Basic and Applied Research on Tactile Aids for Deaf People: Progress and Prospects

DETAILS

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Committee on Hearing, Bioacoustics, and Biomechanics
Commission on Behavioral and Social Sciences and Education
National Research Council

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PREFACE

Many readers who work in fields related to hearing and deafness are familiar with the reports of working groups of the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA). These reports are prepared by study committees, known as working groups, set up by CHABA to inform federal agencies on issues of significant national need.

This report reviews research that has dealt with the substitution of touch for processing acoustical information. The 13 members of the Working Group provided the essential and necessary advice, guidance, and review to the chairman and author, Carl Sherrick. On behalf of CHABA I wish to thank them and the chairman for their outstanding effort. The final report was edited for CHABA by David Lim, James Miller, and Charles Watson. Their valuable contributions are also appreciated.

Milton A. Whitcomb
Study Director
CHABA

Editor's Note: *This is the eighty-seventh in a series of review and tutorial papers on various aspects of acoustics.*

Basic and applied research on tactile aids for deaf people: Progress and prospects

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A brief introduction describes the alternative methods for replacement of the sense of hearing, including the educational procedures of sign language and lipreading, the medical procedure of cochlear implants, and the sensory substitution procedures of visual or tactual displays. For the tactual displays, which are most commonly electronically activated, a listing of desirable objectives is discussed in some detail. Among these are a better understanding of the processing capabilities of the skin, the form an efficient transducer may take, and what features of the speech stream may most profitably be extracted for processing and display to the sense of touch. Because the technology for device design and production in this area is seriously retarded, a great amount of space is devoted to the precise specification of a transducer for the tactile display; included is a discussion of direct electrocutaneous stimulation as a realistic alternative. A number of multichannel displays exist, and several of these may be workable systems if their transducer elements can be kept small and use little energy. What is of current, even urgent, importance is the early and widespread deployment of a single-channel tactile aid to permit the general assessment of the effectiveness of a simple sensory adjuvant for a deaf person who has lipreading skills.

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INTRODUCTION

This report summarizes the consensus of a group of American investigators who are presently analyzing the capabilities of the touch and allied bodily senses for processing information that is normally handled by the sense of hearing. For people who have suffered a profound loss of hearing, either congenitally or adventitiously in later life, the necessity for alternative pathways from the acoustic world to the brain is urgent. Such people ordinarily cannot profit from the use of a conventional hearing aid of the air- or bone-conduction type and must be instructed in the use of cues either naturally available or made so by the application of technology. The ability to perceive through the skin a variety of patterns of pressure and vibration has suggested itself as an exploitable talent that can provide one such functional alternative channel.

This report is written for a diverse readership: researchers in the speech and hearing sciences, experimental psychology, biomedical engineering, and medicine; educators; clinicians; practicing physicians; and administrators of educational and research institutions and agencies, within and outside of government, who are responsible for the support of basic and applied research work. We also hope that those hearing-impaired persons who would benefit most from the successful development of an aid that admits them to the busy arena of auditory events will find useful information, if not some comfort, in this report. It is to their ultimate advantage as consumers to know the present limitations and projected improvements that sensory substitution systems may offer. We must be frank at the outset to admit that, although a number of sincere and intelligent efforts have been made to develop a useful tactile aid, a device that has been proved to give reliable and satisfactory results is not currently available. The present report tries in part to specify the steps needed to produce one as reliably and quickly as possible.

A. Available alternatives to hearing

Solutions to the problem of communicating with deaf people have taken many forms over the last two centuries (see Kirman, 1973, 1982; Pickett, 1968, 1982; Sherrick, 1978; Stark, 1974). Those that have survived and been most frequently used have been of two general types: natural unaided systems and synthetic unaided systems (Sherrick, 1978, p. 182 ff). The lipreading or speechreading method is the best-known natural system, and the language of signs, in various forms, is the most familiar of the synthetic systems. "Natural" is meant to convey the fact that the "talker" need not recode his or her speech for the "listener" to perceive it; "synthetic" implies that the talker must recode the message (e.g., in sign language, to body or limb movements) to be understood by the listener.

There are no natural or synthetic unaided systems that provide deaf people with information other than linguistic. Therefore ambient acoustic events such as alarm bells, traffic sounds, and the myriad other signals and noises of everyday life are lost to them, along with the advantages brought by the ability to hear at least some of them. Moreover, the acoustic information of the telephone, radio, and television are unavailable to those who are profoundly deaf without some kind of aid that transforms the signals to nonacoustic energy. Thus telephones can display blinking lights to indicate ringing, as can doorbells or smoke alarms, and television sets can be equipped with converters to provide closed-captioned programs that show subtitles. The addition of teletype (printed message) systems to telephone stations has vastly changed the lifestyle of deaf people, who are otherwise unable to communicate rapidly at great distances. The world of those who cannot hear is perforce significantly smaller than that of their hearing neighbors when there is no means available to bring the world of sound to their attention and convert it to their use.

B. Sensory channels accessible by electronic aids

1. The visual system and visual aids

The uncanny ability of some individuals to "read" the musical passages of disk recordings or to interpret the spectrograms of speech sounds (see Potter *et al.*, 1947; Greene *et al.*, 1982) has encouraged a number of investigators to develop electronic devices that represent running speech as an oscillographic display (see, e.g., Erber, 1978), as a graphic display (spectograms) of speech energy across frequencies (see, e.g., Stark *et al.*, 1968), or as printed text (Stuckless, 1981). Other researchers have attempted to extract a limited number of phonetic elements (voicing, frication, stops, etc.) from the acoustic stream for display as visual patterns (see, e.g., Cornett *et al.*, 1982; Gengel, 1976; Upton, 1968). To examine systematically the present status of visually oriented electronic aids would exceed the scope of this review; visual speech aids are covered in some detail in Levitt *et al.* (1980).

2. The acoustic nerve and implanted stimulating devices

A review of research on hearing aids that terminate as electrodes in the cochlea is provided by Bilger (1977, especially, pp. 3–10), and recent symposia on artificial auditory stimulation update the available information on the status of research on so-called cochlear implants (Keidel and Finkenzeller, 1984; Parkins and Anderson, 1983). The arguments in favor of a cochlear implant aid are generally well grounded in medical and psychological wisdom: an otherwise healthy patient who has suffered the irreversible loss of the auditory sensory sheet, but whose acoustic nerve is intact, should be provided with a prosthesis that processes all acoustic inputs and presents them as electrical signals to the proximal endings of the nerve. The result is the provision of at least some auditory contact for the patient.

It is noteworthy that most of the physicians who advocate cochlear implants have carefully stated the criteria for patients to become candidates for implantation. Age, general health, state of acoustic nerve, age of onset of deafness (before or after language is acquired), and personality and attitudinal characteristics are some of the variables, as they or similar criteria are in all elective surgical procedures. The use of such screening techniques implies, of course, that a large number of people suffering profound hearing loss cannot expect help from this approach. They must then seek another avenue for reduction of their condition: i.e., either visual or tactile aids. The ratio of successful to potential candidates is not known.

Of the implanted systems of the patients studied at length by Bilger (1977, p. 3), 11 of 14 were of the single-electrode monopolar type. Their performance in tests with environmental sounds and with speech showed some improvement with the prostheses activated, mainly when visual cues were also available. Recent research with multielectrode implants suggests that somewhat better performance can be expected with their application, particularly if a solution is found to two major problems: what speech parameters are to be encoded and the undesirable spread of excitation between electrodes (see, e.g., Merzenich *et al.*, 1979). We encounter the first problem again in the discussion of strategies in research on tactile aids.

3. The mechanoreceptive systems of the skin

Attempts to develop electrical devices to channel acoustic messages to the sense of touch (i.e., the tactile system) probably date in an informal way from the invention of the telegraph, and a publication on the use of direct electrical stimulation appeared early in this century in France (Du Pont, 1907). In general, the most recent reviews of research efforts to elevate the sense of touch to the status of a hearing organ by electronic means have been encouraging but do not indicate great success (see, e.g., Kirman, 1982; Reed *et al.*, 1982). To be sure, a large number of investigations have been undertaken using a variety of processing devices, displays, and test methods. The majority of these have not culminated in the production of a sensory aid that can be found in widespread use among the population of deaf persons. In contrast, more than 400 deaf persons have been equipped with cochlear implants.

4. Which channel is better?

It may appear that, between the cochlear implant and the tactile aid, the former must by simple consumer statistics (more than 400 implants to almost no tactile aids) be the better channel. But there are some excellent reasons for not accepting this premature conclusion. Consider the situation faced by a physician who is consulted by a patient who has lost the last vestige of hearing in both ears and wishes for some medical advice, help, or therapy that will restore even a semblance of hearing. To an otologist who has specialized in the anatomy and physiology of hearing, the answer is obvious, i.e., to restore the hearing process by reconstruction. If the acoustic nerve is functional, the reconstruction consists of exciting it with selected features of the acoustic stimulus by electrical means. With the available surgical techniques, biologically compatible materials, and microelectronic processors, the means for reconstruction exist and can be applied. The result is a patient with an implant, a person who becomes an ambulatory testing station as well as a testimonial to modern medical technology.

Contrast the above situation with the one that usually occurs for an investigator who opts for the tactile aid. The investigator is probably not a clinician, particularly not one who sees patients on an individual basis, but rather an educator, an experimenter in psychology or in speech and hearing science, an engineer, or a physiologist. The condition of deafness and its treatment is not centered on the pathophysiology of the auditory system, as it is for the physician. Instead, it involves the general analysis of the two alternative channels to hearing, vision and touch. If vision is not considered an option, then touch is the avenue of choice. The investigator soon learns that this most superficially disposed sensory apparatus has only grudgingly revealed the limited aspects of its processing capacities to a very small number of researchers equipped and inclined to study them. In keeping with the customs of scientific investigation, the approach to development of an aid that displays acoustic information to the skin must be stepwise, with systematic testing of components and their combination until a satisfactory probability of "success"—in the form of a workable alternative to hearing—is achieved.

The result of this development process, as some investigators have repeatedly pointed out, is that there are lamentably few persons in the world today fitted with a specialized tactile aid, however imperfect, and using it, however poorly. Therefore, the difference in the number of people using the two alternative forms of communication has far more to do with the approach to the problem than with the success in its solution. It should moreover be apparent to the thoughtful reader that further advances in either form are more likely to occur in the one accruing a sample of active and interested users who report to motivated and active investigators.

5. Objectives in developing a tactile aid for deaf people

The contrast between the two approaches described above is heightened if their short-term goals are examined. For the implant approach, a critical and early goal was a prosthesis that excited the auditory nerve with as few side effects and as little discomfort as possible for the patient. The tactile aid approach (or the visual aid approach, for that matter) was never in doubt about the possibility of arousing the sensory channel with no side effects and negligible degrees of discomfort. Instead, the focus of attention moved to far more complex questions (which we discuss in greater detail below):

(a) What are the processing capacities of the skin?
(b) What form of transducer system will provide a reliable and efficient display to the skin?
(c) Which dimensions of tactile experience can be mapped to the acoustic stream of events in order to "match" hearing and touch?
(d) If not all speech features can be handled by the substitute channel, which are the important ones to emphasize?
(e) How should the target population be defined? What characteristics of the target population will determine how the aid will be used: e.g., as a speech or sound reception aid, as a speech training aid, as a supplementary aid, etc.?
(f) What are the acceptable educational designs for promoting the acquisition of user skills and for showing a true information gain with the aid?
(g) What forms of testing procedures would demonstrate the gains in aid use, while considering the issues posed by the two preceding questions?

Each of these questions is difficult, both practically and theoretically significant, and worthy of a program of research in its own right. Faced with the task of answering all of them, it is not surprising that no investigator has announced a successful outcome in the form of a wearable tactile hearing aid that, all on its own, communicates speech.

Distinguishing between short- and long-range goals is useful in discussing what could reasonably be expected from research on transmitting speech information through the skin. This division recognizes the fact that, based on what is already known, or relatively easily inferred, certain devices and systems might be developed for limited application, but that for more ambitious applications, e.g., the transmission of continuous discourse exclusively by touch, more time and effort would be required. Furthermore, for long-range goals it is less necessary for each investigator to supply all the answers to all the problems that might arise from a particular approach. Issues such as portability, user acceptability (including cosmetic considerations), power requirements, and so forth are obviously important, but most of them need not inhibit any individual researcher from pursuing useful investigations. Indeed, some of these problems are likely to be solved only after a system is developed that can reliably and usefully transmit speech information. It is worth noting that eyeglasses, which are cumbersome and obtrusive when first fitted, become a very acceptable sensory prosthesis to most people, in no small part because they are so useful.

The balance of this report is devoted to an attempt to provide, if available, answers to the questions listed above, or at least the best current estimate of the means for obtaining such answers.

I. DISCRIMINATIVE CAPACITIES OF THE SKIN

A. Current status of research on discriminative capacities

1. Basic psychophysical data

A number of secondary sources and research reviews cite the accepted values and functional relations for such psychophysical measures as absolute and differential thresholds for touch, vibration, and electrocutaneous stimulation, as well as for the effects of adaptation, temperature, masking, and stimulus level on thresholds and sensory magnitude. They can be divided into general sources (e.g., Geldard, 1972; Kenshalo, 1972; Sinclair, 1967; Sherrick and Craig, 1982; Taylor *et al.*, 1973) and specialized sources (e.g., Bliss, 1970; Darian-Smith, 1982; Geldard, 1974; Gordon, 1978; Hahn, 1974; Kenshalo, 1968, 1979; Kirman, 1978).

The majority of these works reflect the formal, classical orientation in psychophysical studies of all sensory systems. That is, they provide data acquired under ideal conditions of observation, in which the powers of attention, memory span, and motivation are fully recruited, and one-dimensional variations of stimulus patterns (almost always physical) are the rule. Thus for example, the measure of tactile spatial acuity known as the two-point limen is, from classical methods, 2.5–4.0 mm on the fingertip (Weinstein, 1968). However, when a 2-AFC (alternative, forced-choice) detection method is applied, the observer can always discriminate two stimuli from one, even when the stimulators are side by side (occupying a total space of 1.0 mm; see Johnson and Phillips, 1981).

Both of these measures were made with simultaneous application of the stimuli. With a temporal offset between them, complexities of perception may arise: offsets of 0–2 ms may result in the perception of a single locus, similar to the fusion of sensations associated with sounds presented to the two ears in dichotic hearing (Békésy, 1967). Offsets of greater values, e.g., 20–200 ms, may yield a perception of two stimuli phenomenally closer together than when they are presented a half-second apart (Geldard, 1975, 1982; Geldard and Sherrick, 1983). If body sites other than the fingertips are examined, the static two-point limen changes, generally becoming larger on hairy skin, and especially over the thorax and abdomen (4–5 cm; see Weinstein, 1968). The temporal effects described, however, remain fairly constant over a sizable range of distances, i.e., up to 10 cm or so, depending on the region stimulated.

What is important to understand from these data is that the cutaneous system cannot be characterized by a set of values on dimensions that are independent of one another. The cutaneous receptor sheet is analogous to the retina and the basilar membrane in that the orderly distribution of intensitive, spatial, and temporal values over its surface gives rise to a large number of stable and discriminable qualities for which the conditions and their relations are not readily predicted from unidimensional measurement (see, e.g., Geldard, 1957, 1977; Kirman, 1973, 1982).

2. Processing meaningful information

One important question for the present discussion is: can the discriminable qualities of cutaneous perception be encoded to linguistic entities and processed rapidly enough to permit understanding of continuous discourse? Several sources encourage us to believe that the answer is "yes." First, the studies of Tadoma undertaken by the research group at the Massachusetts Institute of Technology have demonstrated that skilled users of this method can process speech at rates and accuracies that approach low-normal values (see Norton *et al.*, 1977; Reed *et al.*, 1982). The Tadoma user places the hand on the face of the speaker in such a manner that lip and jaw motions, oral and nasal air flow, and throat vibrations can be felt. The distribution of the mechanical energy in articulatory effort is accepted and integrated by the tactile system of the hands of deaf–blind persons sufficiently well, after appropriate training, to permit the encoding of the sequence to many linguistic elements.

The reading of braille characters by blind people is a second good example of rapid tactile processing: experienced adult braille readers can read at the rate of 104 wpm (Foulke, 1982). This rate requires that they scan 100–300 separate braille cells with one fingertip in 60 s. Each cell is composed of from one to six raised dots, 1.5-mm diam at the base, separated by 2.3 mm from each other, and by 4.1 mm from the nearest dots in adjacent cells. Although the rate of reading is one-half to one-quarter that of visual rates, it represents a channel capacity of about 25 bits per second (Foulke, 1982).

A similar outcome appears when calculation of processing rates for the Optacon is made. This device converts ink print symbols to a vibrotactile fingertip display that impresses the symbol shape by means of a 144-pin addressable matrix (see Craig and Sherrick, 1982, p. 212). Reading rates for highly skilled users approach 60–80 wpm.

It is clear, therefore, that repeated and independent measures of the information-processing capacities of the skin affirm the belief that this sensory system possesses the channel capacity for decoding a coherent and time-varying symbol set of great complexity, such as speech. It must be borne in mind, however, that the tactile processing rates given above are for skilled users of the methods cited. There are many persons who have been trained in the use of braille, the Optacon, and Tadoma who process information at much lower rates and with far more errors. It is not yet known whether these findings signify that the limiting factor in achievement is the sensory system, the encoding scheme, cognitive or linguistic capacities, degree and quality of training, or motivation.

Of particular concern to developers of tactile aids is the question whether the processing skills cited above exist only in the hands or whether other skin areas are equally capable. The classical literature supports the position that the hands are unique, both structurally and functionally, inasmuch as the character of the skin itself is different (glabrous, or bald, containing several different specialized receptor cells; Geldard, 1972, p. 274), the comparative amount of cortical area devoted to the hands is very large (see Sur *et al.*, 1980), and the absolute sensitivity and spatial acuity of the area rank among the highest of the entire body (Weinstein, 1968). However, available data on tactile acuity, whether measured as available cortical area or functional discriminative capacity, generally does not include time as a limiting dimension. To the degree that the saltatory effect (see Geldard, 1982) is a measure of independence of patterns varying in both space and time among skin regions, recent measurements on the hand, the arm, the thigh, and the thorax suggest that the region with the best resolving power (thus far studied) is the fingertip (see Geldard and Sherrick, 1983). The differences among regions by this measure are of degree and not of kind, however.

Proponents of the dichotomy of sensory function between active and passive modes of observation have long held that this division bespeaks not only a difference in behavioral styles, but also a striking difference in processing capacity (see Gibson, 1962, 1966). It has been held that the probing hand and digits can acquire information about the environment that the passive hand cannot, even if the latter is given the same spatiotemporal patterns in the same time frame. Later research has disputed this contention (see Schwartz *et al.*, 1975), and the matter is moot (see Sherrick and Craig, 1982, p. 71 ff); there must be further research to sharpen the comparisons between the two modes before a final answer can be given.

Examination of other areas of the body for the ability to process patterned stimuli has been done with some success (see, e.g., Apkarian-Stielau and Loomis, 1975; Collins, 1970; Craig, 1974; Loomis, 1980). The skin of the back, the abdomen, and the thigh have been examined for pattern recognition capabilities and have been found to be about equally efficient if the differences in display size are taken into account (see Loomis, 1980). Direct comparison between the hand and other regions has not been made for continuous processing, however; therefore, the rate of pattern information transmission, which is obviously important, is not yet known.

Most of the comparisons just made for pattern processing abilities, i.e., between skin areas, or across observers, have involved letter recognition schemes, in which the patterns presented are constant from trial to trial. But it must be remembered that the tactile patterns that result from transformations of the acoustic code will be more variable from speaker to speaker than would, say, printed material, even considering changes of typeface. Consequently, the extension of results from studies of print recognition to speech recognition may not be possible.

Precisely because of the superiority of hands for both sensing and manipulating the environment, it is probable that a wearable tactile aid should not demand continual use of the hands when they can be doing other tasks. One might consider a "double-barreled" aid system: one site, not the hands, for constant monitoring and alerting or crude interpretive service, a second on the hand to be recruited (e.g., by grasping the display) for finer discriminations of the sound stream.

B. Projected research on discriminative capacities: Discriminable dimensions and their combination

There are innumerable questions such as the one just raised about equipotentiality of stimulus sites. This state of ignorance exists in part because the number of laboratories engaged in such work has never been large, and in part because the technology for generation and control of tactile stimuli has been (and continues to be) severely retarded in comparison to that of the fields of hearing and vision. The result is that a number of questions concerning the available "discriminable qualities" still have incomplete answers.

Studies of the capacity for recognizing absolute levels of vibrotactile and electrocutaneous intensity suggest that three levels are all that can be identified (see Geldard, 1957; Sachs *et al.*, 1980). For vibration frequency, Geldard *et al.* (1981) reported three or four recognizable values, with large individual differences among 18 subjects. The careful work of Rothenberg *et al.* (1977) on the difference limen (DL) for frequency indicated strongly that discrimination of more than a few steps is difficult. When Taylor (1978) combined three stimulus sites redundantly with three vibrotactile frequencies, he found a gain in information transmission over the unidimensional displays when it was measured by increase in correct identification of temporal orders of the three patterns. Similarly, Geldard *et al.* (1981) showed a gain of about 1 bit in information when three levels of intensity were combined redundantly with ten frequencies of vibration. It should not be concluded from the presently available data that any absolute limits on frequency discrimination have been firmly established. An obvious step along this research path is to combine intensity, frequency, and location to enlarge processing capacities further (see, e.g., Houtsma, 1982, p. 203). Two surprises may await the investigator who does so. First, there may be useful enhancement of recognition from redundant combinations due to "standout patterns" of particular dimensional combinations (see, e.g., Garner, 1974, 1978). Second, the addition of dimensions may lengthen processing time (Garner, 1974). It is not clear, however, whether the information gained from the added dimension is inevitably offset by increased reaction time to maintain a constant channel capacity, particularly if users are given extensive experience with the patterns.

The projected research strategy described above follows Miller's (1956) second suggestion for increasing the capacity for absolute judgment, i.e., increasing the number of dimensions in the stimulus pattern to make it more identifiable. Miller's first suggestion was to arrange for relative rather than absolute judgments. It is possible that this is what people do when they distinguish among speakers in a group or learn to identify more and more elements of a limited message set. In the case of a time-varying sequence of tactile sensations, the application of this strategy for expanding capacities may in part be the setting of temporal boundaries on "chunks" of the flow of information.

Miller's third suggestion for channel expansion is far more subtle and demanding, but it also points to the greatest potential of any available for processing time-varying sequences. It is to modify the task to permit making a sequence of absolute judgments, each of which is a recoding of a series of elements numbering less than the memory span and each bearing a small amount of information. Thus, a succession of trills of alternating low and high frequency may be recoded as a single phoneme. This strategy of chunking is possible, indeed necessary, because memory limits the absolute number of elements, not the information per element. These topics have received somewhat less direct research attention than the study of enhancement by multidimensional accretion, but they merit careful consideration in a broad program of research.

Research to date on the processing of braille (Nolan and Kederis, 1969) and of Optacon images (Bliss, 1974) suggests that character-by-character encoding is the rule, i.e., there is no chunking of character strings that would increase the channel capacity, as is done in visual reading or in speech perception. Whether this is owing to the crude and unevolved nature of the elements themselves or the inability of the tactile system to promote the required fusion process is not clear, but the evidence of successful processing from the Tadoma studies of Reed *et al.* (1982) suggests that it is the nature of the display and not an innate deficiency of the tactile system.

In any consideration of a broad-based research program to support applications of the kind discussed here, the question of cross-modal resemblances must be raised. One commonly speaks of touches and vibrations of the skin as "bright," "dull," "high-pitched," "diffuse," etc., thus describing tactile experiences in auditory or visual terms. To the degree that one can make a tactile experience an analog of an auditory one by incorporating dimensions that yield a common response in both modalities, it is possible that a more readily learned and rapidly processed message set may be acquired. However, the generation of a taxonomy of auditory and tactile perceptions and their cross-modal comparison with a large sample of subjects may be needed to substantiate what is now only a very strong hunch. The successful outcome of such experiments might provide some tactile aid users with a set of perceptual elements that would more faithfully simulate those of the natural hearing process.

Care must be taken in the design of experiments to choose at the outset stimulus dimensions that are appropriate to the sensory capacities of the tactile system. What is needed is the means for transforming the ear's frequency–time–intensity domains to a useful code the skin can understand (Pickett, 1980). Rothenberg and Molitor (1979) noted, for example, that rapid changes in vibration frequency were not readily perceived by subjects. Even though vibrotactile pitch is the commonly suggested analog of auditory pitch, it is probably ill advised to code speech frequencies exclusively as vibratory rates. Moreover, there is some justification for the more general argument that tying tactile to auditory dimensions may actually handicap those persons who have never experienced sound. The final decision about such issues will be in the hands of the careful experimentalist.

There is a great deal more to be learned about the discriminative capacities of the tactile system—surely more than is already known. Within the realm of such simple measures as the absolute threshold for feeling transient pressures or vibrations, for example, there are only one or two studies that have surveyed more than a few body sites (see Weinstein, 1968; Wilska, 1954). Similarly, for studies of temporal or spatial summation, adaptation, masking effects, growth of loudness, temporal acuity, synthetic movement, and pattern recognition, the examination of more than three or four sites is rare. Only when experimenters had reason to suspect a systematic variation in function with bodily locus have attempts been made to examine the differences among them (see, e.g., Békésy, 1959; Geldard and Sherrick, 1983; Green, 1982; Stevens, 1979).

As an illustration of the pertinence of such research to the purposes of development of a tactile aid, one question that might be raised concerns the degree of sensitivity of the pinna and outer canal to vibration. It is virtually impossible to determine this threshold in a normally hearing person because the nearby auditory system is so much more sensitive. But the question is really directed at profoundly deaf people—who would be candidates for ear vibrators if one could be fabricated. The answer is not presently available, except indirectly from the work of Nober (1967) and Pickett and Mártony (1970), who measured the response of profoundly deaf children with a standard earphone placed on the ears compared with the response when one is placed on their right hands. The results of this research are usually taken to mean that the response to such intense vibrations is mediated by the tactile system (see Fig. 1). If so, examination of the frequency–intensity function suggests that the pinna and canal thresholds are within 5 dB of those of the hands for the subjects and frequencies studied, suggesting a surprisingly high degree of sensitivity. More direct testing with conventional vibratory stimulators is desirable, not only for the purpose of assessing threshold sensitivity, but also to determine intensive and frequency discrimination as well as spatial and temporal acuities for this region.

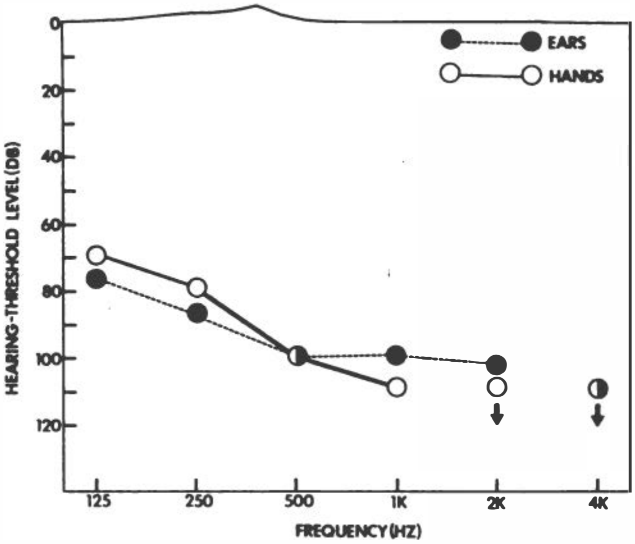

FIG. 1. Audiometric thresholds for the "better" ears of profoundly deaf children. The measurement was done ($N = 42$) in the accepted manner at the ear with the standard TDH-39 transducer and MX-41/AR ear cushion (filled circles). Open circles are vibrotactile thresholds measured by having children ($N = 94$) place the palm of the right hand over the ear cushion. Note that this implies not only that the profoundly deaf are probably feeling, not hearing, their air-conduction hearing aids, but also that the skin of the pinna and neighboring structures may be nearly as sensitive as that of the palm to vibration. Data from Nober (1967).

II. THE DISPLAY OF ACOUSTIC OR ARTICULATORY INFORMATION TO THE SKIN

A. Purpose of the display

The general name for a display that converts the acoustic or articulatory correlates of speech, or the acoustic correlates of ambient events such as traffic noises, alarms, etc., to a tactile input is called here a tactile sound reception aid (TSRA). Among the subcategories of TSRAs are the speech training and monitoring aids, which may be designed for specific training goals over limited periods in a restricted setting. For example, monitoring aids may be nonportable systems that a learner uses at a desk or training station for periods of up to one hour to improve the clarity of some aspect of his or her speech production. [For a thorough discussion of design goals, see De Filippo (1980a).]

The "ideal" TSRA would presumably be a device that could be worn for long periods of time in a cosmetically acceptable manner, would accept and process speech and other sounds, and would present the full set of dimensions of speech to a user's skin in a manner that would permit the understanding of speech without the help of other aids. Thus whether the user is decoding the speech of someone visible and in the same room or of someone whose voice is electronically transmitted, the ideal TSRA could provide as much information as would the auditory apparatus of a normally hearing person.

The development of the ideal TSRA is a prospect for the future, but it represents an important goal in a group of development efforts. We use the term group, rather than series, to emphasize the fact that research in this area (as in most) will not be the evolution of a single line of ideas, but rather the product of convergence and divergence of a number of approaches. Moreover, the goal of the application (e.g., whether general speech training or special speech sounds such as "s," etc.) will obviously influence the manner and substance of research and development.

A simple form of a TSRA would be a single-channel system that converts sound by linear amplification to mechanical displacements or electrocutaneous signals that follow the frequency–intensity pattern of the sound over time. The mechanical, electrical, and neural characteristics of the tactile system are such, however, that an acoustic signal is effectively filtered by an equivalent low-pass circuit, with the result that a "listener" can detect only the lower frequencies, i.e., 50–300 Hz. Hence, the listener detects only some of the prosody of speech, e.g., some aspects of the coarse temporal patterning of the utterance but not necessarily any differences among details such as consonants and vowels. At present, there are no mechanical transducers in commercial production that provide high mechanical energies across only the frequency range of interest with good fidelity and freedom from nonlinear effects. Available devices very often generate audible vibrations at harmonic frequencies that may be distracting to hearing persons in the vicinity.

A common difficulty with the mechanical systems that are currently available is their low efficiency. The mechanical power required to produce perceptible displacements of the skin at frequencies in the 50–300 Hz range amounts to about 0.1 μW at threshold for the fingertip over an area of 0.6 cm^2 (Khanna and Sherrick, 1981). For suprathreshold values of 10–40 dB, the power required increases from 1 μW to 10 mW. When hairy skin is stimulated, the power requirement is increased by an additional order of magnitude (Békésy, 1959, p. 20). To generate such mechanical power, a relatively efficient vibrator such as the Pye-Ling (Goodmans) V-47 consumes from 6 μW to about 400 mW of electrical power: i.e., the efficiency of this electrodynamic shaker is 0.5% to 15%, depending on frequency. By comparison, the normal ear requires sound powers in the range of 10^{-15} to 10^{-9} W, which for a sound generator of the same efficiency as the vibrator requires input powers of only 10^{-14} to 10^{-8} W. Consequently, an ordinary air-conduction hearing aid requires only a fraction of the power that a vibrator does.

In recent years an electromechanical transducer that uses the piezoelectric properties of certain alloys has become available. In their most common form as reed bender Bimorphs, these materials are capable of generating a useful displacement with relatively small power inputs (Sherrick, 1975) and have already been used in the Spens "Speech-Rhythm Indicator" (K.-E. Spens, 1982). In C. E. Sherrick's laboratory, measurement of the real power dissipated in a series Bimorph (measuring 13 mm wide by 18 mm long), vibrating at various frequencies, yielded values from 1 mW (50 Hz) to 4 μW (250 Hz) at 10 times threshold amplitudes. The Bimorph is therefore about as efficient as the electromagnetic vibrator near the optimal frequency values.

A number of investigators see a realistic alternative to mechanical transduction if one uses electrocutaneous stimulation (ECS) produced by noble-metal electrodes (silver or gold) placed on the surface of the untreated skin (see Collins and Saunders, 1970; Saunders, 1973, 1974; Saunders and Collins, 1971). A number of investigators have used the circuit configuration and concentric electrode arrangement that Saunders described when they extended his studies of electrotactile multipoint aids for the deaf (see, e.g., Oller and Eilers, 1981; Sparks *et al.*, 1978). In addition, basic psychophysical studies of ECS permit some comparison of the energy levels required for the range of useful sensation magnitudes (see, e.g., Rollman, 1974; Sachs *et al.*, 1980). According to Sachs *et al.*, the range of useful current required for suprathreshold stimulation is 0.17 to 2.9 mA (rms equivalent current) for one electrode on the skin of the abdomen (the stimuli are brief high-frequency bipolar pulses). Assuming a nominal resistance of 10 kΩ, the power range would be 290 μW to 80 mW. Most of this would be dissipated in the corneum (as heat, presumably, but insufficient to produce a perceptible temperature change). It is not possible to calculate the exact distribution of power in the dermal–epidermal system without knowing more about the perineural current paths.

Investigators in a number of laboratories are now experimenting with ECS aids, generally of the Saunders type and having multiple display elements. These investigators have reported no problems with painful stimuli or with untoward side effects of the electrical stimulation and endorse the method enthusiastically as a means of tactile signaling. With regard to comparative efficiencies of electromagnetic, piezoceramic (Bimorph), and electrocutaneous transducers, mechanical devices are more efficient for low level signals, while the ECS device is slightly more efficient for upper scale intensities. Presumably, this effect results from the steeper slope of the function for sensory magnitude growth for ECS (Sachs *et al.*, 1980). When power per unit weight is the measure of utility, the ECS probably ranks highest, with the Bimorph bender a close second. More applied research is needed to settle the practical issue of efficiency, which is but one of a number of problems bearing on the question of the general utility of tactile aids.

B. Requirements for a good transducer

The working group agreed upon ten characteristics as desirable for a transducer to be used in a single- or multichannel tactile display: small size, low mass, high efficiency, appropriate frequency response, low radiation of acoustic energy, insensitivity to contact pressure, low distortion, large dynamic range, little long-term discomfort, and reliability.

1. Small size

Ideally, a transducer should be small enough to be worn without producing an unsightly bulge under clothing or requiring many conducting elements across the body, especially if it is to be worn as a reception aid, i.e., continually during waking hours. Spens (see Spens and Plant, 1983) has produced a small piezoceramic transducer (about 9 × 15 × 21 mm, weighing about 4 g) that approaches the ideal size for a mechanical transducer. Those mechanical transducers presently available commercially have been reviewed by J. D. Miller (1982), and vary from 8 to 30 cc in volume, compared to about 2.8 cc for the Spens device.

For special placements, transducer size is even more of a problem. For example, for young children their smaller skin areas present difficulties. Moreover, if it became desirable to present the stimulus to the pinna and outer canal of a wearer's ear, size and shape would be important limiting dimensions of the transducer. With suitable care, it might be possible to devise an electrotactile transducer that would provide the necessary energy levels and yet be of the appropriate dimensions for this purpose (F. A. Saunders, 1982).

2. Low mass

Although related to size, mass is of considerable importance if more than 20 transducers and their associated circuitry are worn in a multitransducer array. The desirable weight range for a transducer alone would be 15–20 g. This characteristic is of special importance in applications with children.

3. High efficiency

As noted above, increasing efficiency of transduction will increase the power available to stimulate tissue, while maintaining or reducing the drain on the electrical supply source—presumably a battery. With multiple-element stimulating devices, the problem of current drain increases rapidly with increasing channel number. The task of improving both transducer and processing circuit efficiency (e.g., by arranging to excite only one or two elements at a time) becomes critical as limiting values of battery weight (hence portability) are approached with presently available circuits and transducers.

4. Appropriate frequency response

If the threshold for human perception of mechanical vibration is plotted for sinusoidal displacements over the frequency range of 50–500 Hz, a U-shaped curve usually results, with a minimum near 200 to 300 Hz (Sherrick and Craig, 1982, p. 65; Verrillo, 1966, p. 49). Contours of equal sensation magnitude are similarly shaped over the range of 10–40 dB above threshold (see, e.g., Verrillo *et al.*, 1969, p. 371). For rectangular or repetitive pulse displacements, however, the threshold curve is nearly flat across the 50–500 Hz region, and the variation of displacement required for constant sensory magnitude over frequencies is a slowly increasing linear function (see, e.g., Geldard *et al.*, 1981; Hill, 1967; Rothenberg *et al.*, 1977).

It is clear that the frequency response required for a transducer will depend on the characteristics of the display. If, for example, only a single frequency is to be passed, as in the single-channel aid developed by Beguesse (1976), the device can be "tuned" to the desired frequency for maximum efficiency. When the requirement is that the display vary over a 3- or 4-oct range, the response of the transducer becomes critical, and far more engineering skill is required in its design. Indeed, it is possible that, if the device must pass sinusoids over the 3-oct range with constant acceleration below 200 Hz and constant amplitude above that value, no single transducer could meet the requirements. For ECS (electrocutaneous) devices, sufficient data are not available to specify the character of the functions relating frequency to threshold and sensory magnitude in the way that mechanical vibrations have been scaled (but see Bull *et al.*, 1982; Prior, 1972).

5. Low radiation of acoustic energy

Many devices currently in use (e.g., bone conduction vibrators used to stimulate the skin) emit large amounts of acoustic energy when driven by strong signals, with the result that annoying rattles and hisses are heard by people near the user. Appropriate design of suspensions and cases should reduce these effects, which (as mentioned above) contribute to oscillatory behavior of the system when feedback paths are present. The feedback problem, which can cause serious battery drain, is most severe when a direct transformation of acoustic input is made to vibrotactile frequency. If, however, the coding of the acoustic input is such that the unwanted radiations are filtered or otherwise blocked, the problem disappears.

6. Insensitivity to contact pressure

The driving elements of a transducer should be designed in such a way that static loading of the contactor has little or no influence on the dynamic output force. Because it is extremely difficult to ensure a constant static coupling force of a contactor to the skin without binding or restriction of the user's movements, this requirement is important for comfort as well as for stability of transducer response.

7. Low distortion

The transducer should, as far as possible, be free of amplitude, frequency, and phase distortion to ensure that it responds over the specified frequency range to transient and steady-state signals with a minimum of ringing and clipping effects, in order to guarantee integrity of the stimulus at the skin-transducer interface.

8. Large dynamic range

A desirable dynamic range for a skin stimulator is 40 dB, to accommodate fully the range of sensitivity and loudness growth of various body sites (see, e.g., Békésy, 1959, p. 20). If a transducer is to be used as part of a single-channel system on the finger, the dynamic range could be smaller, but if it is part of a multiple-transducer array to be fitted to sites such as the arm, the trunk, or the legs, the range must be near 40 dB, particularly if intensity of vibration is a coded dimension.

9. Little long-term discomfort

An important aspect of the research on tactile aids for deaf people is the need for continual presence of the aid in the user's perceptual field in order to make the tactile input a natural part of the user's environment. As with all other prostheses—as well as with items of jewelry, clothing, or other accessories—there will be a tradeoff between their subjective utility and their obtrusiveness. What may be called the "signal/encumbrance ratio" becomes an important dimension and may enter into the cosmetic acceptability rating that such items invariably get.

10. Reliability

Experience with prostheses such as hearing aids and laboratory-built experimental tactile aids dictates that a transducer and its connectors and circuitry be designed as ruggedly as possible to withstand the inevitable rough handling its user will give it. Consequently, a procedure for functional testing of the device should be provided to users so that they can maintain a continual check on performance.

C. A single-channel tactile aid

The single-channel aid described earlier is essentially the kind of device first tested by Gault (1927). Speech sounds were transduced to electrical signals by a microphone, amplified, and impressed on a single earphone. Users placed their thumb or finger on "the diaphragm of the single-unit receiver" (Gault, 1927, p. 340, Fig. 1). Assuming that what is passed by such a system is mainly low-frequency energy (say, below 200 to 300 Hz), then what users probably perceive is the stress patterns in speech, i.e., some aspects of the prosody mentioned earlier. In their recent monograph on tactile communication of speech, Reed *et al.* (1982, p. 16) discuss at some length the use of such a display as a supplement to lipreading and suggest that it has shown some benefit in a number of cases. It is not clear from the studies cited whether the degree of lipreading skill has a modulating effect on the gain of information from the tactile display, i.e., whether poorer lipreaders benefit less than good ones, or whether an inverted U-shaped function might result if one plots gain from a tactile display against an individual's lipreading skill. It would be of some interest to increase the number of tested cases for this device, to answer this and other such questions. (For a sharper distinction between lipreading aids and aids to lipreading skill acquisition, see De Fillippo, 1980a.)

A single-channel aid can be modified to generate a single frequency at which the skin is most sensitive, i.e., 250 Hz, as Beguesse (1976) has done. The amplitude of the signal is modulated by the speech signal power to yield a prosodic sequence that mirrors the speech. Tests of the Beguesse aid indicated that it may be superior to the simple aid just described (Reed *et al.*, 1982, p. 16). A still more sophisticated modification of a single-channel aid might be based on findings by Ardell (1980), who showed a significant gain in information over lipreading alone when only the fundamental voice frequency ($F0$) was heard by a listener who was lipreading in a face-to-face tracking situation. She also demonstrated that some information gain occurred when $F0$ was a constant value (average $F0$) but amplitude modulated by speech power, as well as when $F0$ varied normally in frequency but with constant amplitude. The gain in each of these conditions was less than that when $F0$ was both frequency and amplitude modulated.

When Grant (1980) attempted to incorporate one aspect of Ardell's findings in an electrocutaneous aid in which $F0$ (at constant amplitude) was represented spatially as one of ten sites of stimulation on a user's forearm, he found a modest gain in information for two subjects. Grant speculated that some advantage might have accrued if both amplitude and frequency modulation of $F0$ had been displayed (Grant, 1980, p. 94). Therefore, there is reason to test more carefully to see whether tracking of $F0$ with a single-channel vibrotactile aid, in which frequency and amplitude modulation are displayed as rate and amplitude variations of the contactor, may prove to be a useful supplement to lipreading. One problem that may prove an impediment to application of such an aid, at least in natural settings, is that of extraction of $F0$ from ambient sounds. Some authorities view this problem as extremely difficult without very sophisticated processing systems.

Besides its use in the transmission of $F0$, a single-channel aid may find separate application as an "S" indicator (as it has in the past: see Kringlebotn, 1968) or as a nasalization indicator. What may have more significant implications for later training is the possibility of the use of a single-channel aid with very young, profoundly deaf children (Goldstein and Stark, 1976; Proctor and Goldstein, 1980). It remains an important and so-far-unsettled question whether providing a profoundly deaf child with at least some limited correlates of the auditory environment will "lock in" the tactile system to the detection, discrimination, and recognition of self- and other-produced sounds. It would be expected that early and continual use of such a device would provide the best chance for later acquisition of skilled acoustic–tactile processing. A rationale for providing cochlear implants for young children for this purpose has been given by Eisenberg *et al.* (1983), who report that about two dozen children had received implants by August 1982.

D. A multichannel tactile aid

Displays that provide for a division of the speech code into several channels to be spaced over a number of skin sites have existed since Gault's research (Gault, 1927, p. 342 ff, Figs. 3–5; Reed *et al.*, 1982, p. 5 ff, Table I). Such displays have often been intended to substitute the skin for the basilar membrane, i.e., the partitioning of energy in real time among and between channels is made roughly in a way that simulates cochlear activity. This effect is particularly true of a linear, multiple-channel display, in which speech frequency is coded by location on the skin and speech energy is coded by vibration amplitude (e.g., Brooks and Frost, 1983; Englemann and Rosov, 1975; Pickett and Pickett, 1963; Saunders, 1974). Alternatively, multiple-channel displays can be manifest as two-dimensional spectral displays in which speech frequency is coded along one spatial axis and speech energy along another, perpendicular axis (e.g., Yeni-Komshian and Goldstein, 1977; Sparks *et al.*, 1978). In the two-dimensional, frequency-by-amplitude displays thus far tested, vibration amplitude was not varied over time or space and is therefore a potential third perceptual dimension for coding some other aspect of the speech signal (e.g., prosody). There have been no direct comparisons of linear and two-dimensional displays, so it is not known which is superior. Figure 2 is a schematic illustration of the activity of three kinds of displays. Yet to be established for both types of displays are the optimum values for such basic characteristics as the number of spectral channels, display size, and display locus.

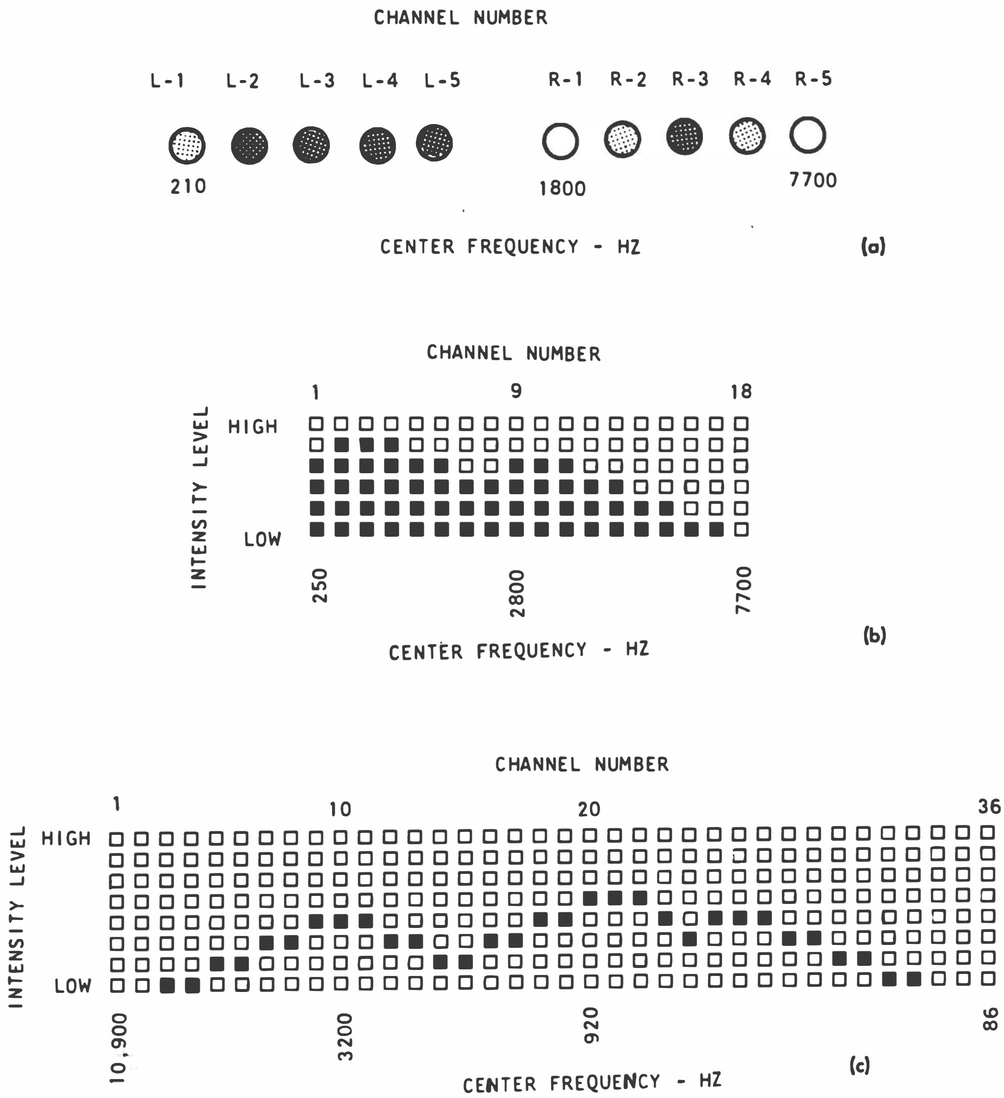

FIG. 2. Schematic representations of responses of three kinds of tactile aid. An arbitrary three-tone complex is sounded steadily at microphone inputs. The complex is 400, 800, and 3200 Hz, with the 800-Hz component set to twice the intensity of the other two. (a) The Pickett and Pickett (1963) tactile vocoder: the darker the disk (representing the vibrator at each finger), the higher the intensity of vibration. (b) The Goldstein and Stark (1976) Optacon system: squares, which are individual pins pressed on the fingers, are vibrating if filled, silent if open. (c) The Sparks *et al.* (1978) MESA electrocutaneous display: each square is an electrode on the abdomen; the filled squares signify active stimulation. The condition represented is a steady-state value, of course. In actual use with speech sounds, the contours of frequency and intensity would ebb and flow constantly. The representations of activity of the displays were constructed from descriptions in the literature; they are not intended to be true values of activity, but rather illustrative of the kind of response made by the devices.

However, a few multichannel displays attempt to reproduce not the receiver, but the transmitter: these displays simulate the Tadoma method, i.e., they attempt to partition the articulatory sources either by acoustic analysis (Clements, 1982) or by acoustic–articulatory analysis (Miller *et al.*, 1974).

A second way of dividing multichannel displays is by their treatment of the time dimension. Most systems represent their chosen correlates of speech in real time as a small but finite temporal slice or cross section of a given code. This approach leaves to a user the tasks of collection, categorization, and higher processing of the information stream. If a spectral display of sound energy causes a precise simultaneity of events at different skin sites, masking effects can reduce the available information (see Aston and Weed, 1971; Pickett and Pickett, 1963; Sherrick, 1964; Yeni-Komshian and Goldstein, 1977). One possible solution to this problem involves the introduction of a buffer to permit a larger time-fraction of the speech code to be displayed across the skin (see, e.g., Ifukube, 1982; Kirman, 1974; Reed *et al.*, 1982; Spens, 1982). This strategy, which lengthens the tactile registration period, may reduce masking and improve the chances for accurate categorization of the code elements.

There is not yet sufficient information about multichannel displays to allow us to single out any system for praise or criticism. Indeed, it appears more and more likely that several identifiable strategies will do the intended job of making speech understandable to the skin. Until more research is done, we cannot say which of these will prove to be best after considering ease of training, ultimate intelligibility, cosmetic acceptability, cost, and the percentage of the hearing-impaired population that can be served.

III. THE DISPLAY OF FEATURES AND DIMENSIONS OF THE SPEECH STREAM

A. Two principal modes of representation of speech

The question of what and how many dimensions to represent to the skin is wholly dependent on what in the speech stream is believed to be essential to intelligibility, but there are two fundamentally different approaches to the representation of speech. One approach states that speech can be represented as either a time waveform or in terms of a short-term, time-varying frequency spectrum (e.g., the output of a bank of continuous bandlimited filters). This mode of representation is not unique to speech and can be used to represent any acoustic or electrical signal.

The second approach considers displays, unique to the speech signal, that can be based on either articulatory or phonetic features. An articulatory-based display shows characteristics related to speech production, such as voice fundamental frequency, breath flow, nasal vibration, lip movements, tongue position, and related articulatory positions and movements. Such a display is independent of the language used or of the meaning of what is said. A phonetically based display shows features of speech that identify what is said. An example of this kind of display is a sequence of English phonemes and prosodic markers representing the spoken message. A more subtle example is that of a set of distinctive features. Such a display can be used to represent not only what was said, but also other significant phonetic information, such as the speaker's dialect or tone of voice.

1. Phonetic and articulatory displays

The boundary between phonetically based and articulatory based displays is largely a matter of definition. A convenient way of distinguishing between the two is to note that phonetically based displays almost invariably require some degree of speech recognition: i.e., the phonetic feature or characteristic to be displayed must first be recognized in the input sound stream. In order to illustrate the distinction between the two kinds of display, consider the difference between a display of voice fundamental frequency (an articulatory based display) and a display of intonation (phonetically based). In the former, a physical measure of the speech mechanism, i.e., the frequency of vibration of the vocal cords, is displayed without regard to the phonetics of the utterance. In the phonetically based intonation display, those aspects of the voice fundamental frequency that are phonetically significant are either displayed separately or emphasized in some way. Examples of phonetically significant characteristics include a rapid rise in fundamental frequency, signaling a question, or a terminal fall, signaling the end of a sentence. In the extreme, a phonetic display will show only phonetically relevant information and nothing else. A display of this kind requires a good deal of preprocessing and decision making (i.e., speech recognition) before the information is displayed.

A problem with any display system that makes decisions for a user is that errors can occur: the feature to be displayed may not be identified and hence be omitted from the display or the intended feature may be misidentified and the wrong feature sent to the display.

2. Can speech be successfully represented by nonauditory means?

Two schools of thought have developed regarding the usefulness of feature-based (phonetic, articulatory) and nonfeature-based (time waveform or spectrum) displays. One group (Liberman *et al.*, 1968) argues that speech is a special code and the auditory system a unique decoder. In this view, the auditory system has unique speech-feature detectors, and it is unrealistic to expect either the visual or the tactile system to process nonfeature-based displays of speech, e.g., spectrograms, at rates comparable with those of normal speech. This argument is used to account for the relatively modest gains obtained with spectrum and waveform displays. Proponents of this view feel that such visual or tactile displays can serve as useful supplements to lipreading or as speech training aids, but not as substitutes for the auditory system.

A counter view (see, e.g., Houde, 1980) contends that the gains realized in communicating speech through alternative modalities have been modest because of such factors as the poor resolution of early experimental devices, the use of inappropriate training strategies, and training exposure to displays for only limited amounts of time. In this view, a person can understand speech through a nonfeature-based display, e.g., a display of the spectrum, if information is properly presented and the person is thoroughly trained. Cole *et al.* (1979) have demonstrated that a person can read and understand spectrograms of speech, although the process is very time consuming and impractical as a means of communication for deaf people (see also Greene *et al.*, 1982). It has also been argued that there are critical periods in a child's development when the ability to learn speech and language is at a peak: if effective displays were provided to children during the early stages of speech and language development, they should show greater gains when the displays are later used in communication aids.

A third group believes that, regardless of whether speech is special, it is possible to communicate effectively with visual or tactile symbols if they reflect the features of speech in a well-organized way. A person can understand speech through the printed word or through lipreading even though there is little or no auditory input. As we have already noted, even the somewhat cumbersome Tadoma method of communication allows deaf–blind people to pick up speech cues by feeling the articulatory movements of the speakers' faces.

Displays that rely heavily on speech recognition are already in use, e.g., the closed-captioned television mentioned earlier and the TOMCAT system used in the U. S. Supreme Court (Levitt, 1982). Such displays at present require human intervention for the speech recognition component.

B. Aids as supplements to lipreading

We noted above that the ideal tactile aid would stand alone as the sole interpreter for a hearing-impaired user. While this goal is regarded by most investigators as desirable, it is not yet seen as achievable. Consequently, the design of tactile aids is nearly always done with the intention that their contribution of information about the speech stream is to be interleaved with that obtained from lipreading. This approach raises the theoretical question of combinative structuring of the information from the two sensory channels. As Reed *et al.* (1982, p. 21) have indicated, the usual strategy has been to present to the skin information that is not available from lipreading. However, these authors suggest that while this appears to be a sound strategy, it creates an intersensory dependency that will result in serious information loss if either sense channel is noisy. Redundancy across channels may therefore be highly useful. Exactly what dimensions or features should be redundant or complementary are questions still to be addressed by research.

The ignorance we confess concerning the appropriate elements of speech to be coded by touch is shared to some degree by students of lipreading. Recently, however, De Filippo (1980b, 1982a) reported a study of lipreading ability in which she found that the best predictors of criterion achievement of skill were: knowledge of English, identification of (visually perceived) vowels and consonants in isolation, and memory capacity for sequences of lip shapes. For discussion purposes, consider that a normally hearing person must process about 45 different elements to understand speech and a lipreader has (in addition to contextual cues) about 15 visual elements (visemes) available for the same purpose. It would then seem appropriate to inquire whether a supplemental tactile input from an aid should add more elements to the 15 visual ones available or should somehow improve the storage capacity of the visual memory, which De Filippo found to be a critical predictor of lipreading success. Or should a tactile aid be designed to do both of these tasks? Once again, available research provides hints, not answers, to the questions.

An answer to the question of what information to provide will surely vary according to the skills, aptitudes, and perceptual status of potential users. That is, if a tactile aid user is adventitiously deaf and retains an auditory memory of speech, he or she may need an encoder that triggers an auditory replica. Likewise, children who have no worse than a severe hearing impairment, meaning that they are capable of perceiving some of the spectral information in speech through residual hearing, may best benefit from an auditory complement of what they see. It is also possible that profoundly deaf people may be better served by adding visual information directly in order to optimize the viseme system, rather than requiring them to translate from a perceptually fuzzy "phoneme" (the tactile signal) that does not map neatly to a well-constructed viseme hierarchy.

IV. TRAINING METHODS AND MEASURES IN THE USE OF TACTILE AIDS

A. The importance of standardization

To expect reliable test results following haphazard training is to hope for nutritious milk from a mistreated cow. In the most recent review of research on tactile aids for deaf people, Reed *et al.* (1982, p. 10) voiced a complaint that is almost a leitmotif in the literature of this area. It is that (aside from differences in the method of coding speech and displaying it to the skin) wide variations exist among developers in the methods of training and evaluation procedures, which have been described as "orphans of sensory aid development" (Elliott and Sherrick, 1976, p. 488). In many cases such variations are not only understandable, they are necessary: the methods of instruction for a prelingually deaf infant cannot be the same as those for an adult with a recently acquired hearing loss. Within identifiable groups of this kind, however, it is imperative that sufficient attention be paid to training and testing procedures to allow comparisons among laboratories involved in development of tactile aids.

Because training and evaluation are often carried out in a school or clinic (at least in the late stages of development of an aid), it is essential that the educational and psychometric resources of the institution be engaged to the degree it is possible. At the minimum, persons who are to supervise and conduct a training program with an aid should have personal experience with its properties in enough practice sessions to demonstrate a gain in their communication skills. Only by this means can a thorough understanding of the system be achieved. Moreover, nothing takes the place of a teacher's confidence in a method: without this leavening ingredient, many experiments have failed. In a very real sense, careful familiarization of trainers with a tool and its application represents an important part of standardization procedures.

A second observation concerning training procedures is reported more and more often by researchers: namely, that the length of time devoted to learning is probably all too brief in both preliminary and regular studies of skill acquisition with tactile aids. An exception is the study by Engelmann and Rosov (1975), who worked for nearly a year with some of their deaf subjects.

There are no established standards regarding the length of time to be devoted to learning a skill as a function of its complexity, but recently Watson (1980) has presented a compelling case for the possibility of scaling this relationship. Watson dealt mainly with auditory perceptual learning and showed that the time required for criterial performance may vary from a few hundred trials (i.e., a few hours) for a simple detection task to 20 or more weeks for pitch or temporal pattern identifications. These, of course, were studies involving normally hearing and otherwise competent young adults who were well-motivated to perform. To paraphrase Watson's conclusions (1980, p. 101), it is altogether unrealistic for us to expect that a recoding scheme involving speech patterns can be well learned in a period of less than 2 or 3 years.

B. Training methods

It has already been suggested that the method of introduction of an experimental aid in the training procedure will depend greatly on the type of patient being treated. Whatever the age, history of deafness, or linguistic status of the individual, however, the tactile speech reception aid is an additional tool for enhancing the receptive powers of the user. The training procedure will therefore be adapted from that already in conventional use for a given class of patient to accommodate the novel influx of information from the tactile display (see Erber, 1982).

An example of the classic paired associates, verbal learning approach is found in Oller *et al.* (1980), who trained eight hearing-impaired adolescents in the discrimination of six pairs of word patterns with the aid of the 12-channel tactual vocoder developed by Engelmann and Rosov (1975). The subject was required to identify which of the pair of words, seen printed on a 3-by 5-in. index card, was presented through the vocoder. Even with the relatively short period of training given (no more than 5 h), subjects showed not only improvement in discrimination scores, but also improvement in speech production (Oller *et al.*, 1980, p. 777).

Shelton (1978, p. 167) has indicated that formal procedures such as classic learning or conditioning paradigms may inhibit spontaneous speech production and that some researchers suggest a more interactive mode involving declarative or interrogative statements relating to what the subject is doing. Wherever possible in such situations, the design of the form and substance of the communication must suggest to the subject that the tactile input, if observed and interpreted, will at least enrich communication if not function as a sole source.

For any method, good practice in experimental design must be followed to ensure that the contribution of the tactile aid to the outcome can be partialed out. The kind of design seen in transfer of learning studies (see, e.g., Bransford, 1979, p. 216 ff) is among the more adaptable paradigms.

1. Tracking procedures

There is a fairly large group of people who have acquired hearing loss in the second decade of life or later and have learned or are learning lipreading. An excellent training procedure is one devised by De Filippo and Scott (1978). A trainer and a subject sit face to face, and the trainer speaks aloud, reading from a prepared text. The subject must "track" or shadow the speech (but only after the talker finishes each phrase), replying with what he or she understood that the talker said, verbatim. The talker proceeds to a new segment only after the subject has correctly reproduced the preceding one. If the subject has some hearing, masking noise or other isolation techniques must be applied, of course.

The technique is very flexible, since the tracking can be for isolated sounds, syllables, words, phrases, or connected discourse. It is thus possible to move a subject from what is regarded as a relatively simple, limited-set identification task to the ultimate performance desired—understanding continuous speech—while evaluating the skill of speech perception at every step. In the criterial stages of performance, i.e., during the training in comprehension of connected speech, the effective number of words per minute tracked correctly can be compared with the number understood by normal-hearing people who listen to the talker. A kind of transmission-efficiency score can thus be derived.

Because the training requires a continuing, possibly prolonged one-to-one relation, it may not be an efficient technique when large numbers of subjects are to be trained. If a written or typed response by subjects is acceptable, however, it might be possible to use standard video recording techniques and computer-assisted response analysis to enlarge the number of subjects being tested. However, such a technique does not assist in another important dimension of the training paradigm, namely, speech production by a subject: it sometimes is as important to assess the improvement in this aspect of a subject's performance as in speech reception skills. Although the original face-to-face tracking technique makes no specific provision for this measure, De Filippo and Scott (1978, p. 1190) have suggested its use for this purpose.

2. Tracking in relation to other methods

When one considers the question of criterion for use of the tracking method, it is apparent that, while rate of tracking alone is not an adequate criterion, a minimum rate of 2–10 wpm should be present for useful training to take place. [Rates for normal-hearing listeners using auditory information and tracking a talker are about 110 wpm (see Grant, 1980, p. 66).] The important consideration for a minimum rate is the confidence that the subject's difficulties lie more in the area of speech perception than production, and that the rate will improve as familiarity with the task grows. Tracking is a new technique, and only experience with its use will make possible more definitive statements about its conditions of application. A minimum acceptable rate may, however, be a function of the subject's motivation as much as the skill displayed. At an early stage of acquisition, the application of a rate measure may be premature, since as we suggested earlier, the tracking situation can be used just as any teaching situation is, i.e., to develop the ability to identify isolated sounds, words, etc. In this respect the procedure blends with more traditional methods of training in speech reception and production, involving more or less subtle forms of the technique currently called "behavior modification" (see, e.g., McReynolds, 1978; Shelton, 1978).

Another question of some importance arises in the training of young subjects: if they are undergoing instruction in lipreading at the same time, should they be given the tactile aid simultaneously or should teachers wait until lipreading skills reach a certain point? Arguments can be presented for either approach, although it is clear that for a profoundly deaf child for whom a hearing aid is useless, some input is essential (M. H. Goldstein, 1982). The problem is especially knotty when one considers that any negative effects produced by either strategy may be lasting ones (see De Filippo, 1982b; Erber, 1982). The conservative treatment would be to withhold the tactile aid until lipreading skills develop, since that is what would have been done, in effect, if tactile aids were tested on older hearing-impaired children. However, if a program of developmental prosthetics were instituted in order to promote the acoustic–tactile bond described previously, there would be every reason for the tactile aid to be available from the very beginning of instruction, especially in view of the fact that the aid plays a role in learning to lipread (De Filippo, 1980b).

C. Testing methods and materials

1. Speech perception tests

As in the training situation, the need for standardization in speech perception tests should be underscored. The possible contribution to the total variance in test results of careless testing or nonstandard methods can make otherwise useful comparisons almost meaningless. A number of speech and sound-comparison tests with adequate instructions for their use are available; a selected set is shown in Table I.

The listing in Table I is not by any means exhaustive; it is intended to give a sample of good procedures. Additional tests can be found in Subtelny (1980; see especially Levitt, 1980). It is also quite possible that none of the tests shown is suited precisely to the evaluations some developers wish to perform. It is more than likely that a necessary component of future research is the development of new and better tests for evaluating tactile speech reception alone or in combination with lipreading, residual hearing, or cochlear implants. A recent paper by Pickett (1983) compares testing strategies in aided speech communication, citing some specific tests as well as alternative strategies for administering them.

2. Speech production tests

We have already pointed out that a part of the final evaluation of performance is speech production. If an aid forms a part of the closed-loop system to improve speech by feeding back performance information to the aid user, the production test may help to measure how well the aid does. One older test still in use is that of Magner (1972); a more recent one is the CID SPINE test (Monsen, 1978).

Testing procedures should follow the conventions for standardized application so that comparisons across experiments as well as among laboratories will be possible (see Spens, 1980, for a unique comparative study). The questions of use of synthetic speech materials, recorded voice, and live voice testing are important in the final analysis of any communicative device that is developed. For the study of specific transmission properties of an aid-user system, the use of artificial or recorded speech is often appropriate, but the real test of performance will be in situations that involve different live talkers, with all the variants of speech patterns that they present to a listener.

V. CONCLUSIONS AND RECOMMENDATIONS

We hope that decisions to promote or discourage certain categories of research do not use this report as best evidence. Indeed, if any certainty is to be extracted from the lessons of research of any kind, it is that the quality of the research being done, and not the category or kind of research, more often determines the "cash value" (as William James put it) of the ideas that emerge.

There is one research effort that could eliminate a serious bottleneck to the development of useful tactile aids: the development of a small, efficient, wholly portable transducer that will excite the human tactile system at adequate levels to make possible the effective coding of intensity, fundamental frequency, and possibly place of excitation. Wherever possible such a device should meet the specifications described in this report.

A number of members of our working group arrived independently at one major conclusion: despite the general dissatisfaction with the performance of the tactile aids thus far developed, it is necessary as soon as possible to commit some time to the production of one or more variants of the single-channel aid and to fit a sizable sample of subjects with the devices to determine their functional utility for a limited class of hearing-impaired persons.

There are a number of reasons for recommending what may seem to be a precipitous move to those who know that our understanding of speech perception and of the processing capabilities of the skin, as well as of the technology of transducer structure, is unsatisfactory. First, some deaf persons can make good use of even a limited aid [Reed *et al.*

TABLE I. Some tests of speech perception for application to performance with tactile aids (these tests may be used with or without lipreading as an additional cue source. MAC, Minimal Auditory Capabilities; CAT, Children's Auditory Test).

Purpose of test	Name of test	Reference
Perception of gross prosodic structures; best for single-channel aids	Parts of the MAC	Owens *et al.* (1981)
	The CAT	Erber and Alencewicz (1976)
	Tennessee Rhythm Test	Koike and Asp (1981)
	Sound Effects Recognition Test	Finitzo-Hieber *et al.* (1980)
Perception of segmental speech elements; typically, the first stage for evaluating multichannel aids	Nonsense Syllable Test	Levitt and Resnick (1978)
	Modified Rhyme Test	Kruel *et al.* (1968)
	Multiple Choice Discrimination Test	Owens and Schubert (1968)
	California Consonant Test	Owens and Schubert (1977)
	Picture Identification Test	Wilson and Antablin (1980)
Comprehension of words and sentences; best for assessing extended training with an aid.	Parts of the MAC	Owens *et al.* (1981)
	W-22 List	Davis and Silverman (1970)
	NU-6 List	Tillman and Carhart (1966)
	Isophonemic Word List	Boothroyd (1968)
	CID Sentence List	Davis and Silverman (1970)
	Spin Test	Kalikow *et al.* (1977)

(1982, p. 16) cite three or four studies to this effect]. It is entirely possible that a larger sample of subjects from the population of post-lingually deaf people who use lipreading will provide cases that show a marked increase in processing capability. Second, the results of such a study should put tactile aids into a better position for comparison with the cochlear implants, for which the subject population is growing rapidly. Third, research and development efforts on tactile aids have often ended in the laboratory, i.e., at the threshold of field trials. Yet such trials are the very situations in which individuals will test the limits of their aids, and sometimes develop ingenious uses for them or use them in unforeseen conditions. This kind of experience in applied research is difficult to get in any other way, but it is invaluable to developers, not only for design revisions of current versions of devices, but also for any future system to be tested. It provides an evaluation of system performance that cannot be realized in the laboratory.

Finally, the readers should not be left with the belief that tactile aids and other available systems are incompatible channels that can never work together, nor even that combinations of aids cannot be integrated successfully with lipreading to form a unique speech-processing mechanism. As we have already stated, the differences among the modes of sensory substitution lie more in the approach to the problem than in the final means to the goal. In nearly any system, whether tactile, auditory implant, or visual, the final stages of system development involve the integration of seemingly disparate sources to achieve communication for users. It is from the wedding of such disparate sources that there so often emerges the unique character of experiences that enlarge the world of patients, clinicians, and researchers.

ACKNOWLEDGMENTS

Many readers who work in fields related to hearing and deafness are familiar with the reports of the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) of the National Research Council established by the National Academy of Sciences. These reports are prepared by special study committees, known as working groups, set up by CHABA to advise federal agencies on issues of significant national need.

The present report was developed in response to a request brought to the National Academy of Sciences in 1982 by the National Institute of Neurological and Communicative Disorders and Stroke (NINCDS) of the U. S. Department of Health and Human Services, who asked for assistance in evaluating the prospects of further research on tactile aids for use by people who are profoundly deaf. In response to the request from NINCDS, with the approval of the Commission on Behavioral and Social Sciences and Education and the National Research Council, CHABA created Working Group 90 and charged it with the preparation of a general critical review of research that has dealt with the use of touch and the allied bodily senses for processing information that is normally handled by the sense of hearing.

As the Chair of Working Group 90 for CHABA, I was given the task of organizing the present report for the committee. All the members of Working Group 90 performed their jobs most commendably by participating in our one meeting with enthusiasm and singlemindedness and by responding to early drafts and other correspondence promptly and helpfully. The useful insights and observations the report may offer are the product of thoughtful comments by members of the Working Group, many of whom have spent their professional lives dealing with the problems of communication with the deaf and deaf–blind. I am grateful to them for their help and instruction and for their steadfast pursuit of the goals of excellence in research, treatment, and education. I cannot imagine a better group for our task. Indeed, their names will head any list I would construct to get a difficult task done with intelligence, good humor, and efficiency: Louis D. Braida, James C. Craig, Carol Lee De Filippo, Nathaniel I. Durlach, Barrie J. Frost, Moise H. Goldstein, Jr., Jacob H. Kirman, Harry Levitt, James D. Miller, James M. Pickett, Frank Saunders, and Grace Yeni-Komshian.

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