115).

It appears that testing in all areas with the single-channel
cochlear implants and multi-channel implants needs to be further
investigated before a decision of which aid is the most beneficial
can be made.
Table 1. Means and Standard Deviations: Percentages for Ten of the MAC Scales.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Percentage</th>
<th>Standard Deviation</th>
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</thead>
<tbody>
<tr>
<td>Question-statement</td>
<td>12</td>
<td>10.9</td>
</tr>
<tr>
<td>Verbal</td>
<td>14</td>
<td>12.8</td>
</tr>
<tr>
<td>Nonverbal</td>
<td>11</td>
<td>10.6</td>
</tr>
<tr>
<td>Anxiety</td>
<td>12</td>
<td>12.4</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>12</td>
<td>11.0</td>
</tr>
<tr>
<td>Social</td>
<td>12</td>
<td>12.0</td>
</tr>
<tr>
<td>Cognitive</td>
<td>12</td>
<td>12.1</td>
</tr>
<tr>
<td>Social functioning</td>
<td>12</td>
<td>11.1</td>
</tr>
<tr>
<td>Performance related</td>
<td>10</td>
<td>13.7</td>
</tr>
<tr>
<td>Four choice response</td>
<td>11</td>
<td>10.0</td>
</tr>
<tr>
<td>Social</td>
<td>11</td>
<td>12.4</td>
</tr>
<tr>
<td>Verbal</td>
<td>11</td>
<td>11.4</td>
</tr>
<tr>
<td>Speech clarity</td>
<td>9</td>
<td>13.1</td>
</tr>
<tr>
<td>General</td>
<td>9</td>
<td>13.1</td>
</tr>
</tbody>
</table>

*p < .05
Figure 6. The response time in percent of each subject in the experiment.

Figure 7. Note: response time for 12 subjects in seconds.
Figure 9. Accuracy scores for 12 individual mutant subjects.

Table 2. Frequency of Correct Responses to Subsequent Subunit Tests, Final Command Test.*

<table>
<thead>
<tr>
<th>CLASS</th>
<th>PRIMING</th>
<th>CORRECT TOTAL</th>
<th>CORRECT FNX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps</td>
<td>P</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>h</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>k</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Affiliation</td>
<td>f</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Privileges</td>
<td>g</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>h</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

* The total number of correct responses for each phoneme was 22.

Figure 10. Speech score differences for vision and verum conditions for each of 12 subjects.

Figure 11.
Figure 18. Accent Test

Figure 19. Noise/Voice Test

Figure 20.

Figure 21.
Figure 22.

Sentence Test With Context

Figure 23.

Sentence Test Without Context
The Risks of Cochlear Implantation

Ling and Niemhuys (1983) state, "It may be predicted that the cochlear implantation of infants will provide maximal development of auditory reception of speech and language skills since the implant provides the extra auditory information at a time of optimal development of other cognitive, social and communicative skills," (p. 594).

However, there is still considerable controversy as to whether a child should be implanted with such an aid. Concern focuses mainly on the possible further damage to the cochlea, leaving the ear unfit for any future advances in this area, and other risks. These are the risks involved with mastoid surgery, implantation of the electrodes and internal induction coil and, as stated, further auditory nerve damage.

Risks involved with mastoid surgery are the same risks involved with common otologic procedures. These include infection, facial paralysis and anesthesia complications. These risks are minimal and carefully monitored; furthermore, patients implanted to date, have not experienced these risks (House et al., 1981).

Implantation of electrodes and the induction coil has also shown no adverse reactions. Concern that leakage may occur from the round window has not been confirmed and bones of deceased patients have shown that fibrous tissues seal the round window (House et al., 1983).
Concern has also been voiced about the common occurrence of otitis media in children and the spread of this to the inner ear. House has reported on three patients that were treated for otitis media with the appropriate antibiotics and no disturbances of the inner ear were noted (Midwest Ear Institute, 1984).

The biggest concern for implanting children is that of further damage to the auditory nerve resulting from the electrical stimulation. Research experimenting with electrical stimulation to cochleas of neomycin-treated monkeys, cats and guinea pigs have shown different degrees of spiral ganglion and eighth nerve degeneration and osteoneogenesis in the scala tympani or organ of corti concurrent with high levels of electrical current (> 100 mV/phase). (Duchart et al., 1982, Miller et al., 1983, Sutton, 1983, Sutton et al., 1983). The House Ear Institute's 3M system uses 1250 mcV/cm2/phase of electrical current, which is much lower than the high currents used in those experiments (Linthicum and Salyer, 1983).

Schindler et al. (1977) experimented with electrodes in the cochleas of cats and found contradicting evidence that the spiral ganglion cells had survived. Furthermore, the only change in the cochlea resulted in the formation of fibrous tissue near the electrodes and the loss of hair cell when high levels of electrical current were used.

Linthicum et al. (1993) began research on four temporal bones of four deceased cochlear implant patients. They reviewed the research of Johnson et al. (1973), who studied one pair of bones of a patient who had used a multi-electrode implant and found ectopic bone growth and excessive loss of sensory elements. It was not
conclusive as to whether this damage was due to the implantation, electrical stimulation, or the results of the condition that caused the hearing loss, Syphilis. New bone formation is a common finding in acquired and congenital Syphilis (Linthicum and Galay, 1993) and could have been the cause here. The other four temporal bones, although still under investigation, revealed no hair cells, varying amounts of supporting cells, some dendrites and extensive strial atrophy. Each patient had hearing losses due to either meningitis, ototoxicity, or idiopathy. One of these four bones showed only a formation of fibrous tissue around the electrode.

Review of the current research of stimulation-induced damage to the cochlea seem to coincide with what Button and Miller (1993) deduced, that "stimulation at moderate and high current values can produce cochlear pathology, but intermittent low-level current may have little effect," (p. 57).

Furthermore, patients who have received the JM House system are continuously being monitored in regards to their thresholds and to date it has been reported that no significant changes have occurred. The Midwest Ear Institute (personal communication, 1984) stated:

At this point, the House Ear Institute has had considerable experience with human implanted subjects. In total, these patients have had approximately 900,000 hours of electrical stimulation. This is approximately 155 person-years of use of the implant for a 14-hour waking day. One patient has had electrical stimulation for ten years, with daily use for almost nine years—45,000 hours of electrical stimulation. Eight patients have each used the implant
for seven or more years. More than 50 patients have used the
implant for a year or more. There has been no deterioration over
time in audiological performance or electrical thresholds.
Psychological and neuropsychological assessments show no evidence of
organic brain damage or other psychological problems. Studies at
the House Ear Institute have shown that the electric current does
not even seem to spread to or affect the vestibular system or the
facial nerve. (p. 8).

Furthermore, "behavioral studies of implanted monkeys indicate
that absolute sensitivity to intracochlear stimulation remains
relatively unchanged over long periods," (Sutton and Miller, 1983,
p. 57).

With concern for risks involved with the cochlear implant
centered mainly on the further degeneration of surviving neurons,
one must remember that the particular population chosen for implants
are only those patients with already extensive losses that
conventional hearing aids cannot be utilized effectively. In
addition, it has been suggested that future research may develop a
new implant system that is more promising than the present one.
This is most probable; however, it would take many years for
extensive experimentation with animals and then adults before this new
implant would be approved for children. Hence, many years would be
lost when the child could have been receiving sound stimuli.
Furthermore, if research should advance, the child would still have
the better cochlea available for implantation as only one ear, the
worse ear, is implanted. As seen by the reported research, risks
involved seem minimal and as House et al. (1983) stress, "going

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nothing at all has devastating consequences for the long-term
quality of the child's life." (p. 967).

Although the cochlear implant is not for all children, as it is
not for all adults, it can help that small segment of children in
whom conventional amplification does not benefit. In July, 1980, a
profoundly deaf boy, ten and a half years old, received the first
implant at the House Ear Institute. Since that time 15 other
profoundly deaf children have undergone surgery for the cochlear
implant. With the FDA approval in 1994 for clinical study, directed
by the House Ear Institute, it is likely that one will see
considerably more children implanted with this aid. Currently, with
only four years pass the first implantation of a child, literature
is still scarce and inconclusive as to the amount of help this aid
will provide the prelingually deaf child.
History of the Tactile Aid

Using the sense of touch for communication for the deaf and the deaf-blind is not a recent phenomenon. In the 1890's, a teacher by the name Hofgaard introduced a method of tactile speech communication called Tadoma, to his Norwegian deaf-blind students. This method is based on monitoring the actions present on the speaker's face and neck during articulation. Usually, the thumb rests lightly on the lips and the fingers spread over the face and neck (Reed et al., 1982). This method was used by Helen Keller and proved to be very successful in conveying speech to those who are well trained; however, this method does require extensive training and social acceptance because of the intimate touching involved.

Success with Tadoma was followed by the first formal effort in developing a tactile aid by Gault (1928). This was a tactile speech amplifier named the Teleaker. This device was a system of amplifiers-filters with a range of 0-2000 cps. The speech signal was passed through the amplifier-filter to the hand over a set of five vibrators, one vibrator stimulating each separate finger. This device enabled the profoundly deaf person to receive cues of accent, tempo, emphasis and rhythm and is very similar to the single bone conduction vibrator used today. Although somewhat successful in aiding speech reception, this aid assumed that the skin was as sensitive to acoustic frequencies as the ear and thereby utilized frequencies above the skin's optimal range of about 75-800 cps (Pickett and Pickett, 1963).
In order to overcome this spectral difference, Dudley (1936),
invented the vocoder. The vocoder divides the frequency spectrum by
a set of band-pass filters into a number of narrow low frequency
channels. Each channel then relays its information to the right of
stimulation. Each channel’s output uses voltage proportional to the
amount of energy fed into that band pass. The first tactile vocoder
was built by Levine and others (1949-1951), and was tested with
some success. This vocoder was named Felix. For a more
comprehensive history of the tactile sensory aid, the reader is
referred to Kirman (1973).

Since this time, a wide variety of tactile devices have been
developed and used experimentally. These more recent devices differ
in relation to a) which aspects of speech is encoded; b) how the
speech is analyzed and processed to derive these aspects from the
acoustic signal; c) the method used to transfer this information to
the skin (vibratory or electrical); and d) where to stimulate the
skin (fingers, sternum, arm, thigh, abdomen, etc.). Although
research concerning communication aids has been ongoing for the past
fifty years, and although there have been developed many different
types of such aids for the profoundly hearing-impaired person, it is
disappointing to note that only a very few of the devices to be
discussed have been made commercially available to the general
public. This has not only hampered the growth of many individuals,
it has also hampered any long-term investigations that would
ultimately determine the greatest benefits that an aid may provide.
The skin also is limited in intensity ranges for vibration and thresholds centers around 55dB (see Table 6) (Friel-Patti and Roeder, 1983). Bekassy states further that the similarity between loudness and the sensation of vibration magnitude holds only for the very sensitive parts of the skin, like the finger tip, but not for the less sensitive skin of the upper arm," (p. 8).

<table>
<thead>
<tr>
<th>Speed</th>
<th>Awareness</th>
<th>250</th>
<th>500</th>
<th>750</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>6000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-40</td>
<td>40-55</td>
<td>40-60</td>
<td>50-65</td>
<td>55-66</td>
<td>60-65</td>
<td>60-75</td>
<td>60-65</td>
<td>55-66</td>
<td>60-60</td>
<td>55-60</td>
<td></td>
</tr>
</tbody>
</table>

Another limitation of the skin is that it requires 1 second for full subjective sensation compared to the ear which needs only .52 seconds and it also has a much longer decay time (Bekassy, 1958).

One phenomenon that Gedard (1957) reported was the perception that "a lessening of amplitude is promptly judged as 'faster' while adding it invariably results in the judgment, 'slower'," (p. 118).

An interesting finding that Bekassy reported was the similarity of the vibratory patterns on the skin and in the inner ear. When a needle vibrated against the skin, (under stroboscopic observation) traveling waves were seen spreading out in concentric rings and felt only where the needle touched. As the frequency increased, the wavelength became smaller. This same occurrence is seen in the inner ear; however, the location changes in the ear also, depending on the frequency. Furthermore, when presented with a 100 Hz tone for
hearing at the ear, it is felt at ear level and this feeling moves up the skull as the frequency is increased. When the 1000 Hz tone is presented as vibration to the skin, it is felt on the surface of the skin and the feeling moves outside the skin as the frequency increases.

Localization is another similarity between the tactile and hearing senses. If sound clicks are presented to both ears with a time difference between the two ears, two separate clicks will be heard, each on its respective side. As the time delay is lessened, the clicks will move closer toward the midline. As the time delay becomes smaller still, the images of the two clicks will suddenly fuse on the side presented with the sound click first. As the delay grows smaller, the click moves closer to the midline until there is no time delay and the sound is perceived in the midline. Bekesy (1959) found that this is the same as localization of the tactile sense. He states, "It was surprising to find that the time difference necessary to make the fused sound image travel from one side of the head to the other was the same as the time difference necessary to make the vibration sensation travel from one area of the skin to the other. The nervous systems controlling these kinds of inhibition must be very similar in both cases," (p. 12). Figure 29 demonstrates this similarity between the ear and the skin.

Bekesy further discovered that at zero time delay the sensation area on the arm was much larger than for other time delays as can be seen in Figure 28 depicted by open circles. He also found that when the distance was great between the two vibrators (20 cm) at time zero, the magnitude of the sensation became so small that it was
hardly felt. However, when the phase difference was larger, the magnitude increased and lateralized to the proper vibrator.

Figure 29

Frost and Richardson (1976) tested this phenomenon of tactile localization using two single-channel vibrators. They also reported that there was no difference between active (head movements permitted) localization auditorily versus tactually. They reported also that intensity difference cues were not used to make the judgment, unlike the ear which uses time and intensity cues for localizing the sound source. In Frost and Richardson's study, they reported that if the subject moved his head 5 degrees to either side of the stimulus direction, a sensation of apparent movement moves from one finger towards the other. They further found that sound localization was also possible with two competing sounds. In all their studies, the researchers noted that accuracy improved with practice.

The last parameter to be mentioned here will be the point of stimulation of the skin. It has generally been thought of that the finger tips would be the most sensitive towards receiving vibration.
and Bekesy (1950) supports this idea in his article. However, it has been shown that once an individual has become familiar with the vibrations of a tactile aid, they can generalize their learning to other sites of stimulation and produce the same accuracy (Yeni, Komshian and Goldstein, 1977; Traunmüller, 1980; Engelmann and Rose, 1975).
Tactile Aids

The tactile aid, like the cochlear implant, to date, cannot be used as a sensory substitute for hearing. As seen with the implant, the tactile aid cannot adequately process the speech signal to provide understanding of speech. "Despite the variety of talent attracted to the problem, speech communication through the skin still remains an unattained goal," (DeFilippo, 1978, p. 1). Whether this is a result of inadequate equipment or due to the natural limitations of the skin, is still a dilemma. Kirman (1972), states, "First, all previous attempts to build a successful tactile display of speech has been disappointing. Second, a major current theory of speech perception maintains that speech is a special sort of code which is uniquely and biologically tied to the auditory system and that the skin (as well as any other sensory modality) is doomed to fail in decoding it. Third, the psychophysical literature on tactile sensitivity suggests that the resolving power of the skin, both temporally and spatially, is too limited to deal with the complexities of speech." (p. 54).

The tactile sensory mode has therefore taken the role of a sensory aid to the more dominant sense of vision. This role can be to add complimentary information to the vision component as well as redundant information. By providing the speechreader with tactile vibrations in the form of complimentary and redundant cues, the speechreader will in all probability, gain more information, more adequately and quickly, from conversational speech; and furthermore,
probably with more confidence.

Many different types of tactile aids have been developed. These range from the simple, single-channel bone conduction vibrator to the MESA (Multipoint Electrotactile Speech Aid) which incorporates 200 stimulating electrodes (Sparks et al., 1979; Sparks et al., 1976). The single-channel vibrator like the Tactaid I (see Figure 30) (Franklin, 1984) will enable the user to perceive voicing information, first formants, speech rhythm, intonation, environmental sounds and manner of features of speech. The single-channel vibrator can be referred to as a feature coding device because the manner of articulation, such as nasality and frication is easily perceived.

Another more complex tactile aid is the vocoder, or spectral coding aid. For the vocoder, "[the] acoustic signal is analysed into frequency bands and the envelopes of the output of these bands are used to drive an array of stimulators in such a way that frequency is transformed into place of stimulation." (Reed et al., 1982, p. 5). The geometry of the array can vary from linear to planar. In the linear array, the location of stimulation represents frequency region and the acoustic amplification is related to the stimulus intensity. Figure 31 is a block diagram of an example of such an array (Pickett and Pickett, 1963).

The planar array uses two dimensions to encode the speech signal. One dimension codes for frequency, as seen with the linear array, and the second dimension codes for amplitude or time. The planar array is nonspatial as compared to the linear array because it relies more on perceiving a pattern of tactile qualities over...
time. Figure 3E is an example of a tactile aid which uses a planar array with 225 solenoid drivers (Kirman, 1973). The spectral displays can also differ in the number of simulators (a few, as seen in Figure 31 to a few hundred, as seen in Figure 32). They can also differ in the type of stimulation, such as electrical versus mechanical, and in place of stimulation, such as the fingers, hand, arm, thigh, or abdomen.

The signal processing can also vary among the different spectral displays. This can differ in the choice of filters, center frequencies of the filters, time constraints, and sampling rates.

The reader can see by this brief description of the variety of possible combinations, that different tactile devices can, and are, developed. A few different examples of some of these devices will be covered in more depth later in the paper; however, the reader is referred to Kirman, 1973, Reed et al., 1982, and Strong, 1975, for a more complete reference.

Whether a single-channel aid or vocoder is developed, it must be kept in mind that a) they will need more power to drive the tactile transducers than needed for a conventional hearing aid, b) they will need to utilize a scheme for frequencies above 1000 Hz., where there is no tactile sensitivity, and c) they will need to eliminate excitations caused by background noise.

The next section will look at the single-channel vibrotactile aid. To date, because of its size (wearability), power requirements, and simplicity, it is the only commercially available tactile aid.
Figure 30.

Figure 31. Block diagram of actual vocoder and overall channel sensitivities. The response curves of adjacent channel filters overlapped at three to eight dB below the center level. Relative channel sensitivity at the center frequency is based on equal-intensity judgments between adjacent channels by two measuring subjects, stimulating one channel-finger at a time.

Figure 32. Views of the tactile display: (a) side; (b) top.
Single-Channel Tactile Aids

As stated earlier, to date there is no sensory aid that can process speech in such a way as to make receptive speech comprehensible for the profoundly hearing-impaired. In order to achieve this, there is the need to develop a speech-processing system that will automatically extract the important features of speech and present this information in a comprehensible form using a visual or tactile display. Until this is possible the simple single-channel tactile aid seems to be the most practical and effective way of delivering at least some cues to the profoundly hearing-impaired individual to aid him in speechreading. The single-channel vibrator can extract the simple features of friction, nasalization, voicing, fundamental-frequency contours, speech rhythm, and stress. These cues will be quite beneficial when trying to discriminate between the many homophonic phonemes in speechreading.

The main advantages of the single-channel aid over the vocoder are that it is wearable and self-contained. In appearance and use, the wearable tactile aid is similar to the conventional body-type hearing aid but differs with its signal-processing scheme which are adapted for the tactile sensory system. Unfortunately, it is not possible to measure precisely how well each individual will be able to do with any tactile aid because of the external factors of training time and time in life of onset of the hearing loss; however, the following studies will give the reader an idea of what
the aid is capable of doing.

Erber and Cramer (1979) evaluated a bone conductor vibrator on six hearing adults who were appropriately "deafened" with masking noise and ear plugs. They were researching a task of recognition of sentences and after twenty hours of practice they reported that all six subjects achieved high levels of recognition. Erber and Cramer noted the cues each subject said they used to achieve their success, these were:

1) overall duration
2) number of (stressed) syllables
3) variations in intensity and duration
4) prominent pauses or bursts
5) initial or final segments of each pattern

The importance of this study was to suggest that each individual used different combinations of the above cues to form their strategies of utilizing the cues present through the vibrator to achieve success. This is an important indicator for the clinician in regard to which strategies the child can use most appropriately and successfully as each child may need to use different schemes to achieve success.

Hauks (1978) performed a study to see if a bone conductor could present enough cues so that the subject could perceive changes in the meanings of sentences due to modifications of intonation and stress patterns. Hauks presented nine sentences for stress in the initial, medial and final positions with syllabic lengths of four-seven syllables. He also presented nine sentences for intonation (three rising, three falling, three steady state). All
sentences were presented in closed sets of three. An example of a stressed closed set was as follows:

**JOHN** was a good boy.

John was a **GOOD** boy.

John was a good **BOY**.

Hawe's results indicated that subjects could perceive stress patterns better than chance, especially in short syllabic length sentences and in the initial and medial positions. However, the results concerning intonation were no better than guessing. This demonstrates that with the single-channel tactile aid, cues of stress are available but cues of intonation are not.

Traunmüller (1968) developed a single-channel aid, the Sentiphone, with focus on presenting the optimal complementary information to speechreading. Traunmüller contends that "It is difficult to attend to more than one stimulus at a time by the same sense. If the tactual sense is used for complementary information, the two kinds of information are expected to be easier to combine," (p. 186).

The Sentiphone codes efficiently for intensity and frequency dimensions. Traunmüller did not include a third dimension of place coding because of a previous study he did (Traunmüller, 1975) where discriminability of intensity and frequency seemed to decrease when place was added as a third dimension. A block diagram of the Sentiphone can be seen in Figure 3. Figure 3A shows how some consonants and vowels are distinguished by vibratory frequency and intensity using the Sentiphone. In Traunmüller's study, the subject held the cylindrically shaped vibrator next to the cheek bone.
although in practical usage it is held in the hand. The task that
was being researched was a sentence task of the type, "A bag B C,"
(p. 100) where A, B, and C, were words selected by chance from three
respective sets of thirty words each. Training included seven hours
of practice with various material and an additional two hours of
practice was used with the task material. The results of the
testing can be seen in Table 7.

Traunmüller also tested recognition of phonemes by tactile
features. Altogether eight hours were used for the training and
testing of the phonemes and the vibrator was held in the hand. The
results of this test can be seen in Table 9 and Figure 35. The
results for both the tests indicate that tactile cues can aid in
phoneme and word recognition to some extent.

Kaplan (1980) reported on a postlingually deafened student at
Gallaudet College. The student could express himself very well but
had very little receptive ability as he had no experience with
lipreading and no skills with signing.

This student was introduced to the Oticon F11P on-the-body aid,
attached to a bond oscillator by a 36-inch cord and coupled to the
palm of his nondominant hand. The client reported that at 55dB HL,
he could distinguish between speech and noise because speech was
perceived as a random pattern and noise as a continuous tone steady
tone. Parts of The Minimal Auditory Capabilities (MVC) Battery was
given to the student and his results are given in Table 9.
TABLE 3

<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Visual+Tactile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Question/Statement</td>
<td>58%</td>
<td>75%</td>
</tr>
<tr>
<td>2) Recent test</td>
<td>13%</td>
<td>65%</td>
</tr>
<tr>
<td>3) Everyday Sentence test</td>
<td>10%</td>
<td>27%</td>
</tr>
</tbody>
</table>

One semester later the client had increased his scores in the CID Everyday Sentence test in both modes, with the visual increasing to 13% and combined mode increasing to 46%. The client also exhibited better voice monitoring of pitch and intensity control by varying it appropriately in noisy situations.

Franklin (1984) also reported on two individuals who were introduced to the TactaID I (see Figure 30 and 36). The first patient was a profoundly deaf-blind 59-year-old man. He was well-practiced in the Tadoma method and had attained good communication skills; however, he felt his speech was too loud and wanted to correct this. Franklin reported that in approximately one hour of using this single vibrator, the client's voice loudness decreased immediately to the appropriate level. However, without the aid on, he gradually grew louder to his original level. The client was given informal testing while using the aid where he successfully distinguished between the words bat and bit and between the sounds /p/ and /t/ with essentially no errors. Franklin also reported that the client could successfully identify phrases presented in pairs and well above chance with words or phrases selected at random. He was also able to tell the difference between a man's and a woman's voice.
The client also reported that he enjoyed music and could dance rhythmically. After hearing automobile noises and musical instruments, he could also identify these.

Although the client was already well versed in Tadoma, his successful demonstration of the Tactaid I can give the reader an idea of what a tactile aid may have the potential of doing. It can only be predicted that the initial success this client had with the aid will become even greater with practice and training.

The second client Franklin reported on was a 42-month-old congenitally deaf boy. He was fitted with the aid at 35 months old. Franklin reported that the boy "appeared to recognize almost immediately that the feeling [perceived through the tactile aid] was associated with such external events as banging a can or slamming a door," (p. 53).

Franklin reported the following observations regarding the child's behavior which were not characteristic of a child with that degree of hearing loss:

1) The patient's oral sound production had, to some extent, steadily increased from age 35 months to age 46 months;

2) The patient deliberately generated speech-like sounds in conjunction with arm and body motions while attempting to relate to his hearing peers;

3) The patient readily attempted to imitate simple words that were spoken to him on a focused face-to-face basis (this resulted in approximately accurate sound production with very accurate timing);

4) The patient consistently generated environmental
sounds such as banging noises, seemingly for the sheer pleasure of feeling them. (Franklin, 1984, p. 23).

Although the child still wore his hearing aid, Franklin noted that he did not demonstrate the attention toward it that he gave to his tastic vibrator: he was reported to produce vowel sounds to check if the aid was operating properly and then had told his mother if it was not.

In a study by Proctor and Goldstein, a prototype of the Taclaid was worn by a 33-month-old profoundly deaf child for a ten-month training period. It was reported that the child's receptive vocabulary increased dramatically and during the last six months, her vocabulary doubled in size every month. By the time the child was three and a half years old, she had a vocabulary of 400 words.

This study supports strongly the contention that if the child is introduced to the sounds of a sensory aid early, during the optimal language-learning years, perhaps normal communication can be possible.

As seen by the cited studies, the single-channel vibrator does have a justifiable usage. It has been shown to aid in cues of duration, stress, variations in intensity and duration, prominent pauses or bursts, voicing, environmental sounds, and fundamental frequency. It has also helped in the expressive abilities of the four clients who were reported on. More importantly perhaps, the aid has given hope and encouragement to those who have been unable to receive any benefit from a hearing aid. Even though the single-channel aid cannot convey conversational speech alone, it can help with speechreading. It remains to be seen with longitudinal
**Table 8.**

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Context</th>
<th>Number of words</th>
<th>outcomes</th>
<th>vowels</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>A V C a</td>
<td>361</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td>TT</td>
<td>A V C'</td>
<td>100</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>TT</td>
<td>A V C'</td>
<td>100</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>LN</td>
<td>A V C a'</td>
<td>100</td>
<td>21</td>
<td>21</td>
</tr>
</tbody>
</table>

Error by chance:

- 83
- 50

**Figure 34.** Block diagram of Tactile I.
Multi-Channel Tactile Aids

The vocoder, as previously discussed, is a tactile sensory aid that filters the speech signal into bandwidths of a specified size and then delivers the signal to separate channels at separate sites of stimulation. This results in a frequency-to-place stimulation. As discussed, the array of the stimulators can be arranged as linear or planar, resulting in a unidimensional spacial excitation or in a two dimensional spacial or spatiotemporal excitation.

Examples of different types of spectral displays, or vocoders, will be discussed in the following paper, and the reader is referred to Kirman, 1974, Reed et al., 1963, and Strong, 1975, for further information.

An example of a spectral display, or vocoder, is given by Pickett (1963). In his investigation, he used a vibrotactile device which processed the speech into ten channels by filters with center frequencies at: 210, 400, 630, 830, 1050, 1680, 2250, 3325, 5000, 7700 Hz. Each channel drove a single vibrator that was coupled to one of ten fingers; the lowest channel was coupled to the left little finger and the highest channel was coupled to the right little finger.

Pickett states that "Generally, only the second vowel formant was felt due to the pre-emphasis [of the high frequencies] and to the simultaneous vibratory masking of the first formant."

Perceptually a stop was felt as a gap and a continuant was felt as a continuation. Further, voicing compared to unvoicing and nasal
compared to non-nasal was felt as a gradual versus a sudden onset of adjacent vowel vibrations. The short bursts of affrication following unvoiced stops and unvoiced fricatives were felt by the vibration of the upper three vibrators.

Pickett’s subjects for his experiment included 24 deaf children (n=15). In his experiment, he compared speechreading to tactile perception in discrimination of speech sounds and speechreading to the combined mode in the identification of words. In this discussion, only the latter section of his study will be cited. This study, comparing speechreading alone to the combined mode, was completed to show the advantages of using the tactile sense as a complement to the visual sense. The results can be seen in Figures 37 and 38. Pickett used one, two and three syllable words in closed sets of four, nine and finally twelve words. The results show that the added tactile information did improve word recognition by an average of 16.9% for the twelve-item closed set. Pickett explains this improvement in communication in two ways: first, some information that cannot be conveyed through the visual sense can be conveyed through the tactile sense thereby increasing the total channel capacity. Secondly, the redundant information received by both senses will “improve the resistance of the link to interference or distraction in one of the existing sensory systems,” (p. 328). He further states that “In tests with combined lipreading and tactile reception, the tactile information on consonants and the number of syllables was found to improve transmission without detracting from lipreading the visible features of the other sounds,” (p. 328).
Another study by Brooks and Frost (1983) also used a linear vocoder display where the speech spectrum was divided into 16 filter channels with center frequencies at 200, 250, 320, 400, 500, 640, 800, 1000, 1250, 1600, 2000, 2400, 3200, 4000, 4800, 6400, and 8000 Hz. The channels activated 16 vibrators placed 3.5 cm apart and coupled to the subject's right brachial forearm.

The subjects involved were two female, normal hearing graduate students who were taught to identify words, five at a time. Five additional words were added to the vocabulary when the subjects passed a specified criterion of identifying, with 80% accuracy, the practiced words. This continued until one subject reached a 70 word vocabulary after 40.5 hours and the second subject acquired a vocabulary of 150 words after 55 hours (see Figure 39). The investigators noted that only 20 significant confusions were found and gave examples of the confusions as: "plane" for "cone," "from-thing," "see-sing," "not-what," and "chicken-kitten." They further noted that "when an error did occur some correct information was still being obtained through the vocoder...in the "from-thing" confusion both words start with an unvoiced fricative and end in a nasal." (p. 35). They also noted that over time the subjects learned to overcome many of these 20 significant confusions.

In a follow-up study (Brooks et al., 1982) the subject who had previously learned 150 words had increased her vocabulary to 250 words. The investigators evaluated her learning using a) phrases derived from the 250 vocabulary words, b) novel words, and c) novel phrases comprised of frequently occurring English words. All evaluations were given as open formats and presented only one time.
Additionally, the combined mode (CM) of speechreading and the vocoder and speechreading (SR) alone were compared. The results can be seen in Table 10.

Table 10

<table>
<thead>
<tr>
<th></th>
<th>Phrases/Old Words</th>
<th>Novel Words</th>
<th>Phrases/New Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>81%</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>SR</td>
<td>55%</td>
<td>40%</td>
<td>40%</td>
</tr>
</tbody>
</table>

This study shows encouraging results for the vocoder when used as an aid to speechreading, but the investigators state that "the true limits of the system will not be known until:

1. the identification of connected speech is attempted with the tactile vocoder,
2. the device is tested on profoundly deaf subjects, in particular prelingually deaf subjects (results on one profoundly deaf subject are reported in Scilley, 1988),
3. the device is made portable so that lengthy experience in realistic situations is possible, and
4. the device is tested on young deaf children so that advantage may be taken of the neural plasticity that exists in the young human nervous system." (Brooks and Frost, 1983, p. 30).

DeFilippo (1984) reported an interesting study comparing four different vocoders. These tactile devices differed in number and type of stimulators and the type of speech processor. Three of her studies will be cited here. In evaluating each individual aid, DeFilippo used a method called tracking (DeFilippo and Scott, 1973).
The author finds this to be an excellent evaluation tool to test any type of device that is said to be a communication aid to test speechreading and speechreading alone. Tracking is used to rate communication by words per minute. The task is performed by having the clinician (or talker) read from a prepared text, segment by segment. The client (or receiver) is to repeat verbatim after the talker what was read. The receiver repeats the text as s/he perceived it and can interrupt the talker whenever s/he needs help. Whenever the receiver is having difficulty, the talker can aid the receiver in any way to help her/him to understand what is being read. This may be by repeating single words, breaking words apart, using a simile or any other method until the receiver can produce a correct repetition. The object of the evaluation is to see how many words per minute the receiver can repeat verbatim. DeFilippo and Scott note that when comparing data, one must realize that a) the talker may use different strategies (which may or may not be helpful and therefore affect the timing); b) the texts may differ in literary style, complexity and vocabulary; c) the length of interval for each trial may vary; d) the rate of speech production of the talker may vary; e) the receiver's confidence and speech skills may vary; and f) the relationship between the talker and receiver may affect the outcome (DeFilippo and Scott, 1978). Despite these variables, the author feels that this unique technique of evaluation is very effective in finding any inadequacies that a system may have and in evaluation of whether the system can be used as a communication aid.
DeFilippo's (1984) studies were investigated to see if manner of articulation (how the sound is produced) presented tactually could complement visible articulation for the profoundly hearing-impaired. In DeFilippo's second study, she presented the subject with varying qualities of sensation, a temporal code, rather than varying place of stimulation. She used a two-channel vibratory aid; a Suvaq vibrator, with a low-pass filter at 1000 Hz, and a single electrical stimulator with a high-frequency channel that passed speech above 4000 Hz. (See Figure 40). The electrode was placed on the back of the hand opposite of the vibrator.

Interestingly, the electrical stimulation felt like a "pricky, sharp-edged noise (aperiodic)" which corresponded to high-frequency components of speech such as fricatives, affricates and plosives, which are all aperiodic sounds. The vibrator, conversely, corresponded to the periodic lower frequency components such as vowels, liquids and nasals and was perceived as even and regular vibrations.

The tracking procedure and conventional syllable, word and sentence identification tests were used in the modes of unaided speechreading, speechreading combined with the single vibrator and speechreading combined with the "hybrid" aid (vibrator and the electrode). The results can be seen in Figure 41 and 42 for the two subjects. The scores indicate that both tracking and the identification tasks were improved when the tactile sense was added to the speechreading; furthermore, the hybrid aid seemed to give better results than the single vibrator alone. (Tracking rate with the hybrid aid: x=38 wpm for E.I.S. 50 wpm for C.O.F.).
In the third study, the device was expanded into three channels. One channel transmitted high-frequency consonant information with a high-pass filter at 8000 Hz, to an electrode placed in the middle of the back of the hand. A second channel, with a band-pass filter centered at 2400 Hz, passed mid-frequency vowel and consonant information to two electrodes which were located on either side of the high-pass channel. The third channel was the Suvag vibrator, which had a band-pass filter at 20-300 Hz, and gave first formant (F1) information (see Figure 43).

Perceptually, the subjects felt a prickly sensation in the middle for sounds such as /s/ and /z/ and a diffused prickly sensation (due to the second channel spacing) for sounds such as /s/ and /z/. Low F1's were felt as rough on the vibrator while high F1's were felt as smooth vibrations. DeFilippo only used the tracking procedure in this study, using the same two subjects. The results can be seen in Figure 44. The tracking scores did improve with the three-channel aid (after ten hours: \( x = 54 \) RPM for B.L.G.) 71 RPM for C.D.F.

In study 4, a three-channel vibratory aid was used and can be seen in Figure 45. The vibrators used were the Suvag, placed in the center, and two RadioEar 870A vibrators, one on each side of the Suvag. These vibrators were coupled to the skin just below the sternum.

The perception of /s/ for the subjects, was an aperiodic sensation stemming from the center vibrator while the /z/ produced a larger spread of an aperiodic sensation as all three vibrators were activated. A diffused periodic sensation of either rough (low F1)
quality or smooth (high F1) quality was felt for vowel sounds, and all three vibrators were activated.

Eight subjects were used for this study and the tracking procedure was repeated. The three-channel hybrid aid used in study 3 was also used in this study for comparison. The results can be seen in Figure 46.

The subjects using the hybrid aid (x=27 wpm) scored about as well as those using the all-vibratory aid (x=38 wpm). The investigators contend that the "two devices are comparable in benefit over a short practice period, but that a longer time may be necessary to optimize cues from electrical stimulation as in the hybrid aid." (p. 225). The investigators further note, regarding the three studies reproduced here, that the "broad spectral information...was shown to increase lipreading efficiency when displayed in a temporally cohesive pattern that does not rely on spatial cues across the skin surface... [Furthermore,] the temporal code was accepted readily by the subjects in study 4." (p. 226).

One last dimension of the vocoder should be mentioned, that of comparing electrical stimulation with vibratory stimulation. In the study, by DeFilippo (1984), the investigators changed from using electrical stimulation to mechanical vibratory stimulation because of the reported variability from day to day in optimum positioning of the electrodes. "Small changes in location tended to produce large changes in sensation, from a level below detection to discomfort," (p. 229). DeFilippo also cautioned about parental acceptance of electric shock as a speech cue for children which may be a problem.
Many investigators prefer vibrotactile devices over the electrotactile devices as a result of the availability of vibrators for experimental use and the inherent difficulties experienced by applying an electrical current to the skin. (Roese, 1984).

When comparing vibrotactile stimulation to electrotactile stimulation, Sachs et al. (1980) suggests that the vibrotactile devices are more efficient in the lower frequencies and the electrotactile devices are more efficient for the higher frequencies. DeFilippo's study, as cited previously, used this strategy with the hybrid aid.

To determine which stimulation would be the most beneficial and practical, long-term studies need to be undertaken and it is possible that these studies will show that DeFilippo's method of combining the two stimulators may be the best solution.
### Lip-Reading Response

<table>
<thead>
<tr>
<th>Word Spoken</th>
<th>Eng</th>
<th>Dig</th>
<th>Skägg</th>
<th>Äng</th>
<th>Skn</th>
<th>Sknöde</th>
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<tbody>
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<td>12</td>
<td></td>
<td></td>
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<tr>
<td>äng</td>
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<td>12</td>
<td>1</td>
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</tr>
<tr>
<td>sknöde</td>
<td>30</td>
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</table>

### Tactual Response

<table>
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<th>Äng</th>
<th>Skn</th>
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<td>4</td>
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<tr>
<td>äng</td>
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<td>26</td>
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<tr>
<td>sknöde</td>
<td></td>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3: Classification of Swedish words by lipreading alone and by combined lipreading and tactual. In the four-word test, talker A spoke five of each word in each of the six deaf subjects under each receiving condition. In the nine-word tests, the talker spoke four of each word in each of the six deaf subjects under each receiving condition.](image)

---

12
### LIP-READING RESPONSE

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
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<tbody>
<tr>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
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### TACTUAL VOCODER AND LIP-READING RESPONSE

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<td>7</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>7</td>
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<td>3</td>
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<td>0</td>
</tr>
<tr>
<td>TALKER G</td>
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<td>1</td>
<td>3</td>
<td>2</td>
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<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
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</tbody>
</table>

60% correct 85% correct

**Fig. 26** Identification of Swedish words by lip-reading alone and by combined lip-reading and tactile vocoder. Each of the talkers spoke three of each word to each of seven deaf subjects under each receiving condition.

**Fig. 27** Individual learning rates for subjects 1 and 2.
Figure 7. Block diagram and illustration of a two-channel hybrid aid (vibratory and electrical) used in study 2. A wide elastic band (not shown) was worn around the hand to hold the vibrator and electrode in place. The electrical pulse generator was designed by F. Saunders and built by R. Sachs.

Figure 71. Study 2: Identification of syllables, words, and sentences in percent correct by two normal-hearing observers listening without an aid (unaided), with a single-channel vibratory aid (vibrator), and with a two-channel electrical-vibratory aid (hybrid). The sentences were scored after each of five successive presentations in each condition.
Figure 2: Lipreading rate in sign for two normal-hearing observers without aid (unaided), with single-channel vibratory and with two-channel electrical-vibratory aid (hybrid). The task was tracking. Observers B. L. S. did not enter the study until the 4th hr. A new talker was introduced for the 17th and 19th hours, indicated by the arrows.
Figure 43: Block diagram and illustration of a three-channel hybrid aid (electrical-vibratory) used in studies 3 and 4. A glove-like band (not shown) was used to secure the transducers to the hand. The aid was designed by R. Scott.

Figure 44: Study 3. Lipping rate in words per minute for two normal-hearing observers without feedback and with (added) a three-channel electrical-vibratory aid (hybrid). The task was tracking.
Figure 45. Block diagram and illustration of a three-channel vibratory actuator in study 4. The transducers were embedded in a silicon sphere, just below the helmet. The actuator was attached by the patient as shown in Figure 14.

Figure 46.
Single-Channel Versus the Multi-Channel Tactile Aid

Few studies have been reported where an actual comparison is made of a single-channel aid and a multi-channel aid such as the vocoder. Until such studies are accomplished, a comparative evaluation will be difficult to make because of the use of different methods of training and different subject populations. Kirman (1962) also notes that "even if one could conclude, however tentatively, that one device is superior to another, it would not be clear whether the superiority is due to differences in the signals applied to the skin or to differences in the mode of presentation," (p. 297).

A single-channel vibrotactile aid was compared with a two-channel electro-vibrotactile aid and these results were compared to speechreading alone. This study was investigated by Scott (1979). The single-channel aid consisted of an amplifier, a low pass filter at 1000 Hz and the Sveog vibrator. The two-channel aid used this single-channel aid plus a high frequency electrovibrotactile channel consisting of a high pass filter at 4000 Hz, an electrical pulse generator and a bipolar electrode (see Figure 47). Scott evaluated the combined mode (aid plus speechreading) of each aid by using the tracking method (see Figure 48). As can be seen in the results, the two-channel aid did give a 7% and 8% (S1 and S2 respectively) increase over the single-channel aid. The single-channel gave a 20% and 16% improvement relative to speechreading alone performance. These results indicate that the
multi-channel aid may have the potential of conveying more usable information in speechreading.

In a different experiment by Scott (1974), he compared a bone conductor vibrator and a five-channel spectral-type aid (coder). In this study the subjects performed much better on making same-different judgements on syllable length material using the spectral aid compared to the vibrator. However, when discriminating sentence material, the subjects fared better with the vibrator. The results of the latter part of the study may suggest that there is a perceptual difficulty in ordering five separate channels of information in time for sentence length units of speech.

Garney (1968) also made a study comparing the perception of phonetic features of speech using a single-channel aid and a multi-channel aid. His study revealed that there was no substantial difference.

Kirman (1973) suggests that the limited success of the coders or single-channel bone vibrator is a result of the following:

1) The tactile sense has many inadequacies as a receptor for a complex acoustic speech stimulus.

2) The frequency information is processed inappropriately for the skin's usage.

3) The limited spatial resolution of the skin results in simultaneous masking.

In reference to the third point, Pickett and Pickett (1963) state that when two or more fingers are stimulated simultaneously, the identification of the stimuli deteriorates and as more fingers are stimulated at the same time, more deterioration takes place.
furthermore, this phenomenon will occur even over widely spaced body loci.

Kirman suggested that instead of using a device which stimulates a specific loci per frequency, such as a vocoder, the device should instead present a pattern across the loci as a moving spacial configuration. He terms this as a spatiotemporal display. He states, "If simultaneous stimuli were arranged in a spacial pattern, they could not tap into the perceptual organizing possibilities of the tactile sense—precisely because of their lack of temporal unfolding, their lack of movement," (1973, p. 66). Gibson (1966) had also suggested that all sensory systems are organized to pick up patterns of stimulation and not individual points of loci of stimulus energy.

Kirman goes on to suggest that Braille is an example of temporal unfolding whereby the fingers are using their natural kinesthetic ability by moving over the contours of the upraised letters. Braille has certainly been used very successfully in the blind community for this very reason. Perhaps this is also why the Tadoma technique, previously discussed, has also been successful because it utilizes the natural perception of touch. Kirman (1973) however, suggests that there are still inadequacies in the systems such as Braille, because information is presented too slow as a result of the small linguistic units (the individual letters). He suggest that an adequate tactile aid should include:

1) spatiotemporal processing
2) larger patterns
3) rapid presentations
4) retention of pertinent linguistic information

Kirman (1974) has further developed a device which presents "spatiotemporal patterns integrated by apparent movement [and] aims at the direct perceptual synthesis of linguistic segments of at least syllabic size," (p. 169). In this study, Kirman used a 15 x 15 matrix of solenoid vibrators spaced 0.2 in apart, with 225 stimulators stimulating the palm of the hand (see Figure 32). A formant-tracking computer program was used to analyze the speech samples to obtain the two lowest formants of the speech signal. These formants (sampled at 100 Hz rate), were entered vertically on the leftmost column of the array and were then shifted one column to the right every succeeding 10 msec as new information entered on the left. With this type of array, the subjects did not receive any information about speech or about intensity. The subjects, with 30 sessions of practice, were trained to identify 15 common words that contained only vowels and vowel-like speech sounds. The subjects were tested on slow and fast pronunciations of the words and by additional pronunciations of the words by the original speaker and three different speakers. The results of the testing can be seen in Figure 49. Although the resulting scores were not very high, Kirman (1982) notes that they were achieved solely with the display of frequency information about the first two formants.

Sparks et al. (1978 and 1979) investigated a different type of two-dimensional array called the MESA (Multipoint Electrocutaneous Speech Aid), where the frequency was coded through the horizontal rows (36 rows) and intensity, not time as seen with Kirman's device, was felt by the vertical columns (8 columns). This gave a total of
200 concentric electrodes that were activated. This device, placed on the abdomen, utilized 38 channels filtering frequencies between 65—10,000 Hz and had an average of 25 electrodes that were activated at any point in time during normal conversation. In Sparks' et al. (1970) first study, the device demonstrated that it was capable of transmitting information of the segmental features of speech very well in isolation. However, in testing reception of connected discourse (Sparks et al., 1970), the results were very poor. Sparks et al. used the tracking procedure and found that during the first hours of training the tracking scores of using the aid combined with speechreading, increased 6—10 wpm over speechreading alone; however, by 12 to 15 hours later, these scores became equal to speechreading alone at 50 wpm.

In sum, Kirman (1988) states, "With respect to my suggestion (Kirman, 1973) that two-dimensional spatial displays would present coherent spatiotemporal patterns more congenial to tactile perceptual organization than those available from linear displays, the evidence thus far is equivocal," (p. 252).

"The simple persistent caution remains, however, that the measure of success of any special device be significant (meaningful) benefit to the hearing-impaired user beyond that which is already available in the unprocessed speech delivered through one ordinary bone-conduction vibrator," (DeFilippo, 1984, p. 236).

Comparing the benefits in regard to the perceptual cues each aid can give in connected discourse, still has yet to be accomplished adequately enough to show "significant benefit" of the multi-channel aid over the single-channel aid. There are other
parameters that must be noted also that are almost as equally important as the perceptual benefits. These are maintenance requirements, acceptance by the teacher/clinician, acceptance by parents of vibratory or electrocutaneous stimulation, and perhaps more importantly, wearability and availability. It would seem to the author, that maintenance and acceptance by the teacher or clinician will affect the success of the aid. If the aid malfunctions and the teacher cannot easily and adequately troubleshoot for the problem because of the complexity of the device, s/he will not readily accept such an aid. This is a crucial factor, teacher acceptance, in guaranteeing the success of the child's usage of her/his aid.

Another factor involved when choosing between a single versus multi-channel aid is acceptance of electrocutaneous stimulation. Although no ill-effects have been reported, especially with the MEGA (Sparks et al., 1978, 1979), the idea of electrically stimulating the skin is still a frightful thought for most parents.

Wearability and availability would seem to be the most important factors to consider between these types of aids. As described in the section, Single-Channel Tactile Aids, the single vibrator is similar to a body-type hearing aid. This does not pose a great problem concerning wearability. However, the multi-channel aid can become large and bulky (see Figure 32) and constrain movement considerably. In most cases, because of the size and power requirements, the multi-channel aid cannot be continually used throughout the average day; furthermore, this inability to wear the aid throughout the day may be detrimental to the growth of the child.
learning a new language system through his sensory aid.

Availability is also equally important. To date there are only single-channel aids that are commercially available, these include the Tactaid I by Audiological Engineering Corporation, the Mini-Fonator by Siemens and the Silent page by Quest Electronics. The Tactaid I (see Figure 30) is discussed in the section Single-Channel Tactile Aids. This device's physical dimension measures 2.5 x 4.5 x 1.5 in. and weighs close to 200 grams (7 ounces). This aid is very similar to a body-type conduction hearing aid and utilizes a RadioEar B78A bone conduction transducer for use on the ear or a RadioEar B72 transducer for use on the sternum.

This device has a frequency lowering system to reduce frequencies to 250 Hz and an automatic noise suppressing network to reduce background signals (Bosser, 1984). The Tactaid I has a suggested retail price of $750.00 (Audiological Engineering Corporation, 1985). For further information concerning this aid the reader can write:

Audiological Engineering Corp.
9 Preston Road
Sumerville, MA 02473
(617) 888-1433

The Mini-Fonator is also available and can be seen in Figure 30. The physical dimension of this aid measures 3 1/2 x 3 x 1 1/8 in. and also weighs 200 grams (7 ounces) with batteries. This device's signal processor has external and internal adjustments to control the sensitivity and frequency response characteristics of the aid. The Mini-Fonator transposes acoustic frequency to peak
frequency of 250 Hz and the vibrator is worn on the wrist. The unit is also capable of being coupled with FM auditory trainers, hearing aids, or pre-recorded material (Roesser, 1984). The suggested retail price of the Mini-Fonator is $795.00 (Siemens, 1985). For more information the reader should write:

Siemens Hearing Instruments

622 Liberty Avenue

Union, NJ 07083

(201) 688-9122

The third commercially available aid is the Silent Page. This aid is not used as an aid for speech processing but rather as an alerting system of specific sounds occurring in the environment. A sensor-transmitter is placed near a sound source that is desired to be monitored (telephone, doorbell, baby, fire alarm, etc.) (see Figure 51) and when it is activated by an acoustic signal it sends a coded radio signal to the vibrator-receiver worn on the wrist of the hearing-impaired individual. Perceiving the vibrations on the wrist, the wearer can identify the sound source by looking at the coded lights on the receiver. There are four channels located on the receiver which can monitor up to 16 different sound sources by activating the lights in different combinations. The wrist-worn receiver weighs only 90 grams (3 ounces) and has a transmission range of 100 feet (Roesser, 1984). The suggested retail price of the Silent Page is $1,200.00 (Quest Electronics, 1985). For more information on the Silent Page, write: