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Development and preliminary evaluation of an earmold sound-to-tactile aid for the hearing-impaired*

JANET M. WEISENBERGER, ARNOLD F. HEIDBREDER, AND JAMES D. MILLER
Central Institute for the Deaf, St. Louis, Missouri 63110

Abstract—A binaural earmold sound-to-tactile aid was constructed by inserting a vibrating element into a Lucite earmold. The earmold could be vibrated at either 80 Hz (when incoming acoustic signals were below 2000 Hz), at 300 Hz (when incoming acoustic signals were above 2000 Hz), or both (when incoming acoustic signals were broadband). Subjects were fitted with one of these bimodal vibrating earmolds in each ear. Normal-hearing and hearing-impaired subjects were tested in three tasks: sound localization, environmental sound identification, and syllable rhythm and stress. The device provided some benefit to performance, although the amounts of improvement varied across tasks and subjects. Possible modifications in device design, and potential combinations of auditory and tactile input via earmold systems, are discussed.

INTRODUCTION

In the population of hearing-impaired persons in the United States and other countries are a substantial number who do not receive satisfactory benefit from conventional acoustic amplification. For these persons, some auditory functions can be taken over to some degree by a substitute sensory modality (i.e., vision or touch). Devices designed to use the tactile system to present some set of acoustic information have been studied since the 1920s (Gault, 1924) (4). The majority of these tactile devices were designed for use in speech perception, and after an initial period of discouraging results, more recent devices have shown some success at transmitting speech on the skin (Reed et al., 1982; Pickett and McFarland, 1985) (12,9).

However, the potential usefulness of tactile aids for sound reception extends beyond the perception of speech, possibly encompassing some of the more basic functions performed by the auditory system. These functions include such things as awareness of sound, the ability to localize the source of a sound, the ability to discriminate among common environmental sounds (e.g., to differentiate a doorbell from a telephone), and the ability to follow the basic rhythms and patterns of speech. Some researchers have reported that lack of awareness of everyday sounds creates a sense of isolation that can be associated with depression, particularly in adventitiously deaf persons (Ramsdell, 1978) (11).

There is some evidence that the tactile system can be used to provide some of these basic auditory functions for hearing-impaired individuals. For example, single-channel tactile aids that are commercially available (e.g., the Tactaid I, manufactured by Audiological Engineering Corporation, and the Minifonator, manufactured by Siemens Hearing Instruments) have been shown to facilitate lipreading by young children by providing rhythm and intensity information from speech signals, and have improved awareness of sound in speech and nonspeech signals

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(Geers, 1986; Goldstein and Proctor, 1985; Proctor and Goldstein, 1983) (5,8,10).

Another basic function, that of sound localization, was studied in the tactile system (Richardson, 1982; Richardson and Frost, 1977, 1979; Richardson et al., 1978) (13,14,15,16). Following earlier work by Bekesy (1959) and Gescheider (1965, 1970) (1,6,7), Richardson argued that tactile sound localization must depend on intensity differences only, since the tactile system is not sensitive to small phase differences. Richardson delivered square wave pulse trains to the index fingertips of the left and right hands from microphones placed at the left and right ear. Subjects were asked to report the location of a loudspeaker by turning their heads to face the source. Richardson found that when subjects were permitted to move their heads while the stimulus was still being presented, they performed at levels comparable to auditory localization of the same sounds. Tactile performance was considerably poorer than auditory performance when subjects were required to hold their heads stationary until the termination of the stimulus. In other tasks, including simultaneous judgments of direction and distance and the tracking of a moving sound source, tactile performance did not match auditory performance. But, in many cases it showed a decided improvement with practice, suggesting that long-term training with the device might lead to improved localization.

Richardson's analysis of his stimulus spectrum and the resulting intensity differences at different azimuth angles indicated that a maximum intensity difference between the two index fingertips of 10 dB occurred when the stimulus was located at a 60-degree azimuth angle, and decreased to as low as 2 dB at other angles. Thus, Richardson argued that active head movement allowed subjects to place the stimulus at a 60-degree angle relative to the head, and thus facilitated performance. In addition, Richardson found in further experiments that the tactile system could pay selective attention to one of two competing sound sources, an important ability normally performed by the auditory system.

The studies described above suggest that the tactile system can be a useful processor of acoustic information. In the present study, the design and preliminary evaluation of a vibrotactile aid designed to fill some of these basic auditory functions are described. This device differs from previous efforts in that vibratory stimulation is delivered to the skin of the ear canal, by means of a hard Lucite earmold of the type used in conventional hearing aids. This configuration has several potentially beneficial aspects. First, there is the possibility of binaural stimulation, making the aid feasible for sound localization. Second, an individual who has had previous experience with a hearing aid might be willing to wear such a device, and might even find the sensation more analogous to hearing than if the vibration were presented to some other body site. Third, an earmold stimulator could be made as cosmetically acceptable as a conventional hearing aid, and this configuration leaves the hands and arms free for everyday tasks. Finally, the possibility exists to provide a hybrid auditory-tactile aid to persons who have profound hearing loss in a restricted frequency range, but could benefit from acoustic stimulation at other frequencies. (For example, a person having a profound high-frequency loss, but some residual hearing at lower frequencies, could receive acoustic input through the auditory port of the hearing aid for the low-frequency portion of a sound, and vibrotactile stimulation for the high frequency portion, or vice versa.)

Each earmold receives two channels of vibratory stimulation, providing information about the stimulus to the wearer. The input sound is divided into a low frequency (<2000 Hz) channel and a high-frequency (>2000 Hz) channel. Each channel drives a different vibratory frequency (80 Hz for the low channel and 300 Hz for the high channel). These two frequencies drive two different magnetic elements mounted on the earmold. Thus, for a complex acoustic signal, such as speech, the earmold would receive amplitude-modulated vibrations at both 80 Hz and 300 Hz, and the resulting vibrotactile sensation would be a complex waveform from their mixture. The wearer of such a device should have not only awareness of sound and some ability to localize its source, but could also have some information about the frequency content of the sound.

In the present study, initial testing of several basic auditory abilities was performed with normal-hearing and hearing-impaired adults wearing the earmold vibrator. Specifically, the ability to localize a sound source, to identify a set of environmental sounds, and to identify stress and syllable number in spoken words was measured.

EXPERIMENT 1. SOUND LOCALIZATION

Method

Subjects. Two normal-hearing women (ages 22 and 27) and three prelingually hearing-impaired subjects (two women and one man) were paid for their participation in the experiment. All hearing-impaired subjects were audiometrically classified as having a severe to profound hearing loss (pure tone thresholds audiometrically measured at greater than 70 dB in the better ear across speech frequencies). The hearing-impaired subjects ranged in age from 22 to 34 years. Speech-frequency averages for these subjects in the better ear ranged from 89 to 102 dB.

Apparatus

1) *Earmold sound-to-tactile aid*: The device worn by subjects was designed and constructed at Central Institute for the Deaf by Arnold Heidbreder and James D. Miller (CID Progress Report, 1983) (2). The system extracts the envelope of speech using conventional RC integration and uses the envelope to control a sine-wave vibratory carrier. **Figure 1** and **Figure 2** show a schematic representation of the earmold stimulator and signal processing network.

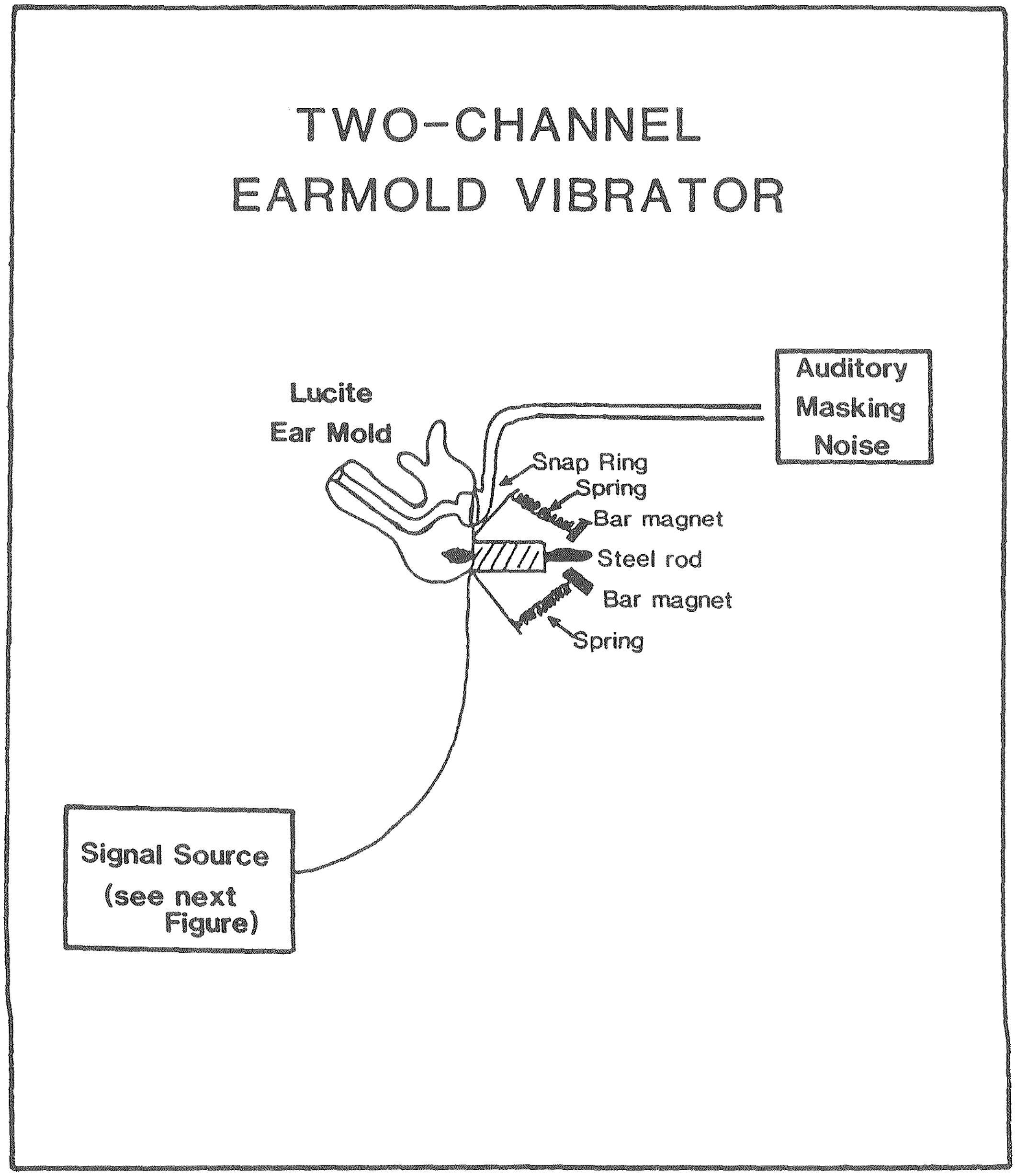

Figure 1
Schematic representation of the vibrating element as attached to the earmold.

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Input sounds are detected by Knowles BT–1754 subminiature condenser microphones worn at ear level on the left and right sides of the head. The microphones have a relatively flat frequency response from 100 Hz to 2000 Hz, and rise to a 12-dB peak at approximately 4500 Hz. The signal from each microphone is divided by bandpass filters into a lowband signal (all frequencies <2000 Hz) and a highband signal (all frequencies >2000 Hz). Filter characteristics are shown in **Figure 3**. The amplitude envelope of each band is extracted and used to modulate the amplitude of a sinusoidal carrier. Carrier frequencies used in the present study were 80 Hz for the lowband and 300 Hz for the highband signal. These modulated carriers were mixed and sent to the earmold.

The vibrating element consists of two small bar magnets mounted on springs and oriented about a steel rod with a solenoidal coil wrapped around it to create an electromagnet. Energizing the coil causes movement of the bar magnets to create a corresponding mechanical vibration of the entire assembly. Each spring and magnet assembly was constructed to have a narrowly-tuned mechanical resonance at a specific frequency: 80 Hz for the lowband magnet and 300 Hz for the highband magnet. The degree of stiffness of the springs controls both the resonant frequency and the damping for the spring-magnet assembly. The vibrating element is affixed to the earmold by screwing it into a hex nut embedded in the earmold.

Each subject was fitted with individual hard Lucite earmolds of the snap-ring type. The vibrating element was mounted so as to leave the snap-ring acoustic port free for auditory stimulation. In the present study, a pink noise was fed through the

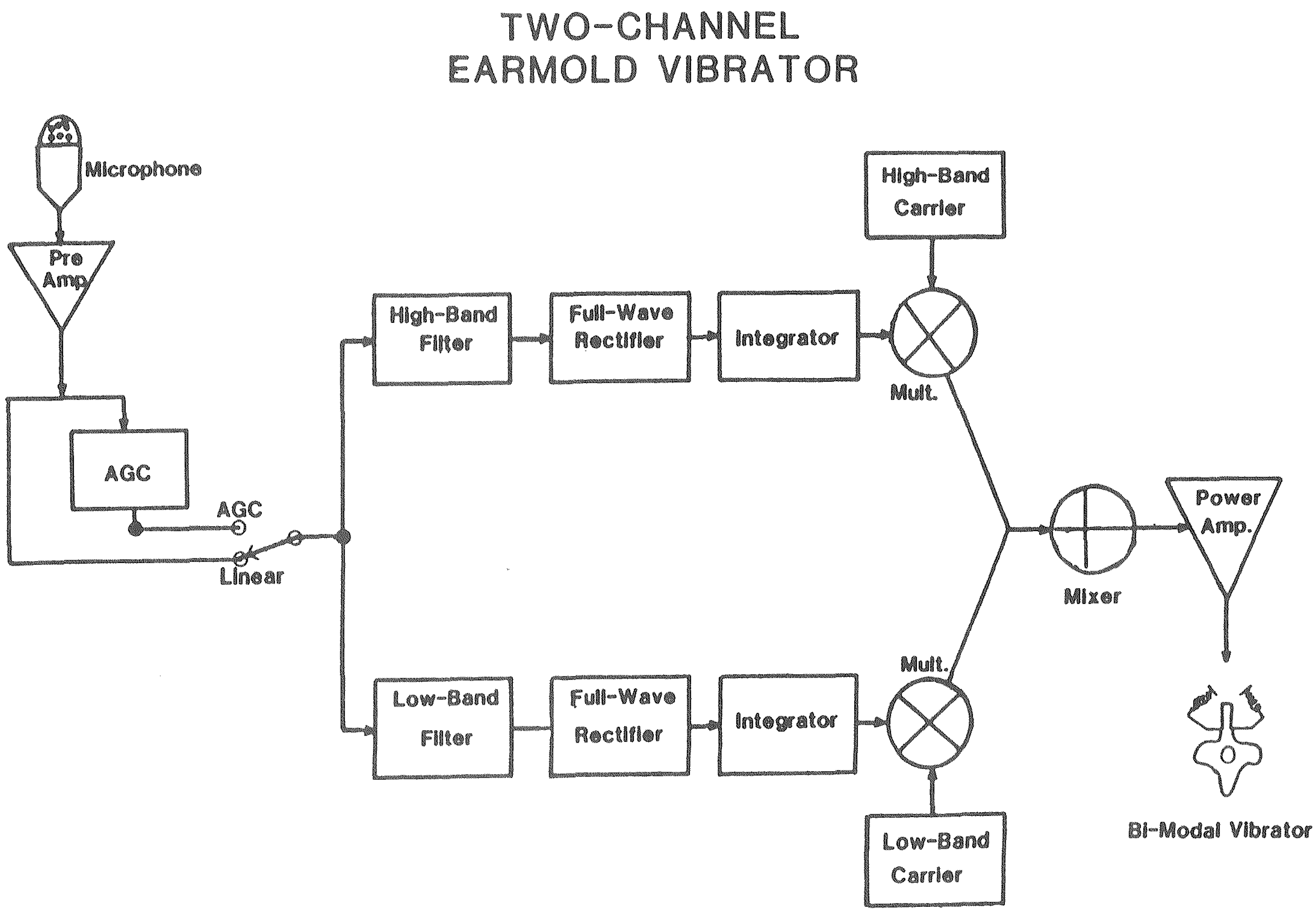

Figure 2
Schematic representation of signal processing steps in the earmold vibrator system.

acoustic port to eliminate auditory cues during the experiment. A pair of circumaural ear muffs further reduced acoustic input.

2) *Test Enclosure*: Testing was conducted in a 5 m x 4 m room, fitted with sound-absorbing panels and carpeted. A subject was seated in approximately the center of the room, at a distance of 1.82 m from each of five loudspeakers. The speakers were FM–42 series Soundelier, Inc., loudspeakers with a relatively flat frequency response between 100 Hz and 12 kHz. The loudspeakers were placed at angles of -90, -45, 0, 45, and 90 degrees relative to the subject. Loudspeakers were mounted on poles such that the center of each speaker was at the level of the subject's head.

The microphones, circumaural ear muffs on which the microphones were mounted, and the earmolds with vibrating element were tethered by long wires to the signal-processing equipment which was located in an adjoining room. The experimenter also sat in the adjoining room to control stimulus presentation and response collection. The experimenter viewed the subject and test enclosure through a small window between the two rooms located behind the subject.

3) *Stimuli*: Stimuli used in the present experiment consisted of pure tones at 500 Hz, 1000 Hz, and 2000 Hz generated by a General Radio oscillator, and a broadband pink noise. Stimuli were pulsed with a duty cycle of 750 milliseconds, with 250 ms on time and 25-ms rise-fall times, and were presented at a level of 72–75 dBA at the location of the subject's head as measured by a handheld sound level meter.

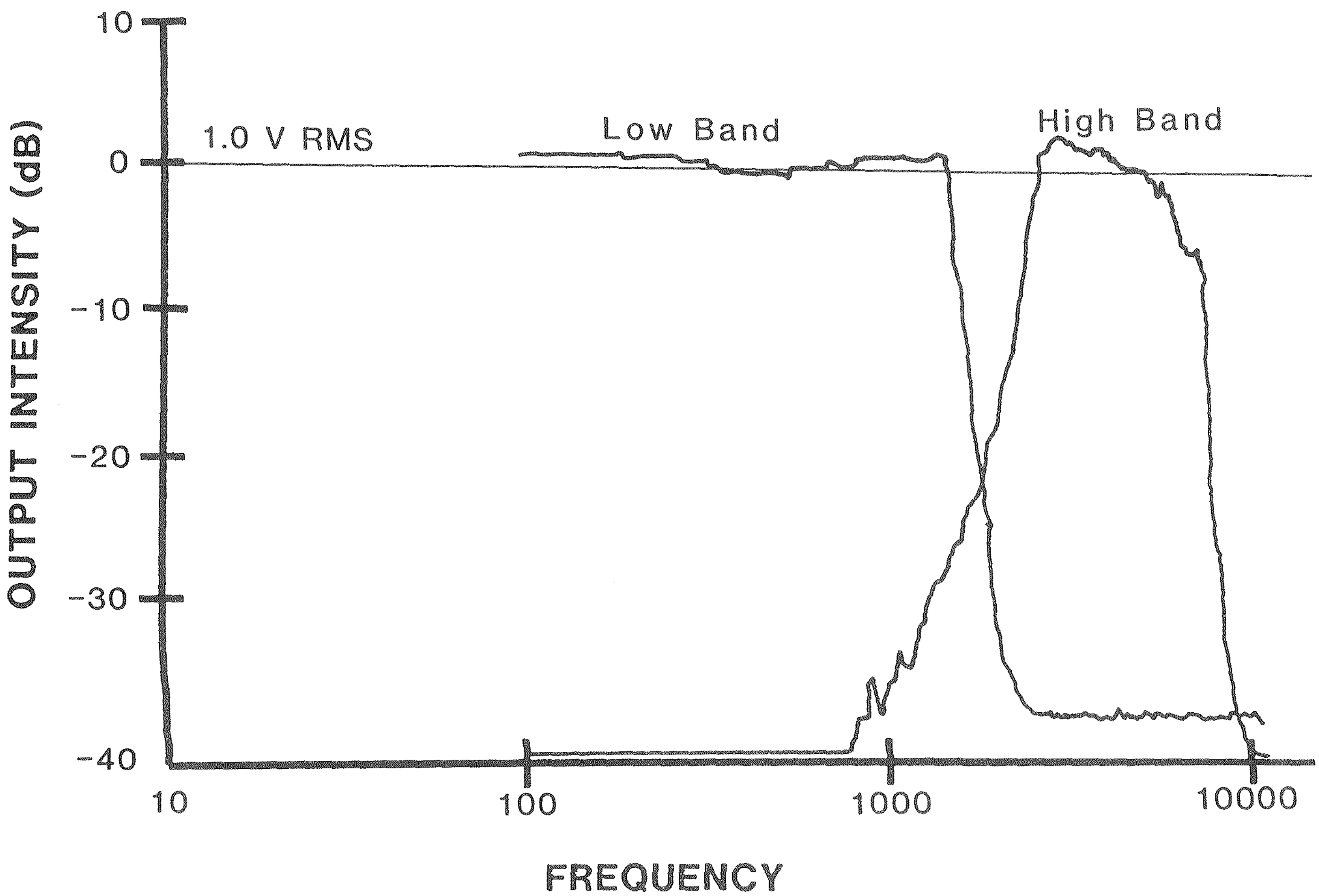

Figure 3
Filtering characteristics used to separate highband and lowband signals.

Procedures

Each subject was seated in the testing room and earmolds were inserted, after which a pair of circumaural ear muffs was placed on the subject's head. At the beginning of each block of test trials, a signal of the appropriate frequency was presented at the loudspeaker directly in front of the subject. The experimenter adjusted the level of stimulation in each ear until the subject perceived the vibratory stimulation to be equally intense in both ears.

Testing was conducted in blocks of 30 trials, such that all trials in a block used the same stimulus. Location of the stimulus was randomized across loudspeakers within a block of trials. On each trial, the stimulus remained on until the subject responded by indicating the loudspeaker from which the sound was perceived. Subjects were permitted free movement of the head on all trials. Feedback was given after each trial by lighting a small light located under the appropriate loudspeaker. A brief rest period was given after each block.

Subjects were tested for a total of 18 blocks of 30 trials each under each stimulus condition (500 Hz, 1000 Hz, 2000 Hz, and pink noise), in daily sessions during which 3 to 6 blocks were run. Subjects were tested at the conclusion of the experiment for one block under each experimental condition without wearing the earmold stimulator. For these blocks subjects wore their hearing aids if they normally did so (one subject did), and otherwise were unaided.

All stimulus presentation, response recording, and feedback delivery was controlled by the experimenter from the adjoining room.

Results

Average performance for normal-hearing and hearing-impaired subjects across experimental conditions is shown in **Figure 4**. It can be seen that performance with the 2000 Hz stimuli was better than any other condition for the normal-hearing subjects. For two of the three hearing-impaired subjects performance was also best under the 2000 Hz condition, whereas for the third hearing-impaired subject performance was much poorer.

A two-factor repeated measures analysis of variance was performed on an arcsine transformation of the data. This analysis showed a significant effect for stimulus condition [$F(3,20) = 16.95$, $p < .01$] and for hearing ability [$F(1,20) = 87.63$, $p < .01$], and also a significant interaction effect [$F(3,20) = 10.04$, $p < .01$]. These factors accounted for 85 percent of the total variance in responding.

Figure 5 contrasts auditory and tactile localization performance for the three hearing-impaired subjects, comparing average tactile performance to that obtained when the earmold vibrator was not worn. Hearing impaired subjects who normally wore hearing aids did so and if not, were unaided. (Normal-hearing subjects localized perfectly under all auditory conditions.) Open bars show unaided auditory performance, solid bars show hearing aided performance, and shaded bars show tactile performance. For the hearing-impaired subjects, in no case was unaided auditory performance superior to tactile performance. This was due to the fact that the stimuli were not consistently audible to the subjects, even when stimulus level was increased to the limits of the equipment (about 94 dBA). Under some circumstances subjects refused to participate after a few trials. Performance in these blocks was assumed to be at chance (20 percent) levels.

Hearing-aided localization performance, after stimulus levels were adjusted so that they could be heard, was superior to tactile performance under the 500 Hz and noise-band conditions, but was not as good as tactile performance under the 1000 Hz and 2000 Hz conditions. Neither the auditory nor the tactile aid could be said to be better in this task.

Finally, data were examined for improvements in performance across sessions that would reflect a learning trend. However, no evidence of learning was found, although it had been expected that the novelty of the vibrotactile stimulation would require some adjustment period.

Discussion

There are several possible reasons why performance was better for normal-hearing subjects than for hearing-impaired subjects. First is the possibility that the normal-hearing subjects had more experience with auditory sound localization on an everyday basis, and this experience could have had a carryover effect in the present experiment. A second, and more likely, possibility arises from the fact that auditory artifact cues from the vibrator were not completely masked by the auditory masking noise, even at very high levels, although auditory perception of the test stimuli from the loudspeakers was effectively eliminated. The fact that auditory sensitivity is better than tactile sensitivity at many frequencies suggests that normal-hearing subjects would hear the vibrations induced in the ear canal in addition to feeling them. This was not a problem for the hearing-impaired subjects, none of whom reported acoustic sensation from the vibrators. However, these vibrator-generated auditory cues most probably contributed to performance by the normal-hearing subjects and may in large part account for differences in performance across groups.

In four of the five subjects, performance was best with the 2000 Hz signal. This effect may be due to two factors. First, the filtering activity of the earmold stimulator system may result in differential activity of both the high and low frequency vibrators at the 2000-Hz cutoff frequency and may mediate detection in some fashion. A more likely possibility is that 2000 Hz signals generated better interaural intensity cues than any of the other signals tested. Since neither the earmold stimulator system nor the tactile system is sensitive to fine phase differences (Richardson, 1982) (13) the 500- and 1000-Hz signals

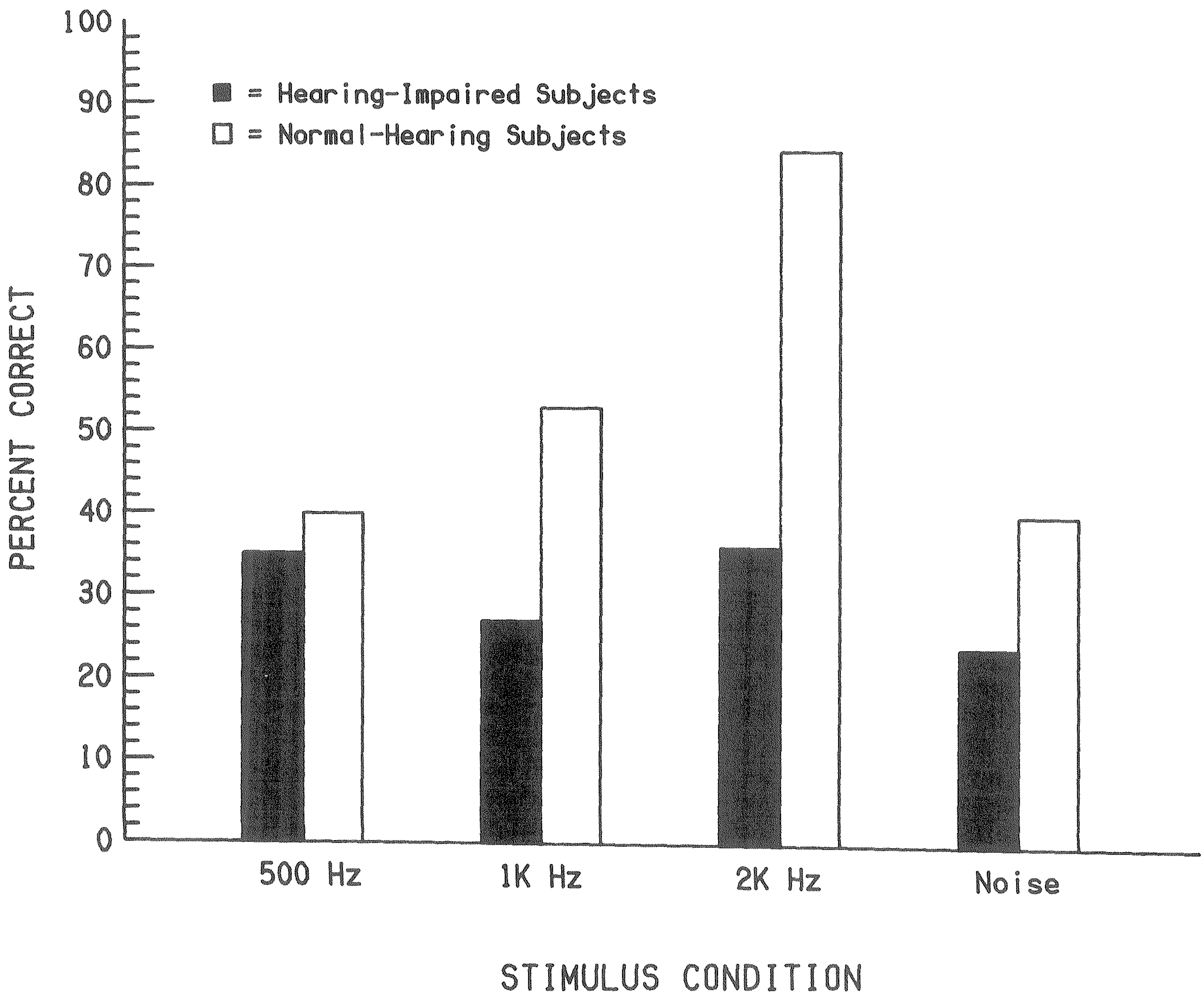

Figure 4
Percent correct sound localization performance, shown separately for normal-hearing (unshaded bars) and hearing-impaired (shaded bars) subjects. Results are the average of 540 trials per condition for each of five subjects, for each test signal presented.

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should be more difficult to localize, because their interaural intensity differences are relatively small and do not change much as a function of azimuth angle, making them poor cues for localization.

Because the test enclosure was not anechoic, one would not expect to obtain orderly, optimal, interaural intensity differences. The test enclosure was reasonably sound-attenuating, but was a much closer approximation to the real-world situations in which a user might need to localize an acoustic stimulus. Thus, actual interaural intensity differences between the two microphones were measured in the test enclosure, with the microphone-earmuff assembly placed on a mannikin to prevent movement. Each of the test stimuli was presented at all speaker locations, and the resultant voltage at the two microphones was recorded. These measurements showed that while the average interaural intensity difference was the largest for the 2000-Hz condition (8.25 dB across all oblique speaker locations, with

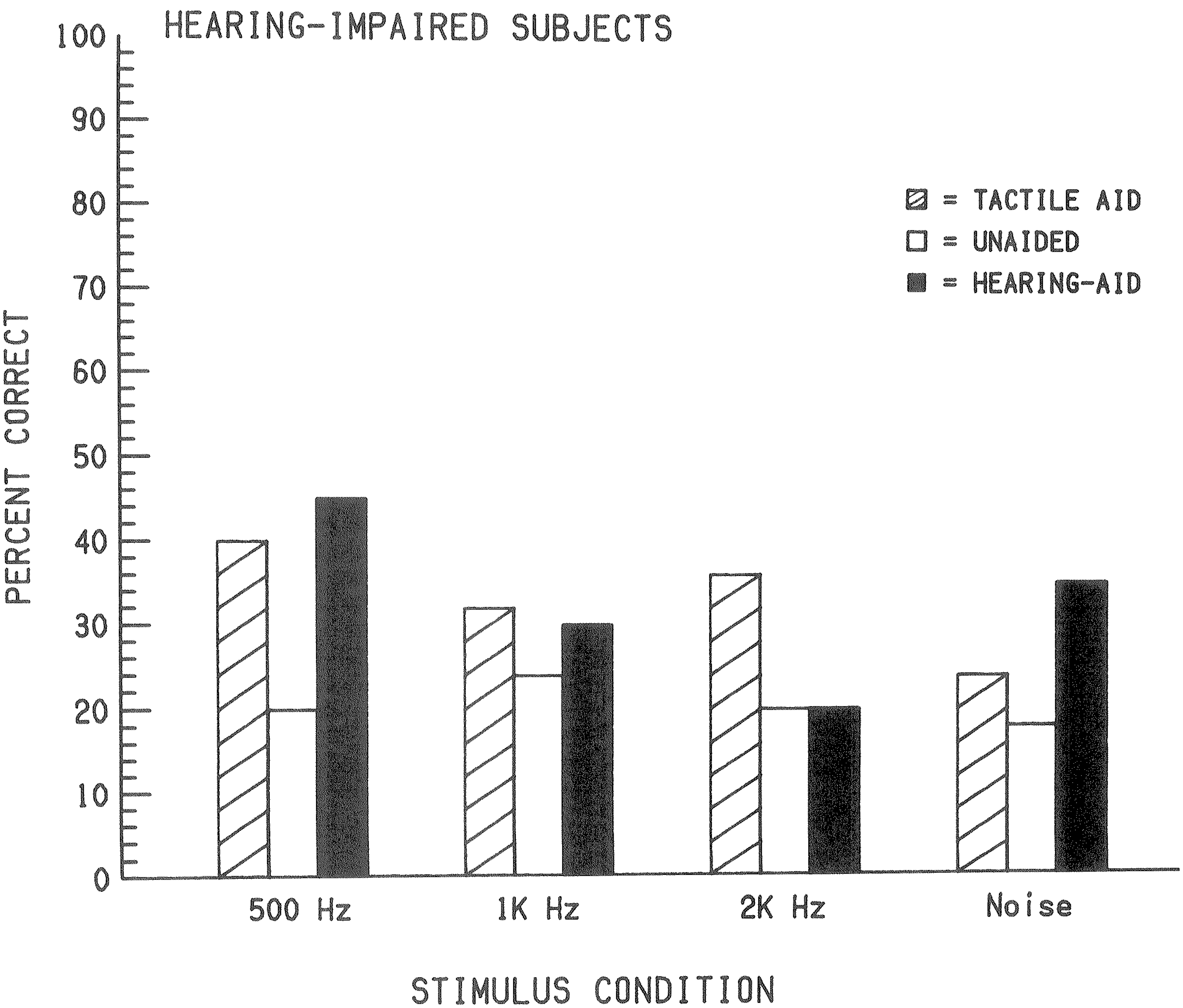

Figure 5
Percent correct localization under unaided auditory (open bars), hearing-aided (solid bars), and tactile (shaded bars) presentation conditions, averaged across hearing-impaired subjects.

a range of 3 dB to 11 dB), the changes in intensity were not an orderly function of speaker location, due to the influence of standing waves and reflections in the test enclosure. The intensity differences for the other stimulus conditions were slightly smaller: 6.4 dB at 500 Hz, range 4–8.5 dB; 8 dB at 1000 Hz, range 3.5–11.5 dB; and 3.8 dB for the broadband noise, range 3–4.5 dB. Measurements were made for three of the subjects (2 normal-hearing, 1 hearing-impaired) to determine the smallest interaural intensity difference at the two earmolds that subjects could reliably distinguish. Stimuli were presented directly to the processor unit and thus to the earmolds, rather than through the loudspeakers, thereby bypassing the microphone of the device. Stimuli were presented at 500, 1000, and 2000 Hz, and at sensation levels of 0, 10, and 20 dB. Masking noise was used, and a modified method of limits procedure which permitted variation of level in one-decibel steps was employed. Mean interaural intensity differences were: 3.6 dB at 500 Hz, 4.2 dB at 1000 Hz, and 3.4 dB at 2000 Hz. Variability across subjects was quite small, with standard errors of .2 to .7. Thus, the actual threshold for detecting a vibratory intensity difference under optimal conditions was smaller than the mean differences generated in the test chamber by the stimuli used in the experiment. This suggests that the task of actually localizing the more intense sensation was more difficult than merely detecting an intensity difference.

Permitting subjects to move their heads during the actual localization task was apparently particularly beneficial in the 2000 Hz condition, and less so in the other stimulus conditions. These measurements do not clarify the nature of such benefit. However, anecdotal reports from subjects indicate that, with head movement, localization in the 2000-Hz condition was considerably easier than in the other conditions, and was accomplished by perceived differences in vibratory intensity at the two ears. It is possible that variations in the placement of the microphones could result in a more optimal arrangement for localization (e.g., mounting them closer to the head rather than on the outside of the earmuffs, to take greater advantage of head shadow). Such variation was not attempted in the present study.

It is not clear why overall results in the present experiment were poorer than those found by Richardson with stimulation of the index fingers. Differences in acoustic stimuli, signal processing, tactile stimulation locus and waveform, and task make it difficult to specify exactly why localization performance differed, and any of these parameters could have contributed.

Because in everyday life a sound source can frequently be localized visually if the listener turns in the correct general direction, the usefulness of the earmold stimulator for this more general localization ability was examined by rescoring the data from the present experiment to reflect near misses, i.e., trials on which the response was incorrect, but within one speaker of the correct location. When the data are analyzed in this fashion, localization performance improves for all subjects under all conditions, adding, on the average, from 20 percent (noise band condition) to 40 percent (2000 Hz) to performance levels. This suggests that the earmold stimulator would be useful in its present configuration as an aid to visual localization, and with design improvements (i.e., some transformation of phase differences to tactile intensity differences) might more closely approach the localization ability of the unimpaired auditory system.

EXPERIMENT 2. ENVIRONMENTAL SOUNDS

In a second experiment, the ability of the earmold stimulator system to transmit more complex information was examined. Another fundamental ability of the auditory system is the discrimination and identification of naturally-occurring sounds in the environment (e.g., telephones, barking dogs, etc.). This ability cannot always be mediated visually, as in the case of telephones and doorbells, and thus for persons who cannot perform this task auditorily, the tactile system might reasonably be used to transmit some of the information.

In the present experiment, subjects were asked to identify items from a set of tape-recorded environmental sounds presented through a loudspeaker. Performance was monitored across experimental sessions for improvement over time, to determine whether this ability could be learned on the skin.

Method

Subjects. One normal-hearing woman and two hearing-impaired persons (one woman and one man) were paid for their participation in the experiment. The two hearing-impaired subjects were measured as having more than 70 dB loss in the better ear, (measured pure-tone average losses of 89 dB and of 97 dB).

Apparatus

General details of the apparatus were identical to those of Experiment 1, except for the stimuli presented. Stimuli consisted of 20 environmental sounds that had been tape-recorded in the field using a Nagra reel-to-reel tape recorder and an AKG microphone. These sounds are listed in **Table 1**. The recordings were read into storage on a Data General Eclipse S–200 computer through a 12 bit analog-to-digital converter. Sounds were then edited to a duration of exactly 4 seconds, output through a 12 bit digital-to-analog converter, and rerecorded onto tape.

During testing, sounds were played from tape through a manual attenuator and presented through one of the Soundelier loudspeakers placed in the test enclosure. All sounds were presented at a level of 70–75 dBA as measured at the subject's head. Six different random-order lists of the sounds were recorded, to prevent the learning of item order in testing.

Table 1
Environmental Sounds

1. dog barking	11. bell
2. doorbell	12. woman's voice
3. siren	13. man's voice
4. teakettle	14. smoke alarm
5. water running	15. ocean waves
6. lawn mower	16. birds
7. auto horn	17. crickets
8. telephone	18. band playing
9. knocking	19. cat
10. baby rattle	20. baby crying

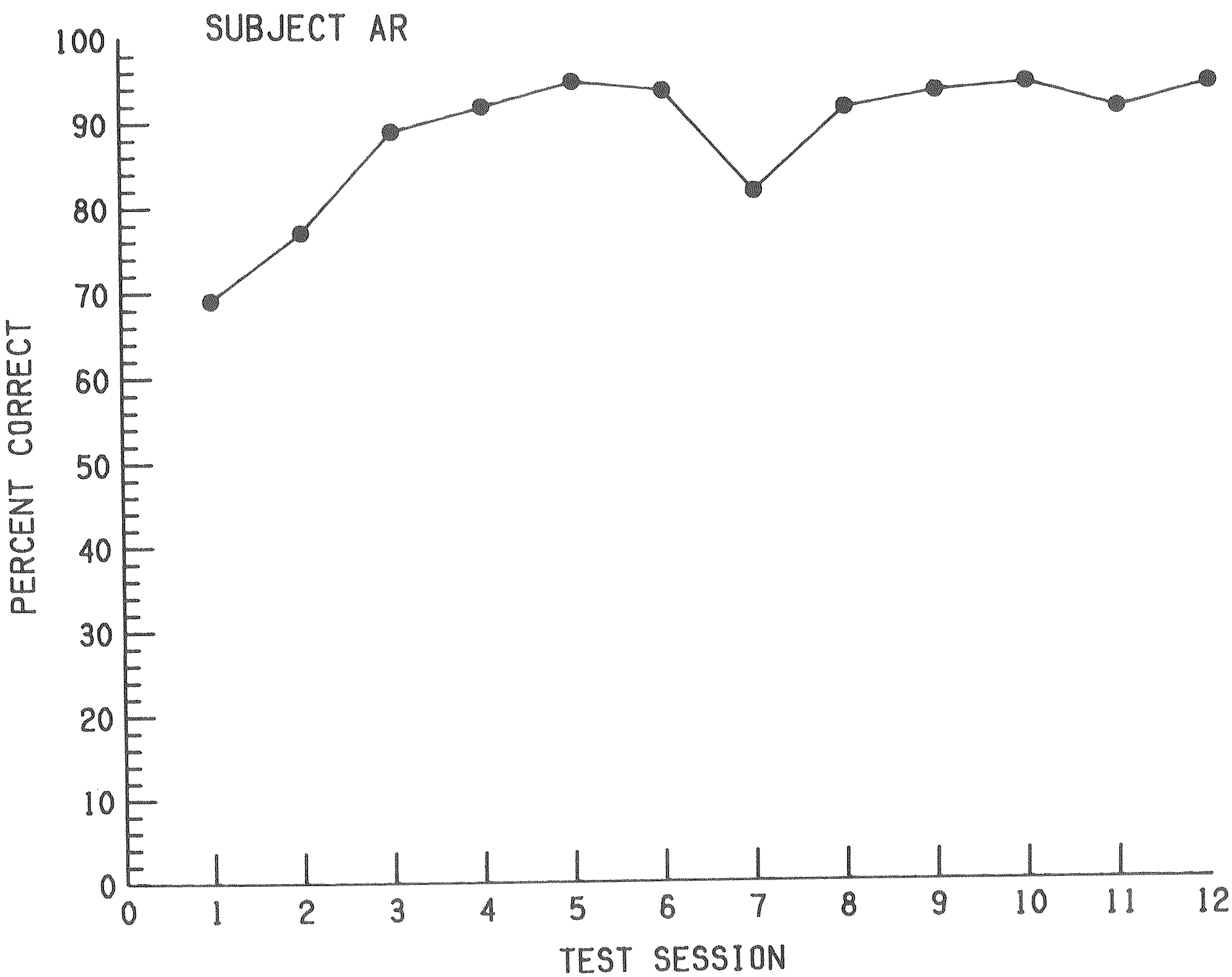

Figure 6
Percent correct identification of 20 environmental sounds, across test sessions, for normal-hearing subject AR.

Procedure

At the beginning of each test session, the experimenter presented a 100-Hz tone through the loudspeaker facing the subject, and adjusted the intensity of vibration in each ear until the subject reported the vibratory signals to be of equal intensity. During each session, one of the stimulus tapes was selected at random and played as training for the subject, who was given a list containing all items in the correct order. Following this, all tapes were presented to the subject in a random order. Before each sound the red light under the loudspeaker was lighted to indicate the beginning of a trial. At the conclusion of the sound, the light was turned off. Subjects responded on a multiple-choice-format answer sheet. Answer sheets were scored at the end of a tape, but no trial-by-trial feedback was given. Rest periods were given between tapes as necessary.

As in Experiment 1, all subjects were presented with masking noise through the auditory port of the earmold and wore a pair of circumaural earmuffs during testing.

A total of 12–14 sessions were run per subject. Daily performance was computed by averaging scores on all six tapes presented in a session.

Results and Discussion

Session-by-session percent correct sound identification is shown in **Figures 6, 7**, and **8. Figure 6** shows data for normal-hearing subject AR, and **Figures 7** and **8** show data for hearing-impaired subjects SM and JH, respectively. In the case of subject AR (**Figure 6**), a high initial level of identification (69 percent) showed a relatively steady improvement to asymptotic performance at 95 percent after 12 test sessions.

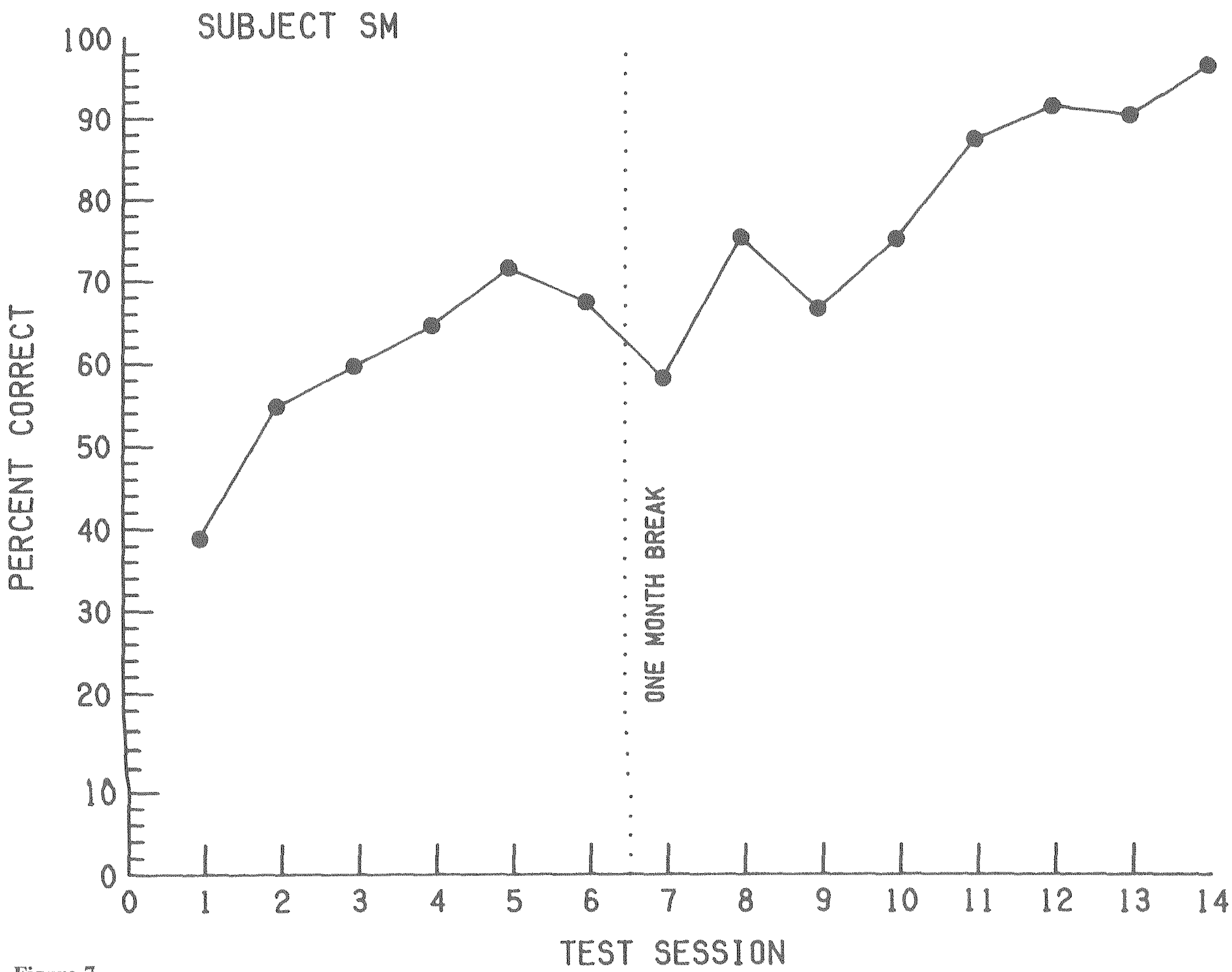

Figure 7
Percent correct identification of 20 environmental sounds, across test sessions, for hearing impaired subject SM.

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In **Figure** 7, it can be seen that hearing-impaired subject SM began at a much lower level of performance (39 percent), but after 14 test sessions had reached 97 percent correct, a level indistinguishable from that of the normal-hearing subject. In a task in which chance performance was at 20 percent, these levels show clear mastery of the identification of these sounds. The fact that final performance was the same for both subjects suggests that identification need not have been based solely on auditory cues that could not be masked by the masking noise, since these were inaudible to the hearing-impaired subject. Rather, the information provided by the vibrotactile signal alone was sufficient for learning.

In **Figure** 8, results for hearing-impaired subject JH are somewhat less satisfactory, but nonetheless show some evidence of learning across sessions. This subject's sporadic attendance at testing sessions may have contributed to his poorer performance levels.

EXPERIMENT 3. RHYTHM AND STRESS PERCEPTION

The findings of the preceding experiment suggested that subjects could obtain some duration, stress, or pitch information about environmental sounds through the earmold vibrator. The present experiment attempted to ascertain whether the information transmitted by the device could be used in identifying stress and rhythm patterns in word lists, where presumably the variability among cues might not be as great as for the environmental sounds, and thus the task might be more difficult.

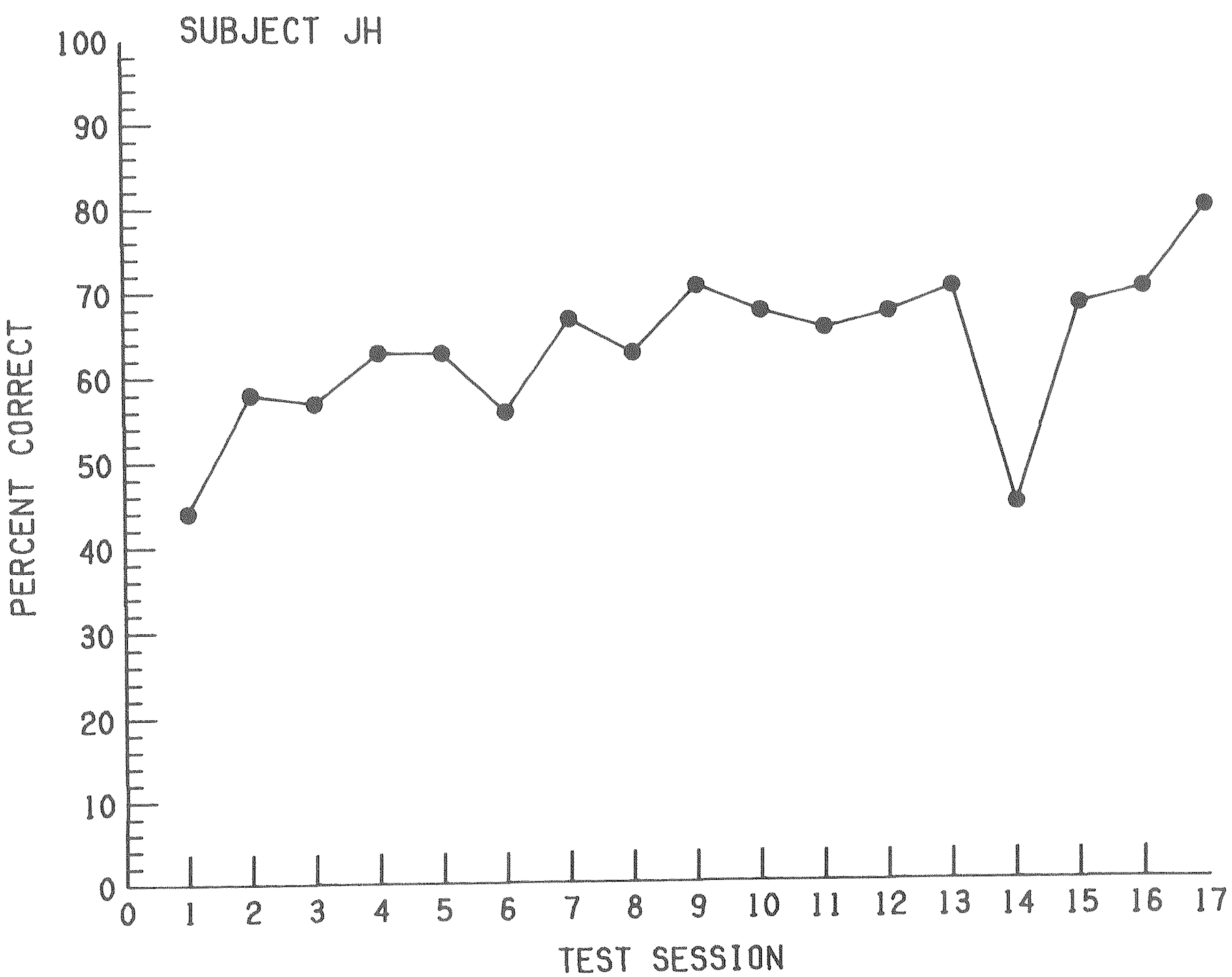

Figure 8
Percent correct identification of 20 environmental sounds, across test sessions, for hearing-impaired subject JH.

Methods

Subjects. Two hearing-impaired adult men, with hearing loss in the better ear measured at greater than 70 dB across speech frequencies, were paid for their participation. One subject (JH) had served in Experiment 2; the other (SR) had not previously participated. Subject SR had measured three-tone average hearing loss of 94 dB.

Apparatus

The test enclosure and earmold vibrator elements were identical to those of Experiment 2. Stimuli used in the present experiment consisted of 30 words spoken by a female. These words were selected according to the criteria specified by Erber and Witt (1977) (3) in what is typically referred to as the Monosyllable-Trochee-Spondee Test. The list contained 10 single-syllable words, 10 two-syllable words with stress on the first syllable, and 10 two-syllable words with equal stress on both syllables. A second criterion used in selecting words was that divisions between syllables be bounded by consonants. Stimulus words are shown in **Table 2**. All words were presented at a level of 69 to 72 dBA, as measured at the subject's ear by a handheld sound level meter.

Table 2
Monosyllable-Trochee-Spondee Test Lists

1. bed	1. cat
2. duck	2. pig
3. top	3. pit
4. back	4. bolt
5. cord	5. guard
6. button	6. chicken
7. doctor	7. turtle
8. table	8. carton
9. teacher	9. pattern
10. bucket	10. garden
11. baseball	11. birdhouse
12. popcorn	12. toothpaste
13. bookmark	13. pigpen
14. cowboy	14. bulldog
15. skindive	15. totebag

Procedure

Stimuli were recorded onto disk and presented in a random order by a PDP 11/23 minicomputer equipped with 12-bit digital-to-analog converters. Subjects presented a stimulus, made a response, and received feedback by contacting a touch screen placed in the test enclosure. On each trial, the subject attempted to identify the word which had been presented from among five alternatives. Trial-by-trial feedback was given.

Subjects were tested in daily sessions in which they received 4 repetitions of the 30 items. An average percent-correct identification score was obtained for each day. In addition, percent correct categorization of the stimulus word was measured, i.e., whether the subject chose a word with the correct number of syllables and stress pattern, even if the exact word was not correct. Thus, to the degree that the subject was able to categorize the sound, rhythm and stress information were being transmitted, and within this, correct identification of the word indicated that some phonemic information was passed on as well.

Results

Learning curves for the two subjects are shown in **Figures 9** and **10**. On each graph, both percent correct word and category identification are plotted for each experimental session.

Chance performance for categorization was 40 percent in this experiment. Chance levels for word identification are somewhat more difficult to specify in this task, because if the subject can categorize perfectly, then the number of items to choose from for identification is limited to the number of alternatives that fit the category (in this case, two). If the subject categorizes at chance, then chance performance for word identification is determined by the total number of alternatives (five). In practice, chance levels for word identification vary between these extremes.

For subject SR (**Figure 9**), excellent performance was obtained. He was able to categorize the stimuli with high accuracy from the first testing session. His ability to identify stimuli within categories also showed good improvement across sessions, with performance in the last session reaching 97 percent. With nearly perfect categorization, chance performance for stimulus identification was close to 50 percent. The obtained performance is always considerably higher than this level, suggesting a good ability to use the earmold vibrator to obtain both rhythm/stress and phonemic (frequency) information about speech.

Subject JH (**Figure 10**) shows lower levels of performance on both tasks. No consistent improvement over sessions is found in these data. However, his ability to categorize is far above chance, as are

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his identification scores. While he does not use the earmold vibrator as effectively as SR, nonetheless some benefit can be seen. His lower levels of performance might be explained by considerable difficulties in maintaining attention within the 30-trial test blocks, as well as across the hour session. This remained true despite the fact that he was permitted to take rest periods whenever he wished. It is possible that a task with more relevance to everyday conversation might have led to better attention and produced better scores for this subject.

GENERAL DISCUSSION

Overall, the earmold vibrator system showed some promise as an alternative aid for hearing-impaired persons. Although the device was not as successful in aiding sound localization as might be desired, it provided considerable benefit in identifying environmental sounds, and in perceiving rhythm and stress in spoken syllables. Some facilitation was also seen in word identification. It should be noted that all of these tasks employed a closed, or limited, stimulus set, and that good performance in real-world tasks might require considerably more training than was provided for this study.

Several aspects of the device might benefit from modification, and improve fidelity in signal transmission. First, work from Verrillo's laboratory (e.g., Verrillo, 1968) (17) suggests that two vibrotactile signals are best differentiated if they fall into different processing channels. Verrillo's duplex mechan-

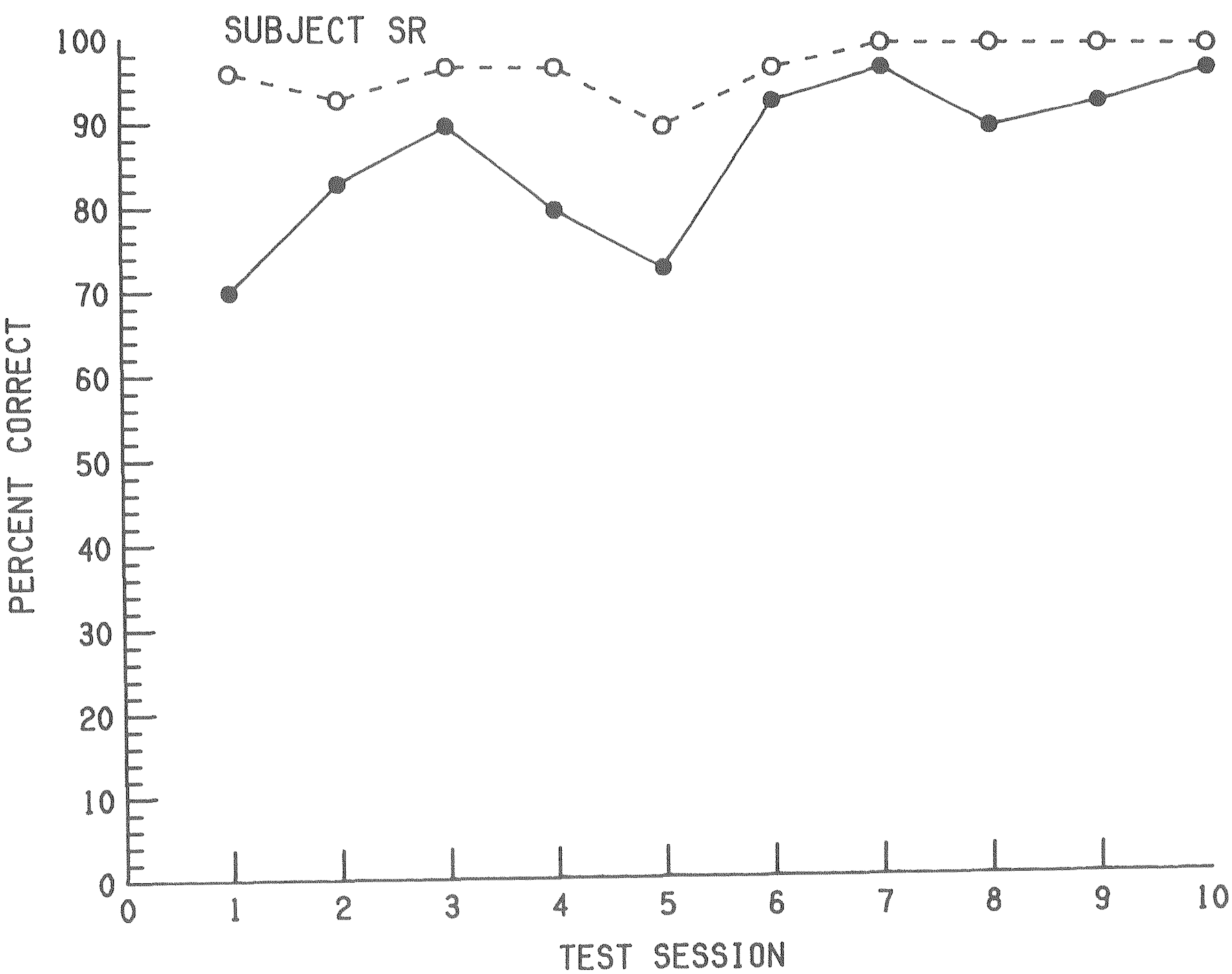

Figure 9
Performance across test sessions of hearing-impaired subject SR on the Monosyllable-Trochee-Spondee test. Open circles (dashed lines) show percent correct category identification, and filled circles (solid lines) show percent correct word identification.

oreceptor hypothesis postulates two vibratory channels, one serving low-frequency (50 Hz and under) stimuli, and the other serving higher frequencies (above 50 Hz). Stimuli that fall into the same channel can interfere with each other (i.e., mask each other), but stimuli in different channels appear to be processed independently and do not mask each other. Thus, the frequencies used in the present device (80 and 300 Hz) are not optimal from this point of view. These frequencies were chosen arbitrarily by the engineers involved and can easily be modified through slight alterations in the spring and magnet assembly.

A second area for possible modification is in the amount of ringing produced by the stimulators. Fine detail following of the temporal aspects of sound waveforms is essential for accurate identification. The amount of ringing observed in the present study was considerable, owing to the extremely high Q values observed from the tuning of the output. Modifications in this aspect to provide a more faithful following of the waveform's temporal structure should result in improved performance.

A third possible improvement could result from optimizing microphone location. Alternate placements of the microphones, and/or the use of a more directional microphone, might lead to improved localization ability.

Obviously, for clinical use the cosmetic acceptability of the device is an important consideration. An improved transducer that should be more acceptable on this basis has recently been designed at CID by A.M. Engebretson. This transducer uses a

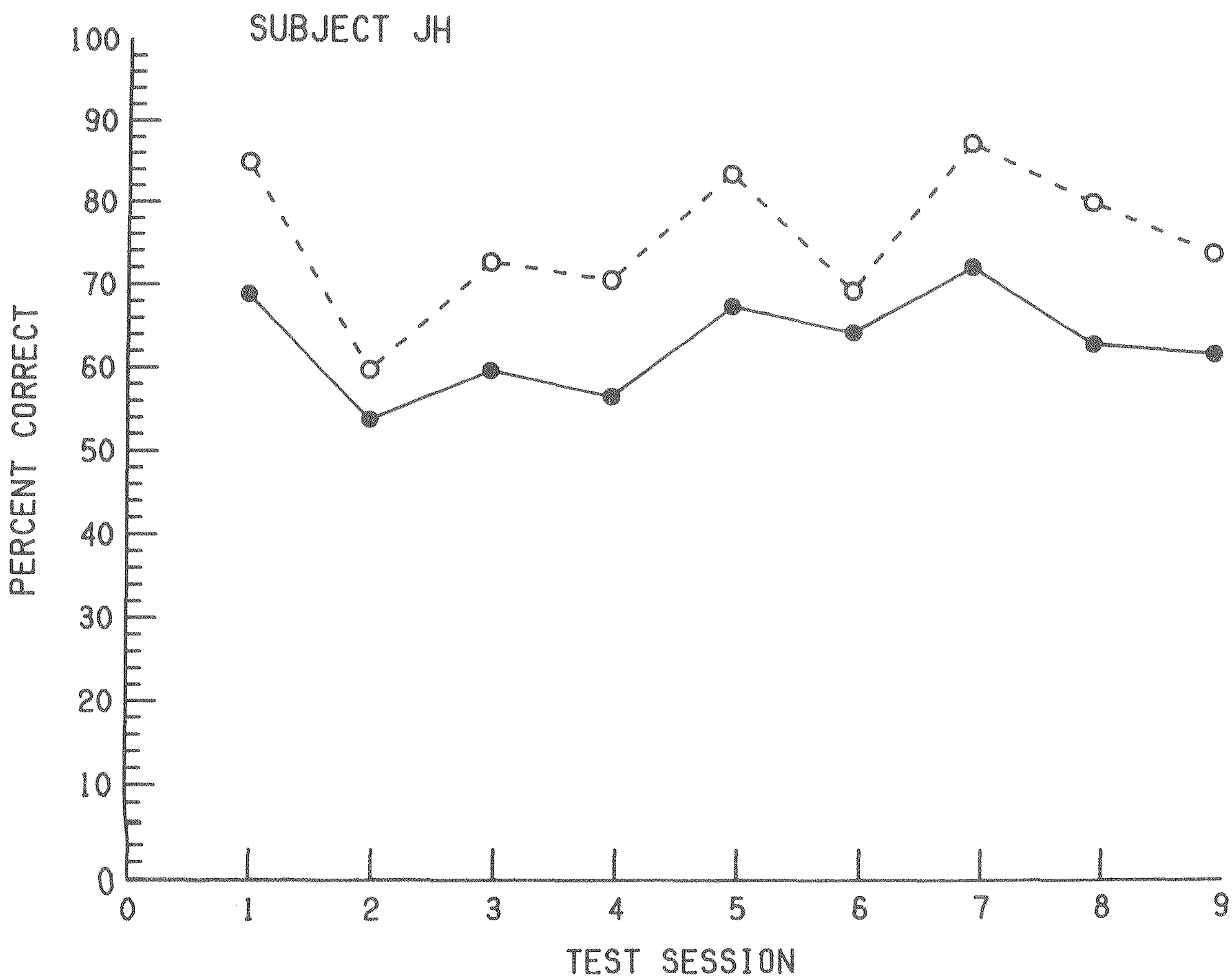

Figure 10
Performance across test sessions of hearing-impaired subject JH on the Monosyllable-Trochee-Spondee test. Open circles (dashed lines) show percent correct category identification, and filled circles (solid lines) show percent correct word identification.

damped piezoelectric bimorph mounted inside an in-the-ear hearing aid case, such that no parts protrude from the ear. The power consumption and tunability of this transducer area are also acceptable. This transducer may well form the basis of a wearable earmold stimulator that could provide the cosmetic acceptability, simplicity, and limb freedom necessary for persons desiring a tactile alternative to a conventional hearing aid.

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