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Speech perception by congenitally deaf subjects using an electrocutaneous vocoder

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Abstract—Two congenitally profoundly deaf adults were trained to perceive words through the Tacticon 1600 electrocutaneous vocoder, an artificial hearing prosthesis. The subjects learned to identify 50 words during 47 hours (Subject One) and 41 hours (Subject Two) of training, with a 41.6 percent rate of success across all sessions. Both subjects showed consistent error patterns during the training phase. Analysis of these error patterns suggested that they were employing word identification strategies based on some general aspects of tactual patterns. Specific characteristics of the tactual patterns that they appeared to be using included: syllable number, tactual locus of word ending, direction of pattern movement, and position of bursts (/t/, /k/, /d/, for example). Following training, the subjects were tested for their abilities to integrate tactual and aided-auditory cues in word identification. Three conditions of aided-audition alone (A), tactual vocoder alone (TV), and aided-audition with tactual vocoder (TV + A) were used. The stimulus-word list for this phase consisted of the 50 words acquired in tactual vocoder training, and 50 "tactually-new" words, i.e., words that had not been presented to them in tactual vocoder training sessions. They correctly identified 93 percent (Subject One) and 56 percent (Subject Two) more trials in the TV + A condition than in the A condition. Tactually-new vocabulary was correctly identified 78 percent (Subject One) and 50 percent (Subject Two) more often when sensory modalities were combined, than when only aided-audition was used. Subjects identified tactually-new vocabulary better than chance in the TV condition.

Key words: *auditory cues, congenitally and profoundly deaf, error patterns, hearing prosthesis, speech perception, tactile vocoder, word recognition.*

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INTRODUCTION

The profoundly deaf do not receive sufficient information from lipreading (6) and aided-audition (8) to perceive speech fully. One way of supplementing these sources of information is to present speech to the sense of touch (7). This approach involves the transduction of acoustic information into tactile stimulation.

Steps toward determining the efficacy of tactual vocoders in speech transmission have included measurement of a subject's ability to identify and discriminate among segmental features and words. Sparks *et al.* (13) tested an artificially-deafened subject in identification of 6 stop and 2 nasal consonants in a consonant-vowel context. Overall identification performance on the 8 consonants approached 50 percent, with the feature of voicing showing the highest performance (nearly 100 percent correct). Using a 24-channel vocoder (5), Oller *et al.* (10) trained deaf adolescents to discriminate certain

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hard-to-lipread word pairs in approximately 1 hour of training. These studies demonstrated that certain segmental features of speech can be identified, and certain word pairs can be discriminated with success, after minimal training on a tactual vocoder. Large vocabulary sets can also be identified successfully with touch (1–5), but research suggests that extensive training and experience is required.

Engelmann and Rosov (5) pioneered training methods for transmission of vocabulary to deaf and hearing subjects using a tactual vocoder. Subjects received 20 to 225 hours of training with a vibrotactile vocoder and acquired 15 to 152 words. Brooks (1) also used extensive training in a vocabulary acquisition study. An artificially-deafened graduate student was trained to identify a 250-word vocabulary after approximately 80 hours of training. Two prelingually, profoundly deaf teenagers were also trained to identify 50 words with a vibrotactile vocoder after 24–29 hours of training. Perhaps most importantly, Brooks *et al.* (3) demonstrated that the tactual knowledge acquired in vocabulary training may be generalized to identification of novel words.

When tactual input is presented along with information from lipreading, wearers of tactual vocoders improve their word identification performance. Several studies have demonstrated such complementary effects of touch and vision in speech perception with artificially-deafened subjects (1,3,4,11,13). The tactual vocoder may effectively transmit information, such as voicing and manner of articulation (11,13), that is largely unavailable through lipreading.

Although tactual vocoder research has been encouraging, there are gaps in our knowledge of profoundly deaf persons' abilities to perceive speech with a tactual vocoder. Much of the research on tactual vocabulary acquisition to date has focused on hearing subjects rather than deaf subjects. The focus of the present studies is on vocoder use by congenitally profoundly deaf adults. Specifically, the studies were designed to: 1) train profoundly deaf subjects in identification of a number of words, using only tactile information; 2) examine the specific tactual pattern confusions of the subjects during this training; and, 3) to examine the extent to which profoundly deaf individuals integrate tactual information with aided-audition.

STUDY I: WORD IDENTIFICATION BY PROFOUNDLY DEAF SUBJECTS

Method

Subjects. Two congenitally profoundly deaf adults participated in Study I. Subject One was a 20-year-old male from a bilingual home, who wore a high-power ear-level aid in his left ear. He had average pure tone thresholds of 113 dB for the right ear, and 115 dB for the left ear. He was an aural communicator who utilized limited sign language.

Subject Two was a 32-year-old female deaf educator who utilized lipreading, sign language, and aural skills to communicate. She wore a high-power ear-level hearing aid in each ear, and had average pure tone thresholds of 110 dB for the right ear and 105 dB for the left ear. She was capable of understanding a substantial amount of spoken language using hearing aids, but required slow and deliberate presentation of speech for acceptable comprehension.

Apparatus. Speech was transmitted through the Tacticon 1600 electrocutaneous vocoder (12). Spoken words were received through a lapel microphone. The Tacticon 1600 then used a bandpass filter to analyze the acoustic waveform into 16 logarithmically-spaced frequency channels (range 100–7000 Hz). Each channel was represented by a single electrode on a belt worn about the abdomen. To reduce initial skin impedance, the subject's abdomen was moistened with water before placing the stimulator belt into position.

Stimuli. The tactual vocabulary acquired by the subjects, in presentation order, is listed in **Table 1**. The words were chosen to provide a wide sampling of the phonemic inventory of English.

Procedure. In order to eliminate extraneous signals, sessions were conducted in a sound-treated room. The subject and experimenter were seated back to back. Subjects deactivated their hearing aids during training sessions; this was to ensure that only tactual information reached them. The entire training vocabulary list was read at the beginning of each session, so that the subjects could familiarize themselves with the tactual patterns while setting the vocoder at a comfortable level.

Each trial began with the recitation of a stimulus word by the experimenter. The stimulus word (X) was repeated until the subject responded. If the

Table 1.
Study I: Tactual Vocabulary.

1. Paper	16. Yam	31. Can	46. Someday
2. Hat	17. Dally	32. I	47. Possibly
3. Man	18. Out	33. Red	48. Complex
4. Sister	19. Joker	34. Give	49. Introduce
5. Leash	20. Sponge	35. How	50. Doorways
6. Sun	21. Zebra	36. Doctor	
7. Two	22. Parking	37. Spanish	
8. Shut	23. The	38. Was	
9. Table	24. Make	39. My	
10. Fast	25. Bath	40. Whenever	
11. Never	26. A	41. Am	
12. Ball	27. Is	42. Comes	
13. Gun	28. Walking	43. He	
14. Chair	29. Watch	44. Bombastic	
15. Calendar	30. Chop	45. Large	

subject's response (Y) was correct, the experimenter said "yes," and the next stimulus word was presented. If the subject's response was incorrect, the experimenter said "not Y, X." This pattern was repeated until either a correct response was given, or until the subject indicated that he or she could not provide a reasonable guess. Each response was recorded for later analysis.

One new word was added to the subject's vocabulary at the end of each session wherein a 70-percent correct performance was attained on the newest word. The criterion required at least 10 presentations of the new word. During all sessions, any word from the acquired vocabulary could be presented for identification on each trial.

RESULTS

Overall, Subject One received 47 hours of training, and Subject Two received 41 hours of training. They correctly identified 41.6 percent of the 11,324 trials presented. This is less than the 75.6 percent level reported by Brooks (1) for a normally-hearing subject with 80 hours of training.

The percent of trials correctly identified by each subject decreased over time. Subject One correctly identified 71 percent of the trials presented in sessions 1–10, 52 percent in sessions 11–20, 45 percent in sessions 21–30, 31 percent in sessions 31–40, and 24 percent in sessions 41–52. Subject Two correctly identified 72 percent of the trials presented in sessions 1–10, 59 percent in sessions 11–20, 43 percent in sessions 21–30, 29 percent in sessions 31–40, 21 percent in sessions 41–50, and 18 percent in sessions 51–64. However, during training, the tactual vocabulary was correctly identified significantly more often than chance.

Analysis of incorrect responses. When a response was incorrect, the substitution was recorded. The substitution errors of both subjects were analyzed to determine which occurred significantly above chance with 95 percent confidence across all training sessions.

The significance of a substitution error was calculated by comparing the difference between its conditional probability and chance probability with the standard deviation of its conditional probability (see Appendix of Brooks and Frost [2]). Subject data generated 94 significant confusions (out of 2,450 possible confusions = 3.8 percent). The significant substitution errors for each subject are listed in **Table 2**.

To interpret the significant confusions, several sources of potential systematic error were considered, and specific perceptual characteristics of tactual patterns were chosen for analysis. These pattern aspects were judged by 2 independent subjects to be salient descriptors of many of the words in the tactual vocabulary. For each significant confusion, 7

Table 2.
Significant Confusions: Subject One

		Subject One	
Stimulus	**Response**	**Stimulus**	**Response**
Hat	Shut	Sponge	Calendar
Leash	Man	Zebra	Walking
Two	Chair	Parking	Paper
Table	Parking	Parking	Joker
Ball	Leash	The	Ball
Ball	Gun	The	Gun
Gun	Man	Make	Shut
Gun	Ball	Make	Out
Chair	Man	Is	Man
Chair	Ball	Chop	Hat
Chair	Gun	Chop	Shut
Calendar	Table	Can	Man
Calendar	Never	I	Man
Yam	Man	I	Yam
Out	Shut	I	Is
Joker	Paper	How	Man
Joker	Table	Complex	Bombastic

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Table 2. *(Continued)*
Significant Confusions: Subject Two

Subject Two			
Stimulus	**Response**	**Stimulus**	**Response**
Chair	Gun	Chair	How
Calendar	Table	Chair	Am
Calendar	Never	Calendar	Walking
Joker	Paper	Calendar	Comes
Zebra	Walking	Yam	Can
Parking	Paper	Yam	My
Parking	Joker	Yam	Am
Make	Shut	Dally	Yam
Make	Out	Dally	A
Chop	Hat	Dally	Can
Chop	Shut	Dally	I
Doctor	Joker	Out	Make
Sun	Table	Joker	Parking
Shut	Out	Sponge	Sister
Shut	Make	Zebra	Never
Never	Table	Zebra	Calendar
Ball	Never	The	Is
Chair	Two	The	Am
Chair	Sun	Make	Hat
Chair	The	Make	Fast
Chair	Can	Bath	Is
A	Two	Walking	Make
Is	A	Chop	Out
Chop	Make	Can	A
I	A	I	Can
Red	Make	Red	Watch
Red	Give	Give	Comes
How	Sun	How	Am
How	He	Doctor	Parking
Spanish	Sister	Spanish	Sponge
Spanish	Introduce	My	The
My	Can	Whenever	Was
Am	Two	Am	A
Am	I	Am	He
He	Two	He	A
Possibly	Someday		

salient pattern aspects were evaluated. These are described below:

1. Number of Perceived Syllables.
2. Perception of Burst in Initial Position: /t, p, k, c, b, g, d, dz/.
3. Perception of Burst in Final Position.
4. Perception of Beginning Locus: The tactual array was divided into 3 regions of left (channels 1–5), middle (channels 6–11), and right (channels 12–16).
5. Perception of End Locus: left, middle, right.
6. Perception of Pattern Movement Direction: left, right, or mixed.
7. Perception of Extent of Pattern Movement: greatest (>10 channels), moderate (6–10 channels), and least (<6 channels).

The significant confusions were subjected to chi-square analysis that involved sorting the confusions into a frequency distribution according to the tactual pattern aspect under consideration. (This was done to determine if any of the tactual pattern aspects described above were sources of confusion during vocabulary training.) For example, in the syllable number analysis, a 2 × 2 table was constructed with rows and columns labeled "1 syllable" and "2 syllables." The rows described the relevant aspects of the stimulus in the significant confusion, and the columns described the relevant aspects of the response. The significant confusion "sun-table" was entered in the cell corresponding to the 1-syllable row and the 2-syllable column, since the stimulus had 1 syllable and the response had 2 syllables. All of the chi-square analyses were constructed similarly. Correct responses were not included in the chi-square calculations. The results of this analysis are given in **Table 3**.

Table 3.
Chi-squares for tactual parameters of significant confusions.

Parameter	Subject 1	Subject 2	df	Significance S1	Significance S2
Number of Perceived Syllables	39.22	30.47	4	.005	.005
Perception of Burst in Initial Position	14.19	3.46	1	.005	>.05
Perception of Burst in Final Position	23.62	53.85	1	.005	.005
Perception of Beginning Locus	7.12	7.83	4	>.1	>.05
Perception of End Locus	10.34	12.31	4	.05	.025
Perception of Pattern Movement Direction	4.83	6.21	1	.05	.025
Perception of Extent of Pattern Movement	4.38	1.50	4	>.1	>.05

In general, the subjects confused words with the same number of syllables, with bursts in final position, with similar final locus, and with similar pattern movement. In addition, Subject One confused words beginning with a burst. Neither subject significantly confused patterns sharing extent of movement or the same beginning locus.

These analyses document the extent to which subjects utilize gross features of the tactual signal to identify words at these relatively limited levels of practice and experience. Study I helped to analyze some aspects of vocabulary acquisition and the error types made by fairly inexperienced deaf perceivers. Study II was designed to examine other important aspects of tactual vocoder perception, i.e., the extent to which the information provided by the tactual vocoder can be generalized to new words and the extent to which tactual information can supplement the aided-audition of profoundly deaf individuals.

Table 4.
Tactually new words.

51. Bat	66. By	81. Zip	96. Best
52. Van	67. Fair	82. Moving	97. Nod
53. Lester	68. Ban	83. Portable	98. Organize
54. Do	69. Ever	84. Run	99. Interesting
55. Done	70. Cow	85. Sit	100. Jail
56. Gable	71. Lad	86. Cause	
57. Past	72. Bait	87. Ned	
58. Me	73. Patty	88. Pull	
59. Why	74. Gully	89. Catalog	
60. Ted	75. Channel	90. Avenue	
61. Oh	76. Talker	91. Varnish	
62. Tall	77. Lady	92. Latch	
63. Fun	78. Barrel	93. Hard	
64. Lamb	79. Forth	94. Perplex	
65. Live	80. Ernie	95. See	

STUDY II. INTEGRATION OF TACTUAL AND AUDITORY CUES BY PROFOUNDLY DEAF SUBJECTS

Method

Subjects. The two congenitally profoundly deaf adults from Study I participated in Study II.

Apparatus. The Tacticon 1600 was used.

Stimuli. The subjects' acquired tactual-vocabulary lists were expanded to include 50 additional words that were "tactually-new," i.e., had not been presented to them in tactual vocabulary training sessions. The added words were often similar to the acquired vocabulary, with some of the tactually-new words differing from acquired words in only 1 or 2 phonemes. (The added words are listed in **Table 4.**) All test procedures in Study II involved this 100-word list.

Procedure. The subjects were tested using a recognition paradigm similar to that used in Study I. In Study II, they were tested in 3 conditions: aided-audition (A), tactual vocoder (TV), and combined (TV + A).

In the A condition, words were presented to subjects with their hearing aids on. Lipreading was not available in any condition. Subjects turned off their hearing aids in the TV condition. In the TV + A condition, subjects activated their hearing aids and the tactual vocoder. Each of the 100 stimulus words was presented twice to each subject in each condition. Words were presented in blocks of 20: for example, 20 words in the A condition, followed by 20 words in the TV condition, followed by 20 words in the TV + A condition. Testing sessions were limited to one-half hour to avoid subject fatigue. The number of 20-word blocks conducted varied slightly from session to session. Each half-hour session was preceded by a break of at least 15 minutes. Word orders were randomized daily via a computer program, and condition orders were counterbalanced.

For Subject One, 2 trials per vocabulary item were presented. At each trial, the experimenter recited a word 3 times, and a response was solicited. If the subject's response was incorrect, the word was recited again 3 times, and a response was again solicited. Following this response, a new trial was initiated with a new word. Subject Two approached ceiling with aided-audition when more than a single trial of 3 repetitions per vocabulary item was presented; thus, Subject Two was required to answer after only 1 trial. Subjects were told whether their responses were correct or incorrect.

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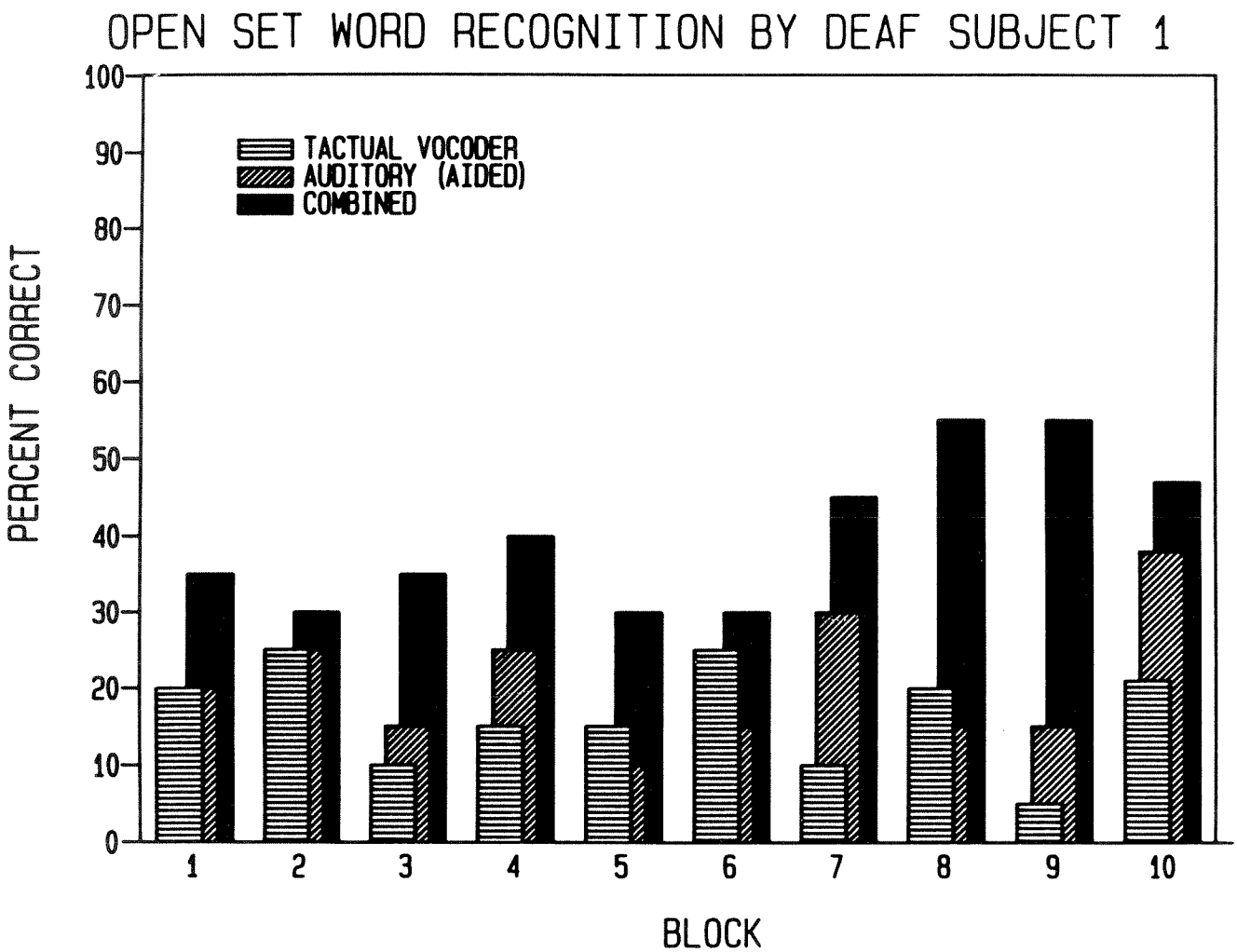

Figure 1a.
Subject One's percentage correct performance across 20-trial blocks for each of the 3 conditions.

RESULTS

The percentage of words correctly identified by each subject was calculated for each condition. **Figures 1a** and **1b** show each subject's percentage-correct score by block for each condition. Inspection of the figure indicates that performance in the A condition was higher than in the TV condition. Performance in the TV + A condition, however, was higher than that in either single modality condition.

Word identification for Subject One was 93.3 percent higher in the TV + A condition than for the A condition. For Subject Two, this increase was 56.1 percent. The mean percent correct in each condition for Subject One was: TV 16.6, A 20.8, and TV + A 40.2; and for Subject Two was: TV 12.0, A 28.5, and TV + A 44.5.

In order to examine differences in performance across conditions, one-way analyses of variance were done separately on each subject's data, with condition as the factor. Each testing block was considered as a subject in a repeated measures design, and each condition (A, TV, and TV + A) was a measure. The analyses indicated a difference in performance across conditions for both subjects, F (2, 18) = 29.96, $p < 0.001$, Subject One: and F (2, 18) = 22.27, $p < 0.001$, Subject Two.

Post hoc analyses indicated that for both subjects, word identification in the TV + A condition was significantly better than in the A condition, t (9) = 5.22, $p < 0.001$, Subject One; and t (9) = 3.69, $p < 0.005$, Subject Two. In addition, Subject Two correctly identified more trials in the A condition than in the TV condition (t (9) = 2.83, $p < 0.05$).

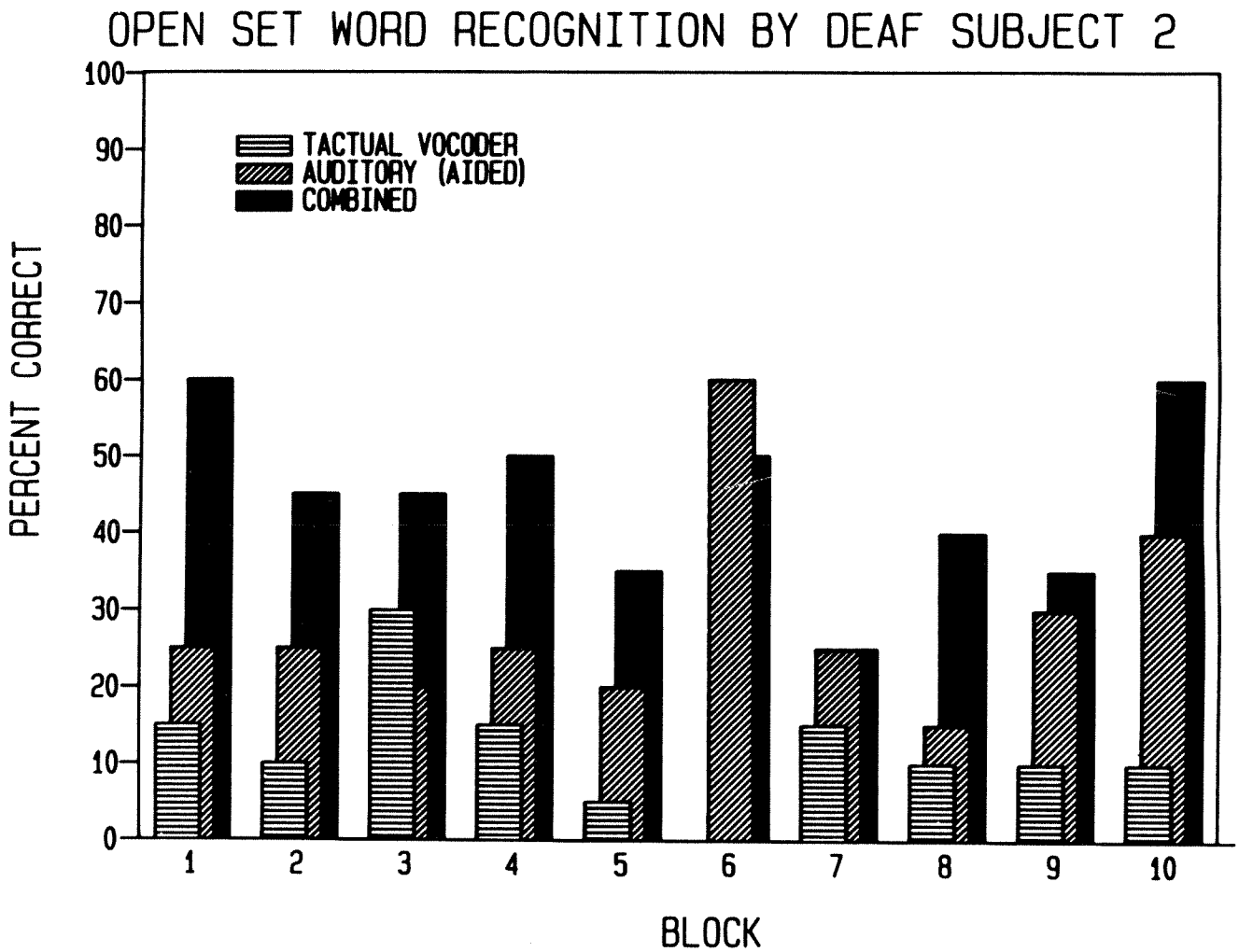

Figure 1b.
Subject Two's percentage correct performance across 20-trial blocks for each of the 3 conditions.

Subject One did not perform significantly better in the A than the TV condition.

Figure 2 shows the percentage of acquired and tactually-new vocabulary correctly identified by each subject in each condition. In the TV condition, subjects identified tactually-new vocabulary 8 to 10 times above chance, but more tactually-new words were correctly identified in the A condition than in the TV condition by both subjects. When sensory modalities were combined (TV + A), however, identification of tactually-new vocabulary was 78 percent better for Subject One, and 50 percent better for Subject Two, than when only aided-audition was used.

Both subjects identified a substantial percentage of acquired vocabulary in the TV condition (24 percent), and there was no significant difference between the A condition (26 percent) and the TV condition in acquired vocabulary identification. Both correctly identified a higher percentage of acquired vocabulary in the TV + A condition (50 percent) than in the A condition. Subject One correctly identified 100 percent and Subject Two 89 percent more acquired words in the TV + A condition than in the A condition.

GENERAL DISCUSSION

Congenitally profoundly deaf subjects received 40 to 50 hours of training with a tactual vocoder on a vocabulary that included 50 words. An analysis of

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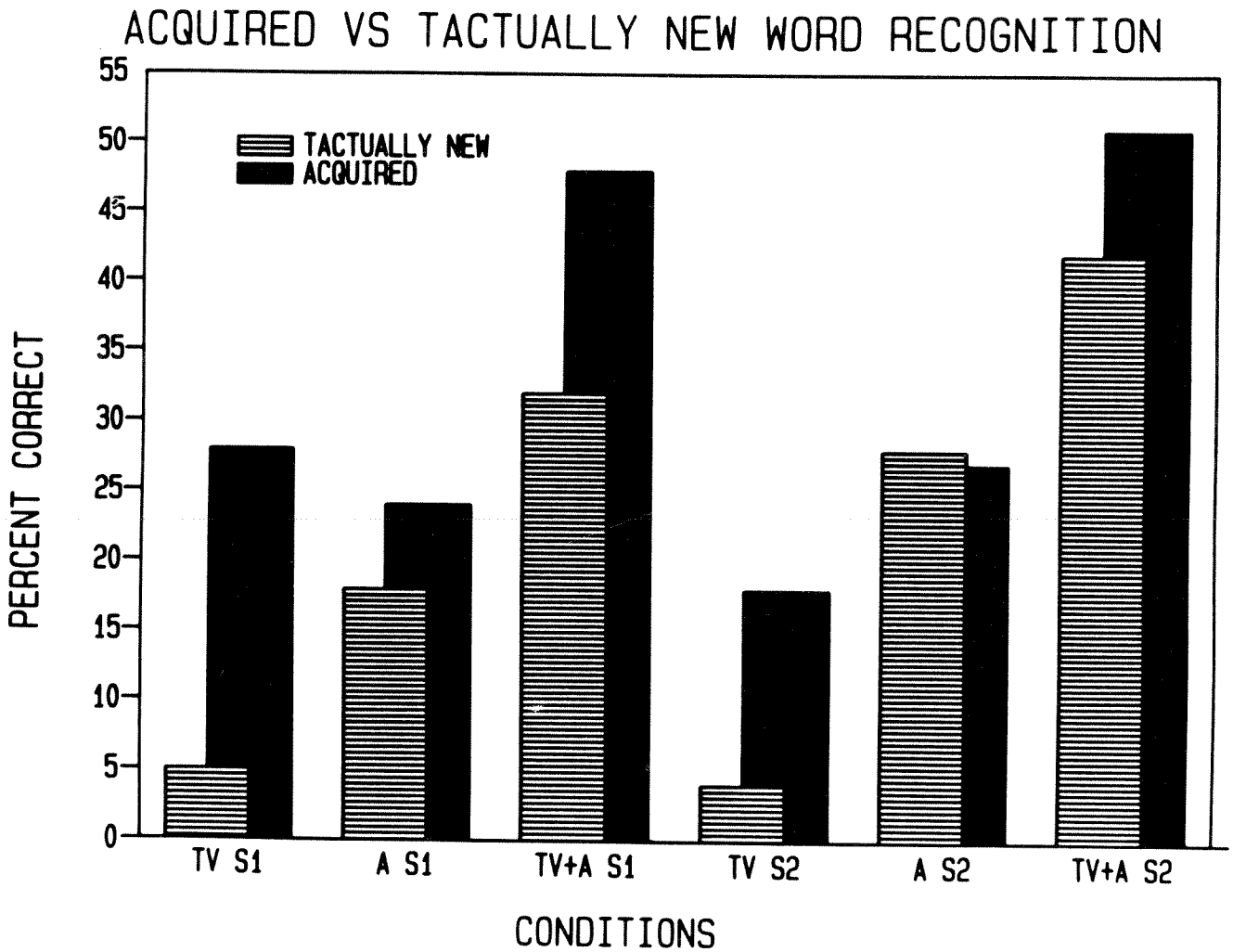

Figure 2.
Deaf subjects' percentage correct performance on tactually-new words and acquired vocabulary in the 3 testing conditions.

significant confusions indicated that, by the end of the training period, subjects at these beginning levels of training were relying on highly salient features of the tactual patterns of words to identify tactual vocabulary. Similarities in syllable number, presence or absence of bursts, general end locus, and direction of pattern movement were systematically involved in pattern confusion. The extent to which additional training can overcome these confusions and help subjects focus on the finer details of the tactual signal remains to be studied.

The overall percentage of correct responses during Study I was poorer than that reported by Engelmann and Rosov (5), Brooks and Frost (2), and Oller and Eilers (9). Several explanations for the poorer performance are possible: 1) differences in training procedure; 2) characteristics of the different vocoders (channel number and filter spacing, among others); and, 3) differences in stimulation methods.

The training procedure used in this study, unlike the previous words cited above, did not require the subjects to maintain a minimum level of performance on all acquired vocabulary, but only on the most recently introduced word. The more rigorous training criterion of the previous research methods might have led to higher performance levels with the present subjects.

A second source of potential difference between performance levels concerns the vocoder configurations. Brooks and Frost (2) used the Queens Univer-

sity 16-channel vibrotactile vocoder. Engelmann and Rosov (5) and Oller and Eilers (9) used the 24-channel Oregon vocoder. The present work was conducted with the 16-channel Tacticon 1600. These vocoders differ in filter characteristics and various processing factors. At this point, it is difficult to determine the effect of vocoder variables on subject performance.

The third factor, type of stimulation (electrocutaneous or vibrotactile), has never been examined in the absence of concomitant vocoder differences. All the previous vocabulary acquisition studies used vibrotactile stimulation, while the present one used the electrocutaneous method. Additional research must be specifically directed toward determining how many channels, which filter spacings, and which stimulation type will be most efficacious in future tactile aid designs.

Despite the overall lower performance relative to previous studies, the results are encouraging, given the extent of performance gain when aided-audition and taction were combined. This supplemental effect of taction, when combined with hearing, was apparent in performance on both the acquired and the new vocabulary presented in Study II. The subjects performed better on identification of vocabulary when tactile and aided-auditory information were combined, than when either aided-auditory or tactual input alone was provided. These results indicate that the subjects successfully integrated tactual and auditory information after 40 to 50 hours of tactual vocoder training, even when identifying novel words.

The identification of novel vocabulary suggests that the subjects may have been applying phonologically-based tactual knowledge to identify novel words (9). The tactual vocoder and aided-audition appeared to provide the subjects with complementary information for word identification. This complementarity is similar to that seen by Brooks *et al.* (3,4), where touch, combined with lipreading, provided an artificially-deafened adult with superior word identification scores when compared to those accomplished with either sensory modality alone.

In general, these results encourage the further development of tactual vocoders for use as sensory aids to deaf individuals. Studies of the long-term development of tactual speech perception skills of profoundly deaf adults will provide further insights into strategies of tactual perception. A better understanding of those strategies would contribute to our knowledge of perception in general, and tactual speech perception in particular.

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