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Relative performance of single-channel and multichannel tactile aids for speech perception

Janet M. Weisenberger, PhD; Susan M. Broadstone; Linda Kozma-Spytek
Central Institute for the Deaf, St. Louis, MO 63110

Abstract—Although the results from a number of studies of the performance of multichannel tactile aids for speech perception have suggested that such devices might provide more benefit to hearing-impaired persons than single-channel tactile aids (3,4), recent studies involving direct comparisons of multichannel and single-channel vibrotactile aids (5,6) indicated otherwise. In fact, for some types of speech information, such as rhythm and stress perception, single-channel aids were shown to be superior. The present study attempted to address this apparent discrepancy by comparing the performance of two single-channel devices with two multichannel devices in a variety of speech perception tasks including both single-item and connected speech stimuli. Results indicated that the two classes of tactile device performed similarly in rhythm and stress perception, but that the multichannel aids in many cases showed better performance for tasks in which the identification of fine-structure phoneme information was required (both single-item and connected speech). Results are discussed in terms of the possibility that the performance of a specific multichannel tactile aid cannot be considered indicative of all devices of the same class.

Key words: *artificial hearing, sensory aids-deaf, single-channel and multichannel devices, tactile perception, tactile vocoder.*

Address all correspondence and requests for reprints to: Janet M. Weisenberger, PhD, Department of Speech and Hearing Science, Ohio State University, Columbus, OH 43210.

Present address for S. Broadstone: Boston School for the Deaf, Randolph, MA 02368.

Present address for L. Kozma-Spytek: Center for Auditory and Speech Sciences, Gallaudet University, Washington, DC 20002.

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INTRODUCTION

Devices that transform sound into tactile stimulation in order to convey sound and speech information to profoundly hearing-impaired persons are often classified by the number of tactile stimulators employed. Thus, single-channel tactile aids present information about the acoustic waveform via a single tactile transducer, and multichannel tactile aids utilize a number of tactile transducers. The design of many multichannel devices has been based on the assumption that the limited spectral resolution capability of the tactile system (14,23) would seriously impair the recognition of spectral characteristics of the vibratory signal of a single-channel device. Thus, in many multichannel tactile aids input acoustic frequency is recoded into location on the skin surface, substituting a dimension along which the tactile system shows good resolution ability (20,26). It was anticipated that such a strategy would permit some degree of recognition of spectral aspects of the acoustic signal, and thus lead to better performance than that found with single-channel devices. However, devices that have found their way into sustained commercial production have typically been of the single-channel or two-channel variety, due to the difficulties inherent in producing a wearable multichannel tactile aid (24). Studies investigating the relative effectiveness of single-channel and two-channel aids* have indicated that the addition of a second channel does not significantly increase subjects' ability to identify

*Broadstone SM, Weisenberger JM, Kozma-Spytek L, Relative benefits to speech perception provided by single-channel and two-channel tactile aids. Unpublished study, Central Institute for the Deaf, 1988.

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phonemes or connected speech material, except in tasks specifically designed for the detection of fricatives.

The assumption of better performance with multichannel devices becomes important in light of recent clinical studies that compare performance of cochlear implants and tactile aids. In such studies, subjects are fitted with currently commercially available devices, and are tested to determine the benefits provided by these devices. The cochlear implant of choice in many of these recent studies has been the Nucleus 22-channel implant (Cochlear Corp). Morever, the lack of commercially available tactile aid options has necessitated the selection of a considerably less sophisticated device, the Tactaid II (Audiological Engineering) for tactile aid testing. In studies comparing the 22-channel implant with the 2-channel Tactaid II, the implant has consistently yielded dramatically higher levels of performance (13,20,22). The results of such comparisons might lead to the conclusion that tactile aids in general are not of significant benefit to hearing-impaired persons. Given the considerable discrepancy in the information available from 22-channel implants and 2-channel tactile aids, such a conclusion may be premature. Studies involving direct comparisons of single-channel or two-channel tactile devices with multichannel tactile devices are of some relevance in considering this issue.

Initial work comparing single-channel and multichannel tactile aids did not suggest that multichannel devices yielded any greater benefits than single-channel or two-channel instruments. In laboratory studies comparing the effectiveness of single-channel and multichannel tactile aids in conveying both phonemic and suprasegmental information from speech, Carney (5) and Carney and Beachler (6) evaluated the single-channel Fonator (Siemens Hearing Instruments) and a 24-channel vibrotactile device that provided a linear spectral array of stimulators (11). In phoneme recognition tasks, both devices yielded similar levels of performance under both tactile aid-alone and lipreading-plus-tactile aid conditions (it might be noted that for some stimuli, i.e., vowels, performance under the lipreading-alone condition was so high that any differences between devices in the lipreading-plus-tactile aid conditions may have been obscured by ceiling effects). In tasks involving the recognition of suprasegmental features such as syllable number, syllable stress, and intonation, the single-channel Fonator was found to be significantly better than the multichannel instrument. These results suggested that the assumption that a multichannel device would produce better performance was incorrect.

Lynch *et al.* (16) focused their attention on performance with connected speech. In their study, one profoundly hearing-impaired adult was tested in connected discourse tracking with two devices, the two-channel Tactaid II (Audiological Engineering, Inc.) and the 16-channel Tacticon TC-1600 (Tacticon Corp.), a 16-channel electrotactile linear display. Although the Tactaid II is technically a multichannel device, it is similar to a single-channel device in that one channel delivers primarily stimulus envelope information, while the second channel provides some indication of high-frequency activity, such as frication. Thus, while this study did not provide a direct comparison of a single-channel and a multichannel device, it might be anticipated that a 16-channel aid would provide considerably more information than a 2-channel aid. In Lynch's study, tracking performance with the Tacticon was *not* superior to that with the Tactaid II; in fact, the Tactaid II generally produced equal or higher tracking rates. Such a result suggests that the use of a multichannel tactile aid in a complex task such as connected discourse tracking does not provide more information than that available with a two-channel device.

The results are disturbing in view of other studies evaluating only single-channel or only multichannel tactile aids, the results of which suggest that multichannel devices *do* provide more information than is available with single-channel devices. For example, Brooks and her colleagues (2,3,4) evaluated the performance of a 16-channel linear vibratory device (the Queen's University tactile vocoder), and found high levels of phoneme and word recognition under tactile-aid-alone conditions. In addition, this device was also beneficial in recognition of connected speech in open-set sentences and connected discourse tracking, yielding an improvement in the tracking task of over 30 words per minute (wpm) in the lipreading-plus-tactile aid condition over lipreading alone. Similarly, Weisenberger *et al.* (27) found good phoneme recognition with the Queen's aid and the Tacticon TC-1600. Further, Weisenberger *et al.* (27) reported improvements in the connected discourse tracking task of 10 to 15 wpm for the Tacticon and 40 to 50 wpm for the Queen's aid, over lipreading alone. Regression analysis of the data from these two devices indicated a significant difference in the amount of benefit provided.

In contrast, evaluations of single-channel devices have generally shown less impressive results. For example, Weisenberger and Russell (28) found only fair recognition of vowels and poor recognition of consonants in limited sets under tactile-aid-alone conditions for subjects using two single-channel devices, the Siemens Minifonator and AB Special Instrument Minivib3. Miyamoto *et al.* (18)

and Skinner *et al.* (25) reported connected discourse tracking improvements of 5 wpm or less with single-channel devices, a considerably smaller degree of improvement than those listed for the multichannel devices above. In evaluating the ability of a single-channel device to convey intonation and contrastive stress, Bernstein *et al.* (1) found improvements over visual-alone conditions that were significant, but quite small (e.g., improvement in percent correct identification of intonation pattern of 3 percent under visual plus tactile aid conditions).

Further, Carney and Beachler's (6) finding that a single-channel device produced better performance in syllable number and stress tasks than that produced by a multichannel device was not corroborated by Kozma-Spytek and Weisenberger (15) in a case study of the multichannel Tacticon and single-channel Minivib3. In their syllable number and stress task, little difference between the two devices was seen, with slightly *better* performance in the Tacticon condition.

The present study was performed in an attempt to address further the question of the relative benefits available with single- and multichannel tactile aids. Both single-channel and multichannel tactile aids were evaluated, using both phoneme and connected discourse tasks, as was done by Carney (5). However, in contrast to the method used in the Carney studies, in which different groups of subjects were tested with each tactile aid, both single-channel and multichannel devices were evaluated in the same subjects, to minimize any intersubject differences that might affect performance.

METHOD

Subjects

A total of six undergraduate students (four men and two women) were paid for their participation. All had normal hearing as measured by audiometric test, and all subjects wore EAR foam earplugs and headphones through which pink masking noise was presented (80 dB SPL) to minimize acoustic cues. Because of the long-term nature of the testing, some subject attrition occurred; therefore, not all subjects participated in all tests.

Apparatus

Tactile aids. The first of the single-channel devices employed in the present study was the Minifonator, manufactured by Siemens Hearing Instruments, but no longer commercially available. The Minifonator has a wrist-worn circular electromechanical transducer with a contactor area of 2.5 cm^2. In the present experiments, the transducer was worn on the dorsal side of the left wrist in the area where a wrist watch is normally worn. The transducer is tethered by a cable to an 8.5 × 8 × 3.3 cm electronics package. The device is driven by four AA batteries. Controls accessible to the wearer include on/off, microphone gain, and vibratory intensity. Acoustic stimuli are detected by a small microphone, which is tethered to the electronics package via cable. Microphone gain and vibratory intensity were set to their highest settings, consistent with the observed preferences of naive tactile-aid users. The Minifonator processor provides a broad-band vibratory signal that preserves aspects of the spectral and temporal content of the acoustic signal.

The second single-channel tactile device used in the present study was the AB Special Instrument Minivib3. The Minivib transducer is rectangular in shape, with dimensions of 6.5 × 4.3 × 1.7 cm, and is tuned to resonate at a frequency at or near 250 Hz. In the present experiments, the Minivib was also worn by subjects on the dorsal side of the left wrist, using the wrist strap included with the device for such purpose. The transducer is connected by a cable to a 1.5 × 2.0 × 1.0 cm electronics package, with a built-in miniature microphone. The device is powered by a specially constructed rechargeable battery whose output is approximately 10 V. Controls available to the user include on/off and microphone gain; vibratory intensity and transducer tuning can be modified by turning a screwdriver in two recessed pots located on the bottom of the device. The gain of the Minivib is quite strong, in that setting it to its maximum of nine permits the detection of sounds occurring at considerable distance. For this reason, the gain of the Minivib was set to one-half its range (4.5) for the present experiments. Vibratory intensity was left at the factory setting. The processor of the Minivib performs an envelope extraction on the incoming acoustic waveform and uses this envelope to modulate the amplitude of a 250-Hz carrier, which drives the vibratory transducer. Thus, this device is a relatively straightforward AM processor.

The first of the multichannel tactile devices evaluated in the present study was a microprocessor-based implementation of the Queen's University vibrotactile vocoder developed at the Central Institute for the Deaf (10). A description of the original device can be found in Scilley.*

*Scilley PL. Evaluation of an auditory prosthetic device for the profoundly deaf. Unpublished master's thesis. Queen's University, Kingston, Ontario, 1980.

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In the CID implementation of the vocoder, input acoustic stimuli are detected by an ACS headset electret microphone and then passed through a logarithmic gain function and high-frequency preemphasis circuit to a bank of 16, one-third octave switched-capacitor filters, with center frequencies between 140 and 6350 Hz (the two lowest-frequency channels have a bandwidth of two-thirds of an octave). The envelope output of each of these filters is used to modulate the amplitude of a 100-Hz square wave, which drives one of 16 magnetic solenoids mounted in a 19.5 cm linear array worn on the underside of the forearm. The center-to-center distance between solenoids is 10 mm. The output voltage to the solenoids is proportional to the input to each channel; overall level is determined internally and is not variable by the subject. Perceived stimulation levels vary over a range of approximately 0 to 40 dB SL, with an average perceived level of approximately 20 dB SL. As worn by the subjects, low-frequency stimulation is felt near the wrist, and high-frequency stimulation is felt near the elbow.

The second multichannel tactile device evaluated was the Tacticon Corporation TC-1600, an electrotactile vocoder that was formerly commercially available, but which has been discontinued. This device is functionally similar in most major respects to the Queen's vocoder, although there are several important differences. Input acoustic stimuli are detected by a Sony ECM 16-T electret microphone and passed through a bank of 16 logarithmically spaced filters, with center frequencies between 100 and 7,000 Hz. The envelope output of each filter modulates the pulse rate of a biphasic current pulse, each phase having a duration of 20 ms and nominal current of 7 to 12 mA as set by the user's display intensity control. Pulse rates vary between approximately 0 and 500 pps. This pulse is transmitted to one of 16 electrodes, arranged in a 22.5 cm array worn on the abdomen. The center-to-center distance between electrodes is 15 mm. A noise-suppression circuit in the processor was operated with an attack time of 5 seconds, and recovery time of 5 to 10 seconds. The primary effect of this circuit is on sounds in the 1.5 to 4 kHz range. The processor and battery enclosure for the device measures 15.5 × 9 × 4.5 cm and weighs approximately 680 g. The processor box can be worn clipped to a belt, in a backpack, or elsewhere, and in the present study was placed on a table next to the subject. The level of stimulation on the Tacticon is controllable by the subject with a dial on the processor box and was set by the subject to a comfortable level at the beginning of each test session. The surface of the abdomen was moistened with water prior to putting on the device.

Stimuli. All stimuli were presented live-voice by three female talkers. All subjects had some exposure to at least two of the three talkers, although the number of sessions with each talker was not equal for all subjects.

Several tasks were employed, arranged in a hierarchy from simplest to most difficult. The first task was minimal pairs phoneme discrimination. Four sets of stimuli were employed. All items in each set consisted of a pair of words that differed in only one phoneme. In the first set (40 items), the initial phoneme of each pair differed in manner of articulation, with place articulatory features (and voicing, where possible) held constant (e.g., tea-see). In the second set (40 items), the initial phoneme differed in place of articulation, with manner and voicing features held constant (e.g., bait-gate). In the third set (20 items), the initial phoneme differed in consonant voicing, with place and manner features held constant (e.g., bat-pat). In the fourth set (8 items), items in a pair differed in their medial vowel, in an /hVd/ format. Stimuli were presented in isolation (i.e., no carrier phrase was used).

The second task was syllable rhythm and stress identification, tested in a manner similar to Erber's monosyllable-trochee-spondee test (12). Fifteen items were used, including five monosyllables, five trochees, and five spondees. Subject responses were scored twice: once to determine whether the correct item had been selected (identification), and again to determine whether a word with the correct syllable number and stress had been selected (categorization).

The third task was integration with lipreading. Sets of eight items differing in either their initial consonant or their final consonant were presented. The initial consonant lists were presented in a /Cat/format, and the final consonant lists were presented in an /aC/ format. Lists were tested both in isolation and in the context of fixed carrier phrase, "Tell me _____, please."

The final task was connected discourse tracking (9). The text material used was *Star Trek IV: The Voyage Home* (17), a low-difficulty adult text, presented in 5-minute tracking sessions.

Procedure

Because it was felt that exposure to all four devices would not permit sufficient training time with any one device, all subjects were tested with two devices, one single-channel and one multichannel. The assignment of single-channel devices and multichannel devices to subjects was random. During a test session, the subject wore one device

for half of the testing time and the other device for the other half of the testing time. The order of test condition was varied across test sessions.

Minimal pairs. The first five sessions were considered training sessions. On each trial in a training session an ABX design was used, in which the talker read each of the words in the pair and then presented one of the words. The subject indicated which item (A or B) had been presented by saying "A" or "B," followed by the chosen word. The experimenter provided feedback by presenting the correct word acoustically through the intercom system. Each item in a list was presented in the above fashion, and each list was presented four times under each testing condition in the course of a session. Subject responses were recorded on a score sheet.

The last five sessions were considered test sessions. On each trial an ABX design was not used and only the test word was presented. Subject responses and feedback were provided as above. As in the training sessions, each list was presented four times.

Syllable rhythm and stress. The first 10 sessions were considered training sessions. On each trial, the talker presented a word selected at random from the 15-item test list, and the subject responded with the word that had been presented. Feedback was presented acoustically. Each item in the list was presented five times in the course of a session, under each testing condition. The last five sessions were considered testing sessions, and were run in an identical manner.

Integration. For stimuli presented in isolation, five conditions were tested: single-channel aid alone, multichannel aid alone, lipreading alone, lipreading plus single-channel aid, and lipreading plus multichannel aid. For stimuli presented in carrier phrases, the two tactile-aid-alone conditions were omitted. Under all conditions involving lipreading, the shade on the window of the booth was raised. Subjects were first tested with stimuli presented in isolation. Following completion of this testing, they were then tested with stimuli in carrier phrases. For each of these phases of testing, the first five sessions were considered training sessions, and the last five were considered test sessions. Within each session, each list (initial and final consonants) was employed. On a trial, the talker presented a word from the list, and the subject responded with a word from the list. Feedback was delivered acoustically. For each testing condition, each stimulus was presented five times during a session.

Tracking. The connected discourse tracking procedure outlined by DeFilippo and Scott (9) was used. In this procedure, a talker reads aloud a portion of meaningful text (word, phrase, or sentence) at a normal speaking rate, and a receiver attempts to repeat the phrase verbatim. If the receiver does not repeat the phrase correctly, the talker may use strategies such as repeating some or all of the phrase, reviewing a previous phrase or sentence, or providing context clues by reading the next phrase or sentence. Specific examples of each strategy are provided in DeFilippo and Scott. If the response is correct, the reader presents the next phrase. In the present experiment, 5-minute tracking sessions were used. The total number of words correctly repeated by the subject during each 5-minute session was counted and divided by the total number of minutes in the session, to yield a word-per-minute (wpm) score.

Three conditions were tested: lipreading alone, lipreading plus single-channel aid, and lipreading plus multichannel aid. Each subject was tested daily in a 1-hour test session. During each test period, five tracking sessions were obtained: one under the lipreading-alone condition, and two each under the lipreading-plus-single-channel aid and lipreading-plus-multichannel aid conditions. The order of testing was varied across days to eliminate order effects. For this testing, a single female talker presented text. A total of 60 5-minute tracking sessions was obtained over a period of approximately 4 weeks.

RESULTS AND DISCUSSION

Minimal pairs

For clarity of presentation, overall results for all tasks are averaged across single-channel devices and across multichannel devices. No significant differences were obtained between single-channel devices or between multichannel devices for the tasks described above. Results for five subjects in the minimal pairs task are shown in **Figure 1**. A two-way, within-subjects analysis of variance was performed on arcsine-transformed percentage scores to determine the significance of differences in performance. The results of this analysis indicated that there was a significant overall effect of type of tactile device (single-channel versus multichannel) ($F(1,4)=8.78$, $p<0.05$), and significant differences among type of stimulus set (manner, place, voicing, and vowels) ($F(3,12)=12.24$, $p<0.001$). Post-hoc analysis by Tukey's test showed that manner features were perceived significantly better than place (0.25, $p<0.01$), voicing (0.19, $p<0.01$), and vowels (0.25, $p<0.01$). No other comparisons were significant. In addition, no inter-

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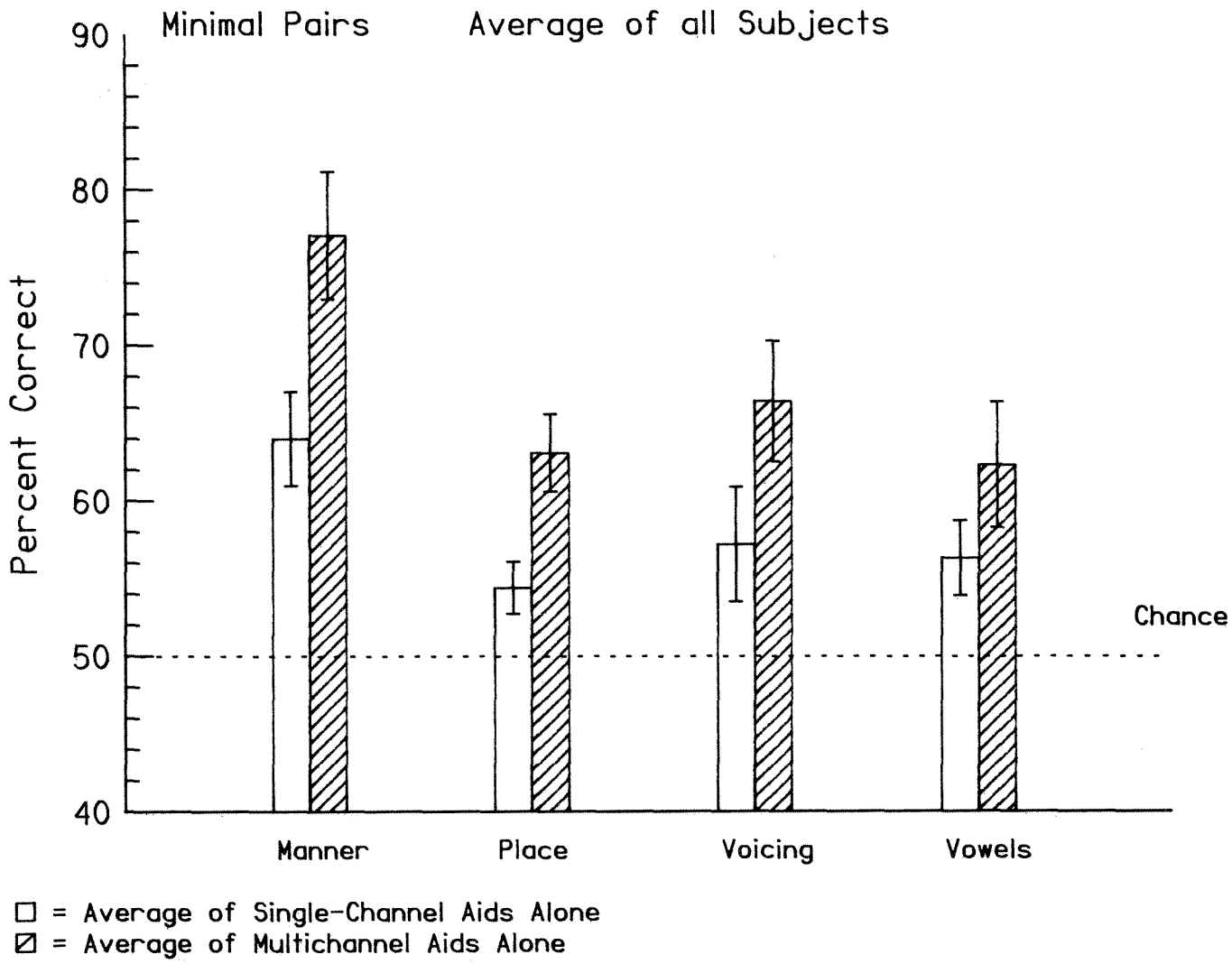

Figure 1.
Averaged percent correct performance of five subjects with single-channel and multichannel tactile aids for the last five sessions of the minimal pairs task, as a function of type of articulatory contrast.

action effect was observed in the analysis of variance ($F(3,12)=0.37$, ns).

These analyses indicate that subjects received significantly more information in this task from the multichannel devices than from the single-channel devices. The lack of an interaction suggests that this improvement was present for all classes of stimuli. The finding that manner features were transmitted more effectively than the other types of stimuli is consistent with previous findings for multichannel devices (3,27).

Syllable rhythm and stress

Results for five subjects are shown in **Figure 2** for identification (selection of the correct word) and categorization (selection of the correct syllable number an stress). As can be seen, performance was similar with both types of device, and no significant differences were observed with a dependent-groups t-test on arcsine-transformed percentages for either identification ($t(4)=0.55$, ns) or categorization ($t(4)=0.24$, ns). Carney and Beachler (6) found that a single-channel device yielded better performance in such suprasegmental tasks than a multichannel device. However, Kozma-Spytek and Weisenberger (5) found in a case study with one hearing-impaired child that, while the Tacticon multichannel aid was comparable to the single-channel Minivib in categorization, substantially better identifica-

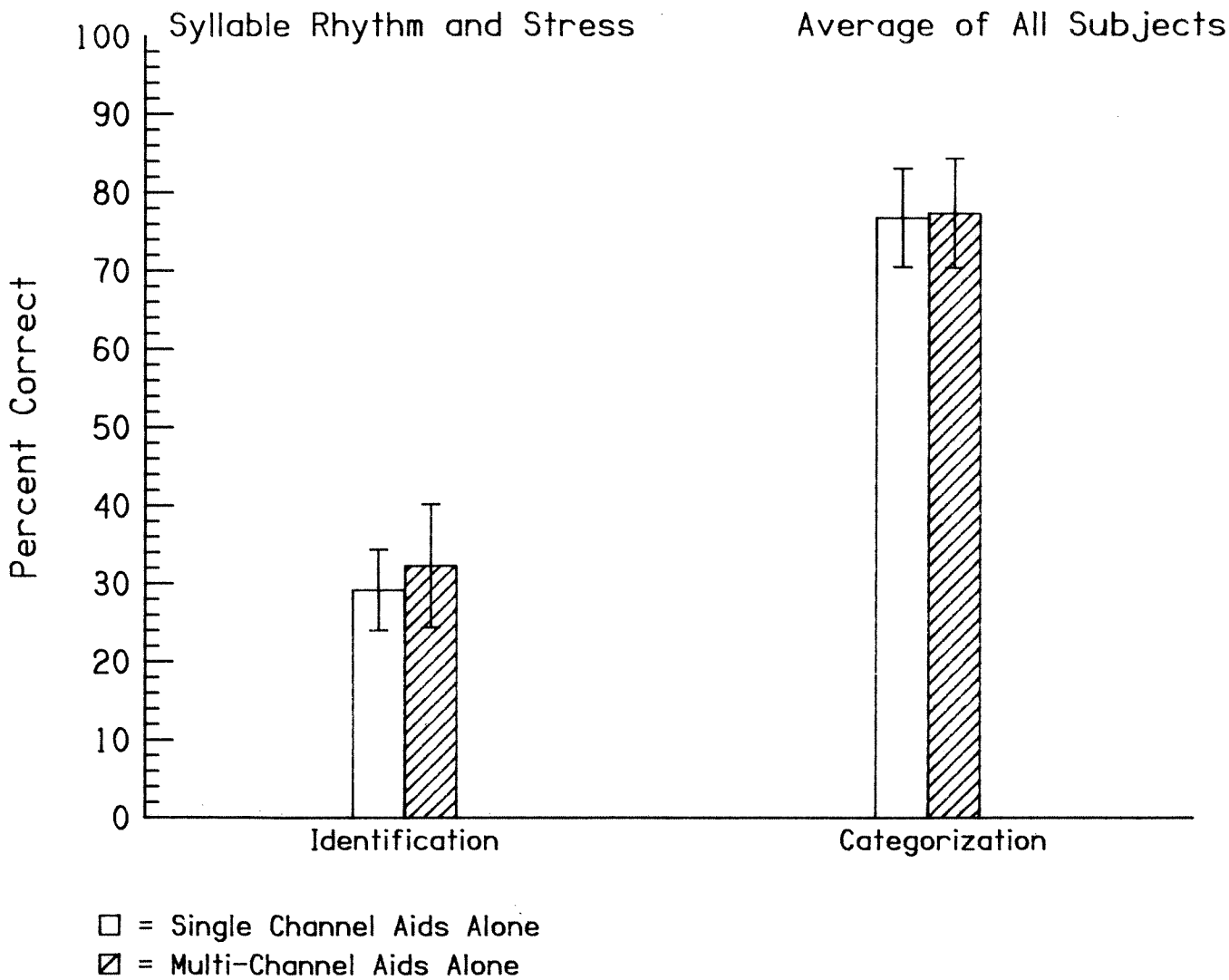

Figure 2.
Averaged percent correct performance for five subjects with single-channel and multichannel tactile aids on the syllable rhythm and stress task, for stimulus identification and rhythm and stress categorization.

tion performance was observed for the Tacticon than the Minivib. It might be noted that the present results are not consistent with either of these previous findings.

Integration

The results for the integration task, completed for five subjects for stimuli in isolation and for three subjects for stimuli in carrier phrases, were somewhat more complex. Data for stimuli presented in isolation and in carrier phrases will be discussed separately. For initial consonant stimuli presented in isolation (**Figure 3a**), a within-subjects analysis of variance for arcsine-transformed percentages yielded a significant overall effect of testing condition ($F(4,16)=28.43$, $p<0.001$). Post-hoc analysis by Tukey's test showed that the single-channel and multichannel aid alone conditions were significantly lower than lipreading alone (single-channel: 0.49, $p<0.01$; multichannel: 0.31, $p<0.05$), and each device-alone condition was significantly lower than the corresponding lipreading-plus-device condition (single-channel: 0.57, $p<0.01$; multichannel: 0.71, $p<0.01$). However, no significant difference between the single-channel and multichannel aid alone conditions was found.

In assessing the benefits of each type of device to lipreading, it was found that the lipreading-plus-single-channel condition was not significantly different from

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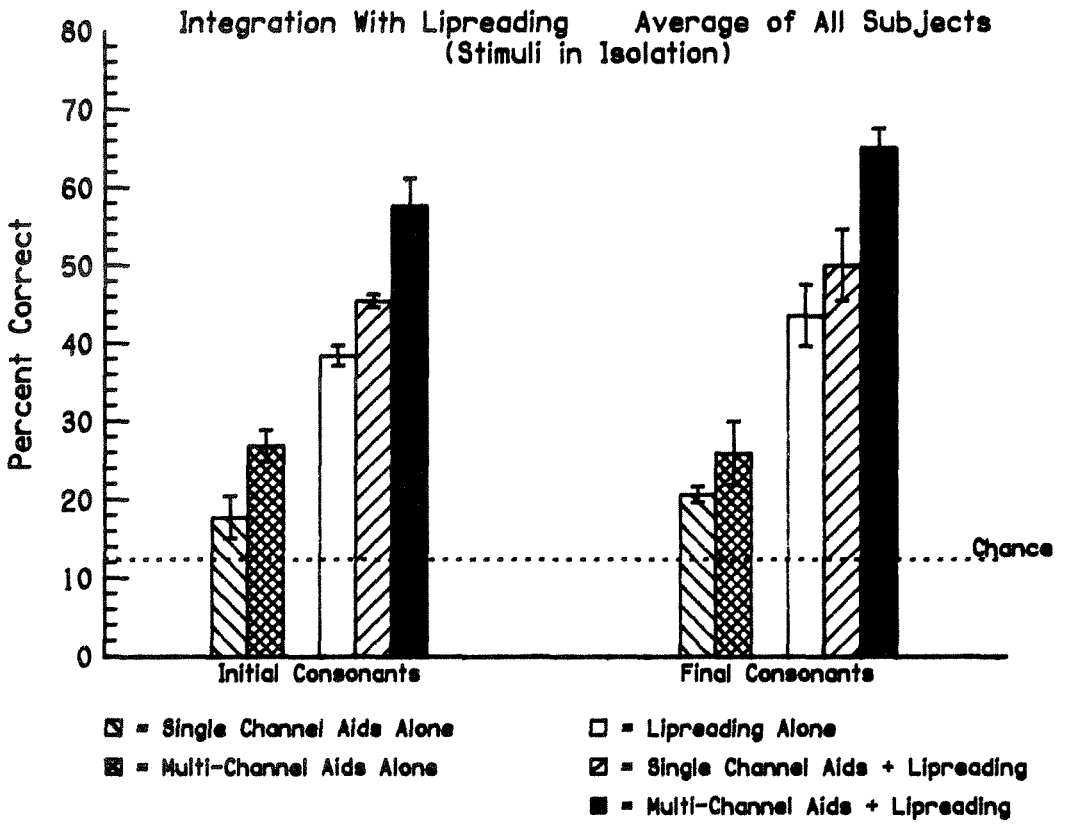

Figure 3A.
Averaged percent correct performance for five subjects with single-channel and multichannel tactile aids on the integration task. Data for identification of initial-consonant and final-consonant stimuli. Results for stimuli presented in isolation.

lipreading alone, whereas the lipreading-plus-multichannel condition showed a significant improvement over lipreading alone (0.40, $p<0.01$). Further, the lipreading-plus-multichannel condition was significantly higher than the lipreading-plus-single-channel condition (0.32, $p<0.05$).

A similar pattern of results was obtained for the final consonants presented in isolation ($F(4,16)=19.28$, $p<0.001$ overall effect of testing condition). Post-hoc testing revealed similar results to those for the initial consonants, with the exception that the lipreading-plus-multichannel condition was *not* significantly different from the lipreading-plus-single-channel condition. Nonetheless, it was still the case that a significant difference was obtained between lipreading alone and lipreading-plus-multichannel conditions (0.27, $p<0.05$), and not between lipreading alone and lipreading-plus-single-channel conditions.

For stimuli presented in carrier phrases (**Figure 3b**), analysis of variance for the initial consonants showed a significant effect of test condition ($F(2,4)=10.24$, $p<0.05$). Post-hoc testing showed only one significant comparison, that between lipreading alone and lipreading-plus-multichannel conditions (0.35, $p<0.05$).

For the final consonants presented in carrier phrases, no significant effect of test condition was observed ($F(2,4)=5.01$, ns). Post-hoc testing was not performed. Although it can be seen in **Figure 3b** that the lipreading-plus-multichannel condition produced slightly higher levels of performance, the differences across conditions are not large.

Overall, the results for the integration task suggest that the multichannel devices provided more assistance to lipreading than did the single-channel devices. Interestingly, there were in many cases no significant differences between performance in the two device-alone conditions, suggesting that performance in the lipreading-plus-device conditions is not a simple addition of device alone and lipreading alone performance.

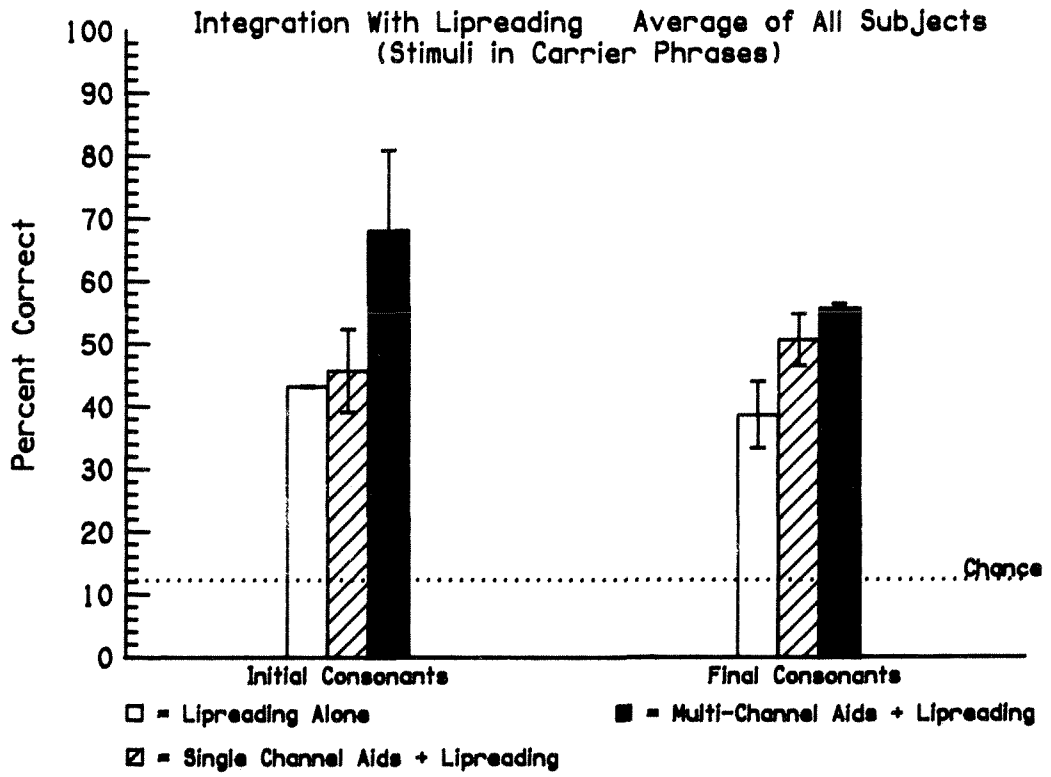

Figure 3B.
Averaged percent correct performance for five subjects with single-channel and multichannel tactile aids on the integration task. Data for identification of initial-consonant and final-consonant stimuli. Results for stimuli in carrier phrases.

Tracking

As a result of subject attrition over the long duration of testing employed in the present study (daily testing for several months), only one subject was available for testing in the connected discourse tracking task. This subject was tested with the single-channel Minivib and the multichannel Queen's vocoder. Results for this subject are shown in **Figure 4** for lipreading alone, lipreading-plus-single-channel, and lipreading-plus-multichannel conditions. As can be seen, the single-channel aid produced a slight improvement in performance over lipreading alone, on the order of about 5 wpm. Performance was much higher with the multichannel device, with an improvement over lipreading alone of closer to 20 wpm.

To test whether these performance differences were statistically significant, regression lines were fitted to the data for each condition using a least-squares technique. The slopes of the regression lines were compared in pairwise t-tests (7). These comparisons indicated significant differences between the lipreading-plus-multichannel condition and lipreading alone ($t(26)=2.089$, $p<0.05$), but no differences between the lipreading-plus-single-channel and lipreading alone conditions ($t(26)=0.49$, ns).

Although it is speculative to draw conclusions from the data for a single subject, it might be noted that performance under the lipreading-plus-multichannel condition is in agreement with data reported by Brooks *et al.* (4) and by Weisenberger *et al.* (27) on the degree of improvement provided by multichannel devices in connected discourse tracking. Further, the results for this subject in the lipreading-plus-single-channel condition are in good agreement with data reported by researchers such as Miyamoto *et al.* (18).

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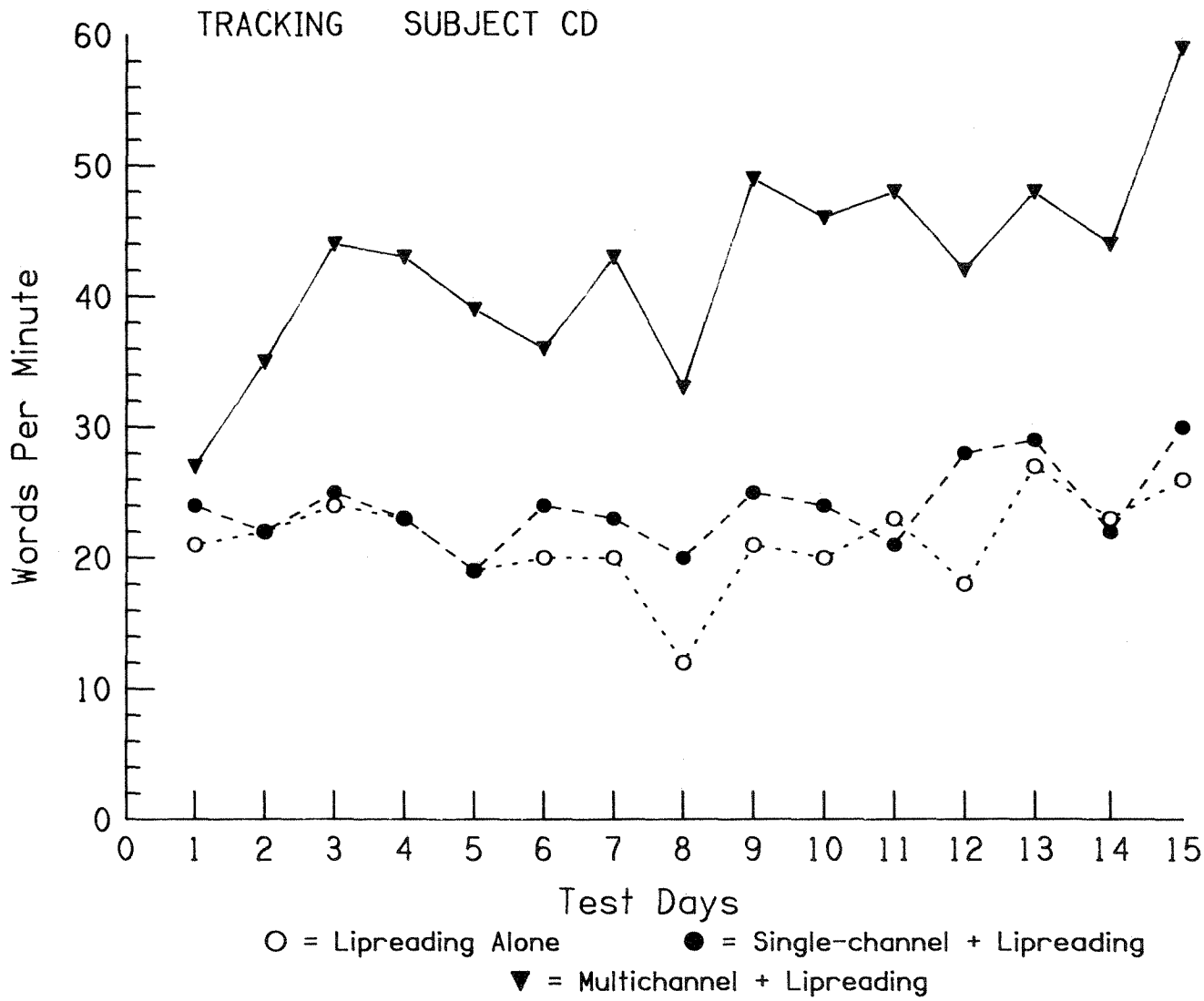

Figure 4.
Tracking performance for one subject with single-channel and multichannel tactile aids, over test days.

GENERAL DISCUSSION AND CONCLUSIONS

Overall, the results obtained in the present study suggest that more information is provided in many cases by multichannel tactile aids than by single-channel aids in speech perception tasks requiring phoneme recognition, but that the two classes of device perform comparably in tasks requiring the perception of amplitude envelop characteristics, such as the syllable rhythm and stress task.

In general, the present results are not consistent with the findings of Carney and Beachler (6) and Carney (5). However, there are a number of differences between those studies and the present study that may have contributed to differences in the obtained results. For example, slightly different tasks were employed. In addition, the present study utilized a within-subjects rather than independent groups experimental design, and a longer duration of training was used in the present study. Perhaps more importantly, the two studies employed different tactile devices. Support for the suggestion that device differences may be important may be found in studies comparing several single-channel or several multichannel devices. For example,

Weisenberger *et al.* (27) compared two 16-channel tactile aids, the Queen's vocoder and the Tacticon TC-1600, in a series of phoneme recognition and connected speech tasks. While the two devices performed comparably on the phoneme recognition tasks, the Queen's vocoder showed much higher performance in tracking, yielding improvements over lipreading alone of more than 40 wpm, as compared to the approximately 10 wpm provided by the Tacticon. Similarly, the tracking data reported by Lynch *et al.* (16) for the Tacticon show rather poor performance for the Tacticon, and further data collected in our laboratory support this finding. In addition, Rakowski *et al.* (21) found poor tracking performance for the Audiotact (Sevrain-Tech), a 32-channel electrotactile aid.

Such results suggest that not all multichannel tactile devices provide equivalent amounts of speech information to the wearer. It is possible that the 24-channel vocoder used by Carney and Beachler (6) and Carney (5) did not provide as much information as was provided in the present study by the Queen's vocoder and Tacticon. Although the two multichannel devices used in the present study did not show significant differences in the single-item tasks employed, it is important to note that the subject for whom tracking data are reported in the present study had been trained with the Queen's vocoder as the multichannel device. Had he been trained instead with the Tacticon, the difference in tracking results between lipreading-plus-single-channel and lipreading-plus-multichannel conditions may have been less dramatic. Conversely, it is also possible that the Fonator, the single-channel device used by Carney, is a superior single-channel aid that provides more information about speech than the Minifonator and Minivib used in the present study. Although the Minivib and Minifonator have also been found to be similar to each other in performance (27), and were not found to be different from each other in the present study, better performance may be attainable with the Fonator than for either of these two devices.

Perhaps the appropriate conclusion from consideration of the results of the present study and of the previous work is that some multichannel tactile devices can provide significantly more benefit to the wearer than some single-channel tactile devices. Generalizing the results obtained in a particular study to all devices of a particular class may or may not provide an accurate view of potential tactile aid benefit.

The data from the present study do suggest that results from comparisons of multichannel cochlear implants and two-channel tactile aids should be considered in view of the possibility that a multichannel tactile aid might provide greater benefits than are seen with two-channel device. As multichannel tactile aids become commercially available, this possibility can be tested empirically. Indeed, Osberger (19) and Robbins (22) reported promising pilot results for clinical trials of the Tactaid VII (Audiological Engineering), a seven-channel prototype tactile device, which was introduced into their cochlear implant testing program. In addition, Cowan *et al.* (8), in studies of the Tickler Talker, an eight-channel electrotactile aid, show comparable performance on some speech perception tasks with this device and a 22-channel implant. Although considerable further work of this nature is necessary before substantive conclusions can be drawn regarding the comparability of implants and tactile aids, the results of the present study, taken together with other reports of multichannel tactile aid performance, suggest that multichannel tactile aids may prove a viable option for speech perception by hearing-impaired persons.

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