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The effects of vocoder filter configuration on tactual perception of speech

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Abstract—Perception of synthetic speech continua through the sense of touch and audition was compared utilizing a 32-channel spectrally-oriented electrocutaneous vocoder display and standard auditory psychophysical procedures. Perception of a consonantal and a vocalic continuum was evaluated utilizing three vocoder filter configurations: logarithmic, linear, and average (geometric mean of logarithmic and linear). Results indicated a close correspondence between tactual and auditory discrimination and identification for the vowel (/a/-/ə/) and the consonant (/sta/-/sa/) continuum regardless of the filter characteristics.

Key words: *artificial hearing, electrocutaneous vocoder, sensory aids—deaf, synthetic speech, tactile perception, vocoder filter configuration.*

INTRODUCTION

Tactual vocoders have recently shown promising results as artificial hearing devices to be used in speech transmission for the deaf (9,11,18,19,20,21). These devices function by displaying spectral information dynamically on the skin in a manner similar to that produced by the human cochlea. The use of vocoders for artificial hearing assumes that if speech information can be transmitted to the brain through the tactile sense, then it can be properly perceived and decoded as speech after some training. Many experimental and clinical data provide support for the efficacy of such an approach (1,2,3,22,27,28). Many aspects of vocoder design, however, have never been tested rigorously under experimental conditions. The justification for the use of tactual vocoders depends in part upon the demonstration of the similarities between the auditory and tactual perception of speech.

In recent research we have found similarities in boundary locations and discrimination functions for the auditory and tactual perception of a consonant and a vowel contrast (8). These results have suggested the intriguing possibility that some aspects of speech processing may operate independently of the auditory system. Moreover, the results provide further support for a sensory substitution approach to the problem of deafness.

Although similarities between tactual and auditory perception have been documented, little information is available to elucidate the underlying mechanisms responsible for the similarities. The correspondence between tactual and auditory perception of speech may be mediated by a number of factors, including cross-modally applicable laws of perception (such as Weber's law), and similarities in acoustic frequency coding in tactual vocoders and the auditory system. The present research represents an attempt to consider the latter of these possibilities.

Our previous demonstrations of cross-modal similarities in speech processing have been based on

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tactual vocoders that employ logarithmic filter spacing. Research exploring the representation of frequency on the basilar membrane in animals suggests that a near logarithmic coding may approximate organization of frequency in the cochlea (5,10). An exception to this general principle can be found at frequencies below 1 kHz (17), where the relationship between frequency and position approaches linearity. To date, designs of tactual vocoders, both in our laboratories and elsewhere, have generally used logarithmic filter spacings (e.g., 1, 11). Given the general similarity of the frequency coding incorporated in a logarithmic tactual vocoder system and audition, one might predict that similarities across tactual and auditory perception would be found using existing devices.

The present research was designed to evaluate the effect of tactual vocoder filter configuration on speech transmission. In particular, the research sought to assess the possibility that similarities of processing in taction and audition seen in our previous work may have depended upon the logarithmic filter configuration. The present work utilized three tactual vocoder filter configurations to compare with audition—logarithmic, linear, and average (mean of the logarithmic and linear configurations). Both labelling and discrimination testing were conducted for the consonant and vowel stimuli from the earlier study. The techniques and stimuli were chosen to be representative of standard speech science tools for evaluating speech transmission in the auditory modality.

METHOD

Subjects

Subjects were four healthy, normal adults with no history of dermal disease or trauma. All subjects had more than 40 hours of experience with the presently-employed scheme of electrocutaneous stimulation in both psychophysical and speech perception experiments.

Apparatus

Auditory. Auditory testing of the speech continua was conducted in a sound-treated booth. Speech syllables were presented through a high quality speaker at 70 dB sound pressure level (SPL).

Tactual. Tactual stimulation was provided through a 32-channel computer-driven electrocutaneous display as described in detail elsewhere (23). Briefly, the system consisted of a minicomputer system (PDP-11/23+) that controlled a 32-channel electrical stimulation system. Each stimulation channel was independently controlled through a parallel output port. Selected channel data were converted to frequency-modulated biphasic pulses through D/A converters, voltage to frequency converters, and constant current pulse generators.

Stimulation was presented to the abdomen through 32 linearly-arranged electrodes. The electrodes were gold-plated (8 mm^2) and set on a conductive rubber ground plane. They were separated by 1.5 cm (center to center) and worn on an elasticized belt supplied by Tacticon Corp. (25). At any point in time, stimulation at a particular electrode site was proportional to the energy in the speech signal within the frequency range of the corresponding filter. Absence of energy in a particular frequency band would result in no stimulation. Thus, depending on the input, between 0 (a silent interval) and 32 electrodes could be simultaneously activated and each electrode could provide stimulation at varying electrical frequencies. The drive circuitry of the display generated constant-current biphasic pulses. Pulse height was set at ± 10 mA; pulse width was under subject control. Typically, subjects adjusted pulse width between 13 and 18 μs. Pulse frequency was proportional to intensity of stimulation. Electrical stimulation for an active electrode varied between 10 and 400 Hz, the frequency range identified to include maximum skin sensitivity (4).

Three filter configurations were designed and named according to the bandwidth calculation procedure described below. In the log configuration, the frequency range (100–4,500 Hz) was divided into 32 logarithmically-equal bandwidth regions. This configuration assigns more channels to the low frequency end of the spectrum than to the higher end. The evidence cited suggests that above 1 kHz, the cochlea of a mammal is characterized by a roughly log configuration. It is argued that the log configuration extracts maximum information with the minimum number of channels (or hair cells) from natural acoustic stimuli (5).

In the linear filter configuration, the frequency range (100–4,500 Hz) was divided into 32 linearly-

equal bandwidth regions. This configuration is different from that found in the cochlea in that there is no special emphasis given to low frequencies.

It is reasonable to assume that speech contrasts which differ primarily in the high frequencies will be better transmitted by a linear than a log configuration and that those with low frequency information will be better transmitted by the log configuration. A compromise average configuration (arithmetic mean of log and linear) was also tested to provide a more parametric perspective on the role of filter configuration in speech perception. In fact, anatomical and physiological data show that the frequency mapping of the cochlea is not exactly logarithmic, but falls intermediate between log and average configurations. Greenwood's formula (14) approximates frequency mapping in many species, including man. **Figure 1** shows a cochlear filter plot based on Greenwood's formulation along with the vocoder filter configurations chosen for study.

In each configuration, bandpass characteristics of the adjacent filters were lined up precisely (i.e., the upper corner frequency of bandpass filter n

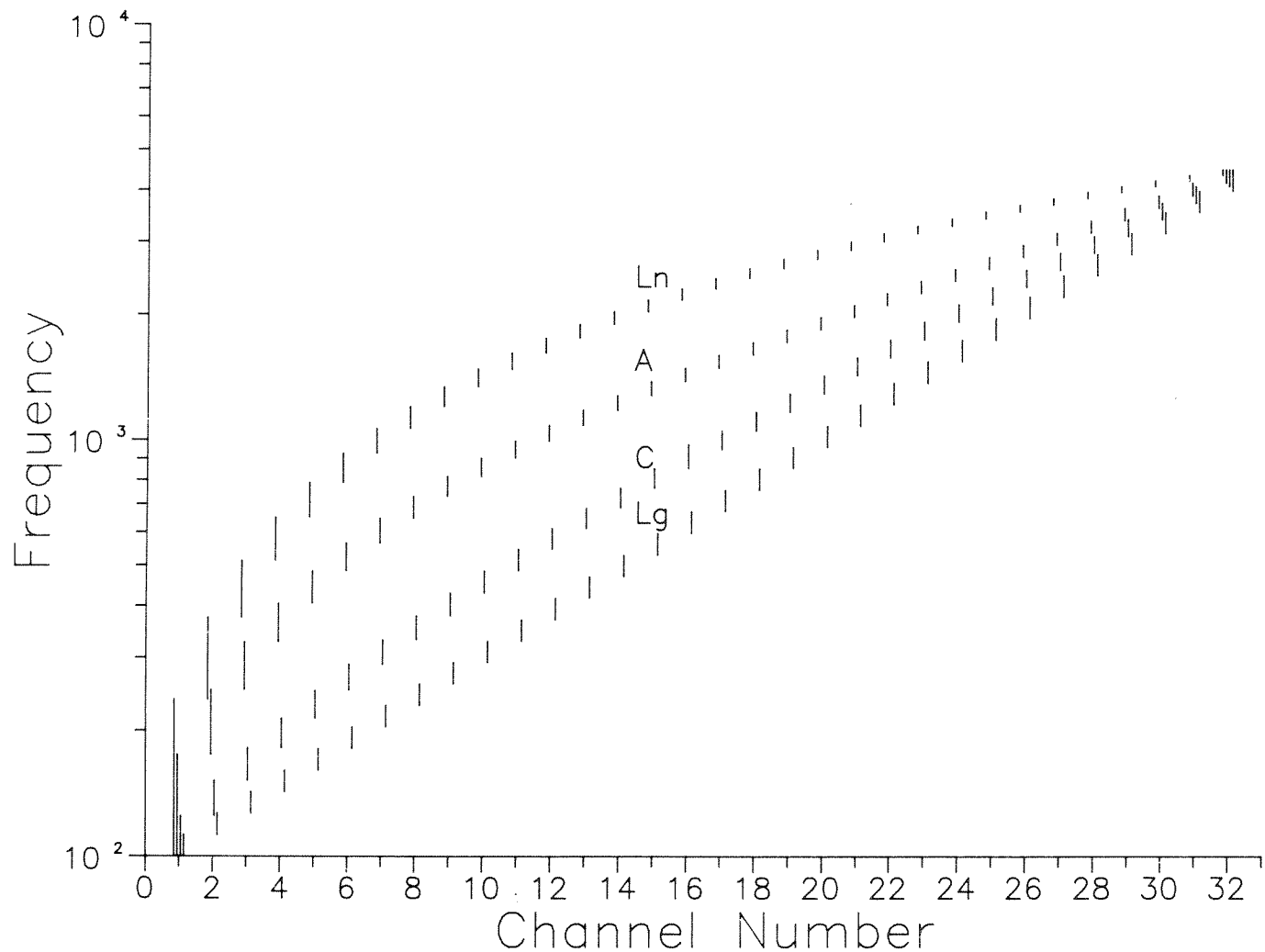

Figure 1.
Greenwood's cochlear (C) function compared to log (Lg), linear (Ln), and average (A) filter configurations used in current study. The length of the lines is equal to the filter bandwidth.

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equals the lower corner frequency of bandpass filter n + 1) so that there were no gaps or overlaps across the frequency range. The characteristic variable for each filter configuration was the bandwidth. Bandpass filters for all filter configurations and a 50 Hz lowpass filter were designed by using the Atlanta Signal Processing, Inc. Digital Filter Design Package. Bilinear transformation of elliptic analog prototypes was employed to create Infinite Impulse Response filters. Filter orders were chosen so that the maximum ripple in the stopband region of all filters was less than −40 dB. Filter order was 6 for all the bandpass filters. The order of the lowpass filter was 4. In order to maintain filter roll-off characteristics consistently across filter configurations, filter cutoff frequencies were set to the filter center frequency plus or minus one-half the filter bandwidth. Slopes of the filter skirts were dependent on the filter configuration. For the logarithmic configuration, the slope was 35 dB/octave or higher for all filters. In the linear configuration, the most shallow slope was 20 dB/octave (lowest frequency) and the steepest slope was 1,240 dB/octave (highest frequency). In the average configuration all slopes were intermediate, falling between the values for the log and linear configurations.

Stimuli

Two 11-step speech continua were synthesized using Klatt's (15) routines. Klatt's software package allows manipulation of a wide variety of acoustic/articulatory parameters (e.g., amplitude of voicing, fundamental frequency, F_1 frequency, F_2 frequency, etc.) consistent with accepted theory of speech acoustics. Waveforms were generated at a 10 kHz sampling rate. The vowel continuum ranged in 11 steps from /a/ (step 1) to /ə/ (step 11). Intermediate stimuli were created by changing the first three formants in equal frequency increments from 742, 1,144, 2,517 Hz for F_1, F_2, and F_3, respectively for step 1; to 450, 1,450, and 2,450 for step 11. All stimuli were 350 ms in duration, and all included an identical natural-sounding rise-fall pattern of amplitude and F_0.

For the consonantal continuum, step 1 was the syllable /sta/ and step 11 /sa/. The percept of /t/ in /sta/ resulted from 130 ms of silence inserted between the /s/ and /a/. Across the continuum, the silent interval was shortened by 13 ms at each step so that step 11 contained no silent interval. All of the /sa/-/sta/ stimuli contained identical /s/ and /a/ segments as well as identical rise-fall patterns of amplitude and F_0. The two speech continua were the same as those studied in Eilers *et al.* (8).

Synthetic speech stimuli were software-filtered in non-real time through the three different filter configurations: log, linear, and average. The output of the filter program was stored on disk and served as input to the tactual display. **Figures 2a, 2b,** and **2c** show the endpoint stimulus for each filter configuration as a three-dimensional dynamic plot with the z dimension representing pulses/second.

The stimuli utilized in the study provided an interesting test of the role of filter configuration in the transmission of syllables. The variations in formant frequencies across the 11 tokens of the vowel continuum produced different patterns of stimulation for each of the three filter configurations. These patterns can be seen in **Figures 2a, 2b,** and **2c**. From the figures, it is clear that the primary variations appear to concern F_1. For each vowel token, the most intense stimulation occurred at F_1 (450 Hz at step 11, /ə/, and 742 Hz at step 1, /a/). For the log configuration, stimuli corresponding to 450 and 742 Hz were separated by 7 channels, while in the linear and average cases, the differences were 4 and 5 channels, respectively. Consequently, subjects had a differing basis for judgment of variations in location of F_1 stimulation depending upon the vocoder configuration. Smaller differences in the relative position of formants in the endpoint stimuli across the three filter configurations can be found for F_2. It is most likely, however, that subjects rely on both F_1 position and amplitude to judge vowel identity, since the stimulation resulting from this formant is high amplitude relative to other parts of the signal.

The stimuli of the consonant continuum likewise differed across the three configurations, although an understanding of the significance of the difference requires attention to the relationship in space and time between the fricative /s/ and the vowel /a/ in the tactile representations. The task of subjects in labelling the consonant continuum can be thought of as one of noting the relative position in time of the /s/ and the /a/, a task that may have been influenced by backward masking of the relatively less intense /s/ by the relatively more intense /a/. Furthermore, the masking may have been heightened by the fact that a larger number of

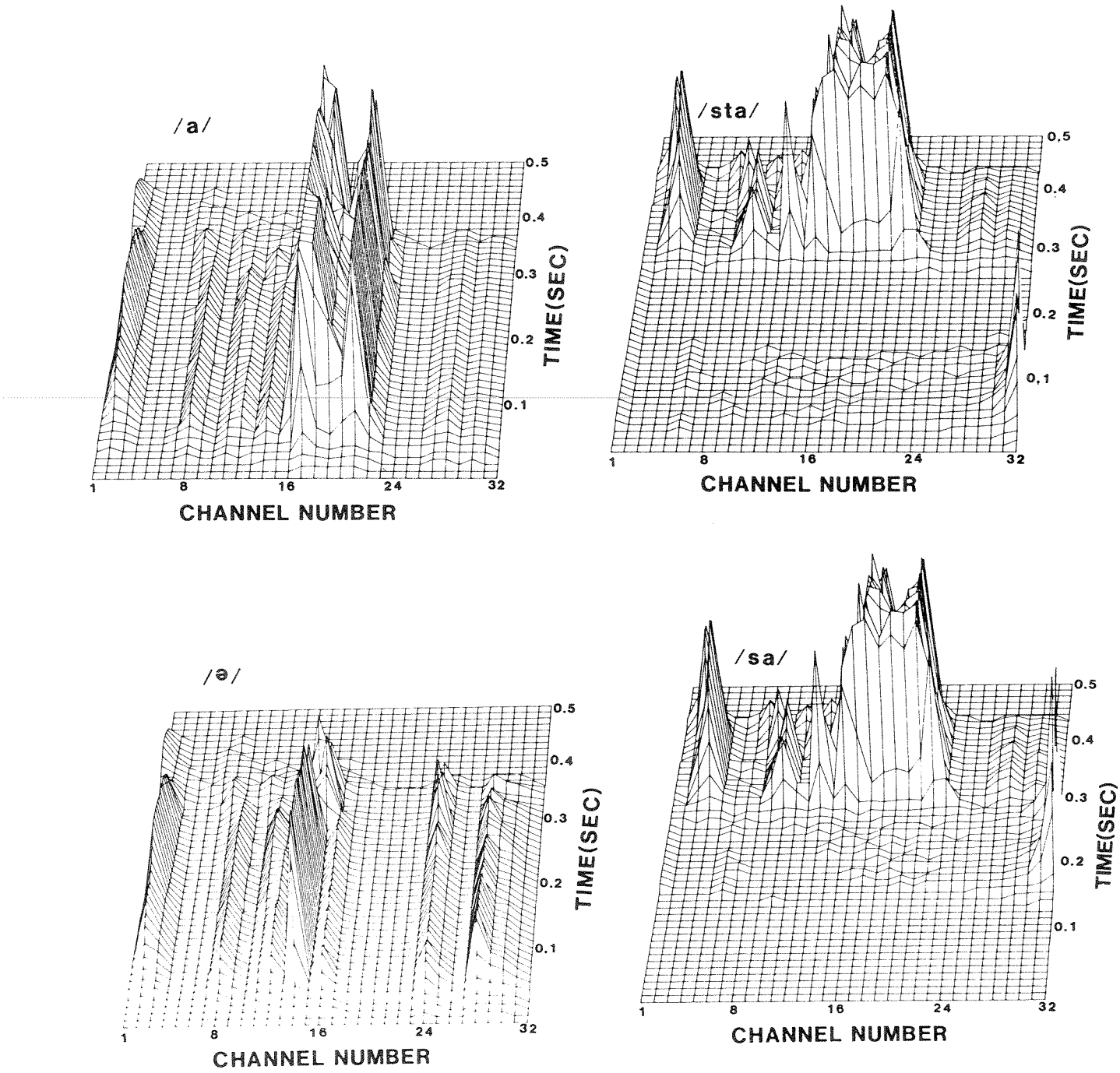

Figure 2a.
Three-dimensional plots of endpoint stimuli for the continuum for the log filter bank showing dynamic representation on the skin. The z direction represents pulses/second.

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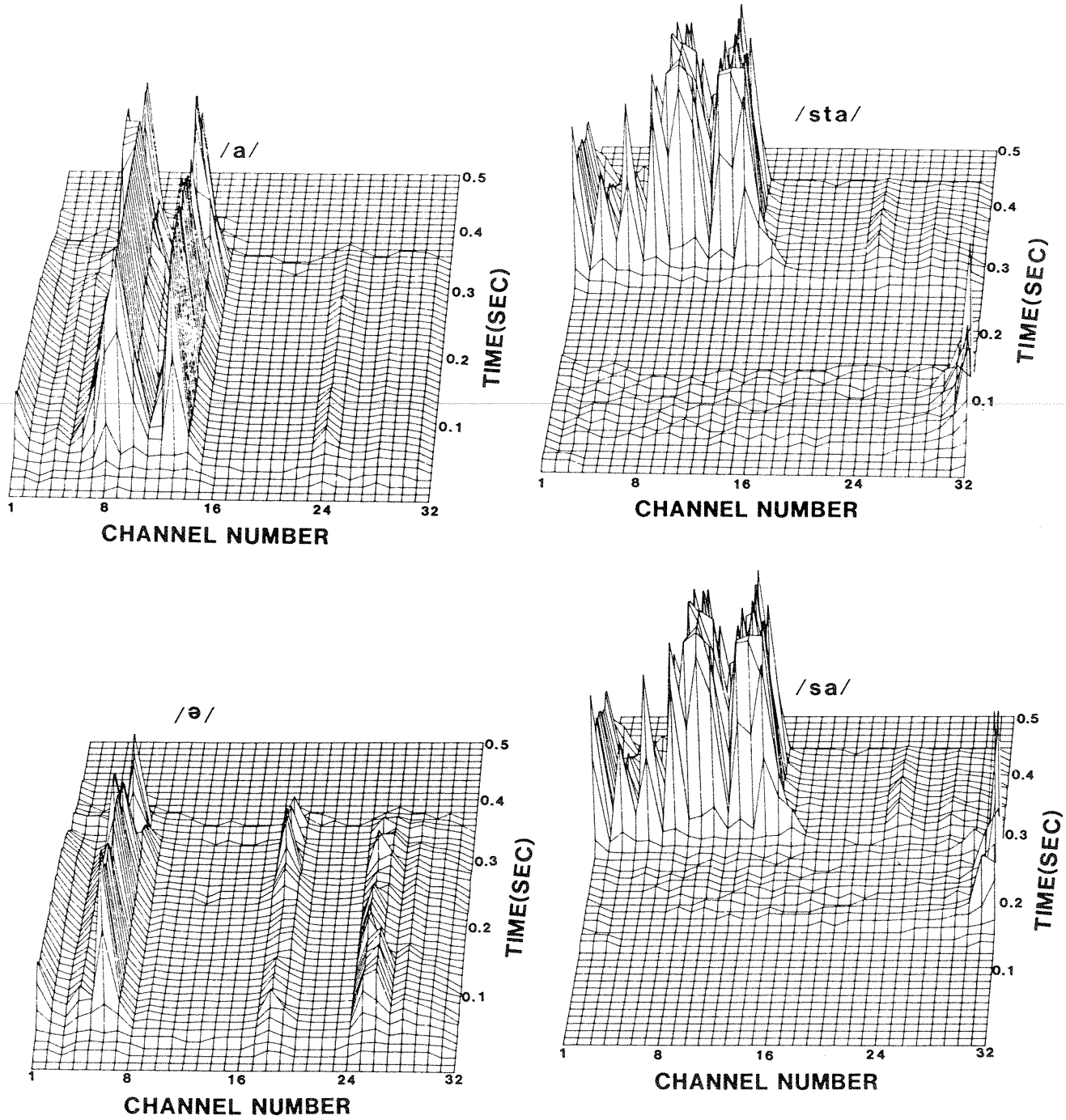

Figure 2b.
Three-dimensional plots of endpoint stimuli for the continuum for the average filter bank showing dynamic representation on the skin. The z direction represents pulses/second.

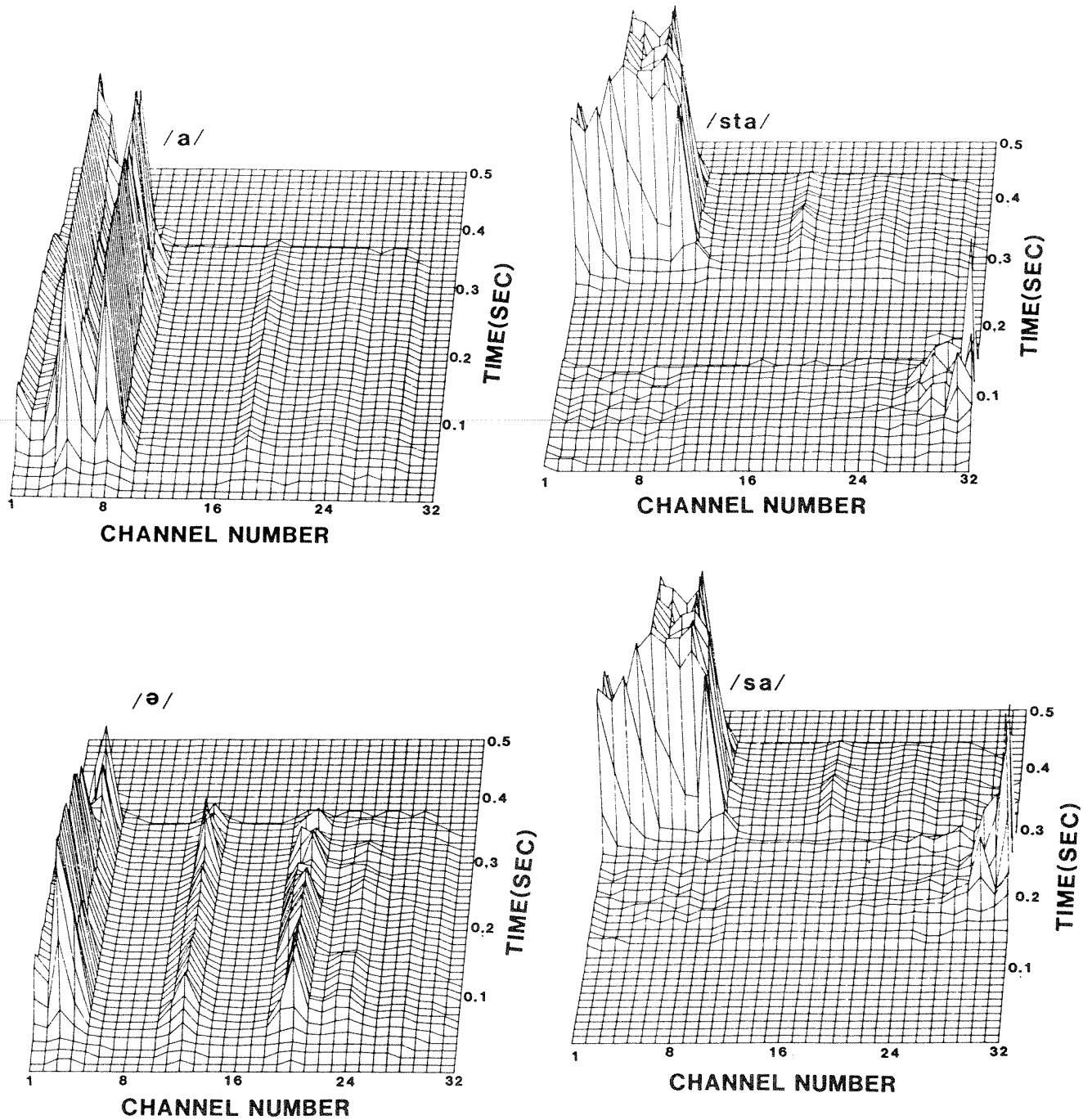

Figure 2c.
Three-dimensional plots of endpoint stimuli for the continuum for the linear filter bank showing dynamic representation on the skin. The z direction represents pulses/second.

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channels was activated for the vowel than for the consonant (see **Figures 2a-2c**). Studies of tactile perception attest to the strength of backward masking and suggest it is enhanced by the intensification of maskers and increasing the number of sites of masking stimulation (6,7,12).

The factors influencing potential masking differed greatly across the three filter configurations. The smallest number of activated /s/ channels occurred in the log configuration (2 channels), while the largest number occurred in the linear configuration (5 channels).

The larger number of channels activated in the linear case may have provided not only a greater resistance to masking, but the potential masking difference may also have been enhanced by the fact that the location of the primary /a/ stimulation (the F_1/F_2 complex in **Figure 2a**) extended up to channel 22-23 for the log configuration, only nine channels away from the location of the /s/. The same formant complex in the linear configuration (see **Figure 2c**) extended only to channel nine, a full 19 channels away from the location of the /s/. Given these distances, potential masking effects would have to apply across the midline of the abdomen for the linear configuration, while the log configuration would have included, at least partially, ipsilateral effects. Electrotactile perception has been shown to include greater masking for stimuli that are closer together (24,26), and vibrotactile research has shown increased masking by ipsilateral stimuli (13). These, and other parallel lines of reasoning, suggest that the effect of masking for perception of the /sa/-/sta/ continuum may have been substantially different for the different filter configurations.

Procedure for identification (labelling) testing

Testing was done in a sound-treated booth for both tactual and auditory conditions. For tactual conditions, subjects followed the warm-up procedures described in detail in Bull *et al.* (4), except that 32 channels, rather than a single channel, were activated during warm-up. In the present study, subjects were permitted to adjust pulse width to achieve a comfortable and clear level of stimulation. Warm-up procedures occurred before each tactual session. Prior to Experiment 1, subjects were familiarized with the test stimuli in both modalities by participating in a standard adaptive discrimination paradigm (16). In this paradigm, subjects were presented with the two most distant (1 and 11) stimuli in a two-interval forced-choice task. They were asked to indicate which of two intervals (one containing a 'target' stimulus and one a 'comparator') contained the targeted endpoint (e.g., 1) stimulus. Feedback was provided on each trial. Correct responses led to the presentation of pairs that were more similar, and incorrect responses led to larger differences between stimuli. A computer-implemented stopping rule determined a threshold of Just Noticeable Differences (JND). These were automatically recorded by the computer. After subjects achieved consistent discrimination scores for each filter configuration and for the auditory condition, they proceeded to Experiment 1. JND values for these stimuli may be found in Özdamar *et al.* (23).

Order of presentation of modality (auditory and tactual), continuum (vowel and consonant), and filter configuration (logarithmic, average, and linear) were counter-balanced across subjects. Tactual and auditory discrimination were tested in separate sessions. The identification paradigm was controlled by computer through a subject-activated response box. To begin a trial, the subject depressed a start button and two repetitions of step 1 or step 11 stimuli (/a/ or /ə/ from the vowel continuum or /sa/ or /sta/ from the consonant continuum) were presented auditorially or tactually. These presentations were separated by 500 ms. The subject indicated by pressing one of two buttons on the response box whether the endpoint was step 1 or step 11. Lights on the response box informed the subject if the response was correct. Subjects were required to respond correctly to 9 out of 10 consecutive trials before proceeding with labelling of intermediate stimuli. Typically, subjects achieved this criterion in 9 to 11 trials. After the criterion was met, feedback was discontinued, and the 11 stimuli were presented in random order a total of 20 times each. Subjects continued to respond by pressing one of the two buttons for each trial, indicating thereby that the stimulus felt or heard was, or was not, like the step 1 stimulus.

Procedure for discrimination testing

Discrimination testing followed the same general procedures described for identification testing. Order of presentation of modality (auditory and tactual), continuum (vowel and consonant), and

filter configuration (log, average, and linear) were counter-balanced across subjects. The discrimination paradigm was under computer control. Pairs of stimuli selected across the continua were presented for discrimination in a same-different paradigm. Half of the trials contained two identical stimuli, while half contained two different stimuli. Subjects pressed button 1 on the response box to indicate different, and button 2 to indicate same. Based on previous studies (8), step sizes were chosen to maximize discrimination peaks. For tactual presentation, the step size was three (stimulus 1 versus 4, 2 versus 5, etc.), while the auditory presentation was two (1 versus 3, 2 versus 4, etc.). Members of the test pair were separated by 500 ms and feedback was not given. Subjects received 40 trials per stimulus pair; 20 were the same and 20 were different.

RESULTS

Figures 3a and **3b** show the labelling functions for each of the filter configurations for each continuum. For purposes of statistical analysis, step 11 of /sa/-/sta/ was compared to step 1 of /a/-/ə/ and so forth through the continuum, so that step 1 of /sa/-/sta/ was compared with step 11 of /a/-/ə/. Comparisons were done in this manner to allow for the statistical analysis of function shapes.

The labelling functions for both continua provided no support for the suggestion that similarities of tactual and auditory processing were dependent on the log filter configuration used in the previous work. In fact, all three filter configurations produced labelling functions that approximated the auditory function.

For statistical analysis, each subject's raw data were fitted with a third order polynomial to smooth the identification functions. After deriving the regression equation, 25 percent, 50 percent, and 75 percent values on the psychometric function (points at which 25, 50 and 75 percent of stimuli were identified as /sa/ or /a/) in steps were calculated for each subject for each identification function. These values in steps from endpoints constituted the dependent variables for an analysis of variance with three factors: Continuum (consonant and vowel), Filter Configuration/Modality (log, linear, average, and auditory), and Psychometric Value (25 percent, 50 percent, and 75 percent points). The analysis yielded the expected main effect for Psychometric Value [$F(2,6) = 592$, $p < 0.001$], an effect that merely reflects slope of the functions. More important was the lack of a significant main effect of Filter Configuration/Modality, a manifestation of the similarity of the psychometric function values in the auditory and tactual conditions. Examination of the figures confirms the consistency of labelling of the continua in all three tactual conditions. The maximum difference between the two most divergent identification functions (auditory or tactual), at any point on the function, did not exceed one step.

The similarity in labelling functions across audition, and the three tactual filter configurations cannot be accounted for solely by stimulus-independent response strategies (e.g., subjects might attempt to parse each continuum as close to the endpoint as possible), since the two continua have different labelling function shapes. Instead, subjects must have responded to the acoustic and tactual properties of the speech signal in the labelling task based on information available from each filter configuration. Furthermore, other data (23) show that subjects' labelling boundaries were quite consistent across a number of speech continua, a pattern that cannot be accounted for by stimulus-independent strategies.

Two significant two-way interactions with Psychometric Value were obtained. The interaction of Continuum and Psychometric Value [$F(2,6) = 11.15$, $p < 0.001$] reflects the fact that the continua were treated similarly at the 75 percent point on the psychometric function, but diverged at the 50 percent and 25 percent points. In other words, the labelling functions for the two continua had different shapes. The interaction of Filter Configuration/Modality and Psychometric Value [$F(6,18) = 3.25$, $p < 0.02$] reflected the convergence of configurations/modalities at the 75 percent value of the functions and divergence at the 50 percent and 25 percent values. These differences in the shape of the functions may reflect the somewhat steeper slope of the auditory function.

While Filter Configuration/Modality and Continuum interacted with Psychometric Value, there was no significant three-way interaction of Filter Configuration/Modality by Continuum by Psychometric Value [$F(6,18) = 1.70$, $p < 0.18$]. The lack of a three-way interaction indicates that the consonantal

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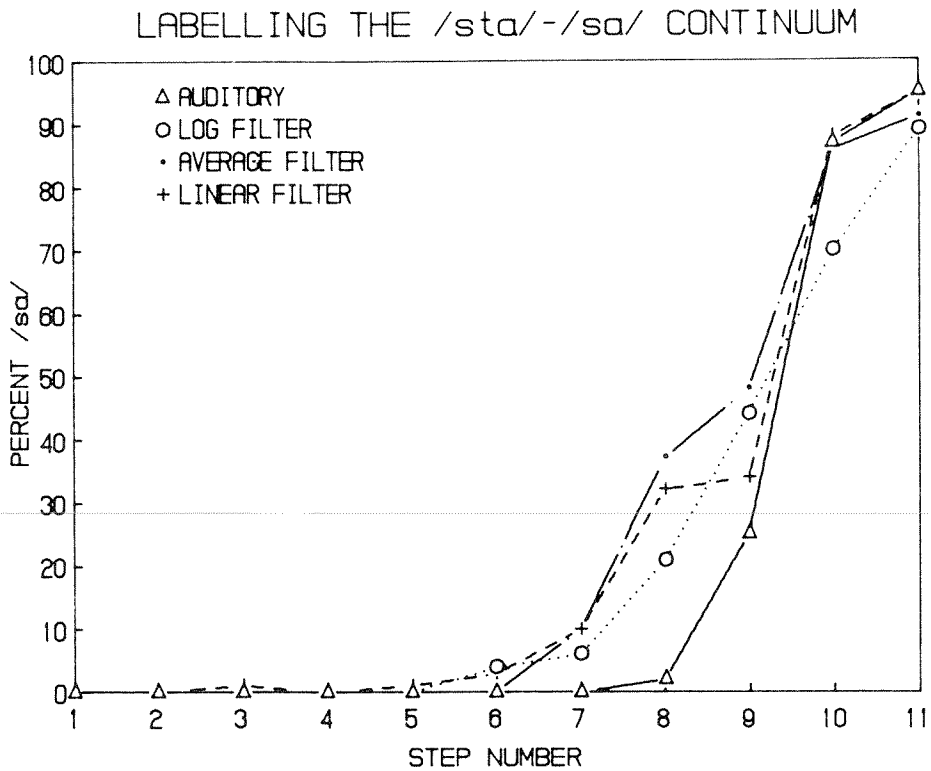

Figure 3a.
Labelling function for the /sa/-/sta/ continuum.

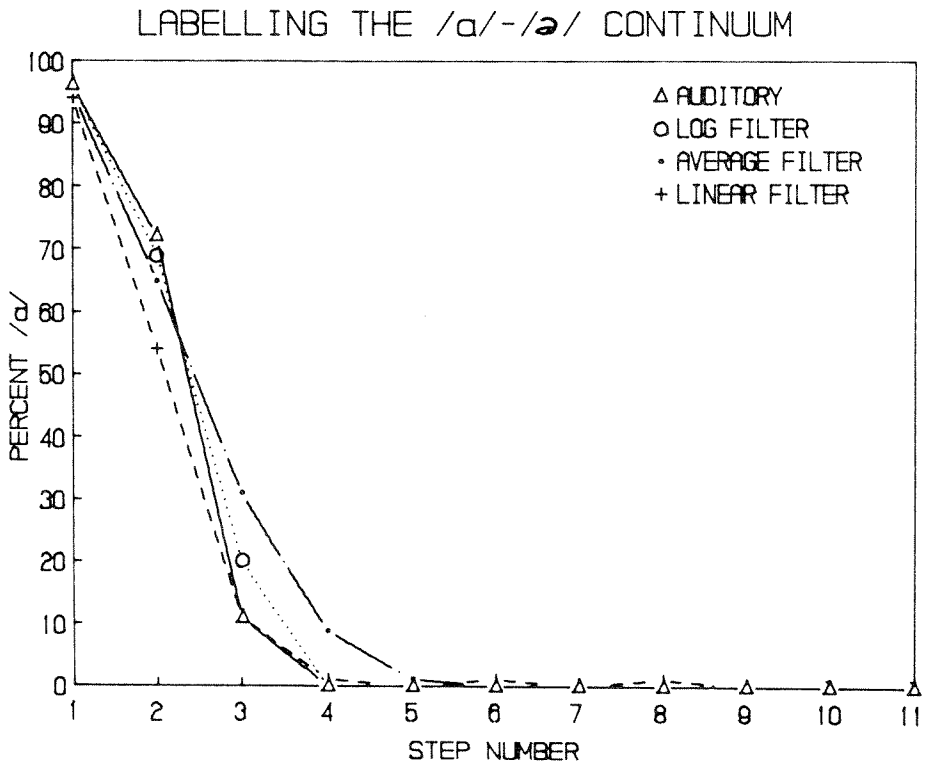

Figure 3b.
Labelling function for the /a/-/ə/ continuum.

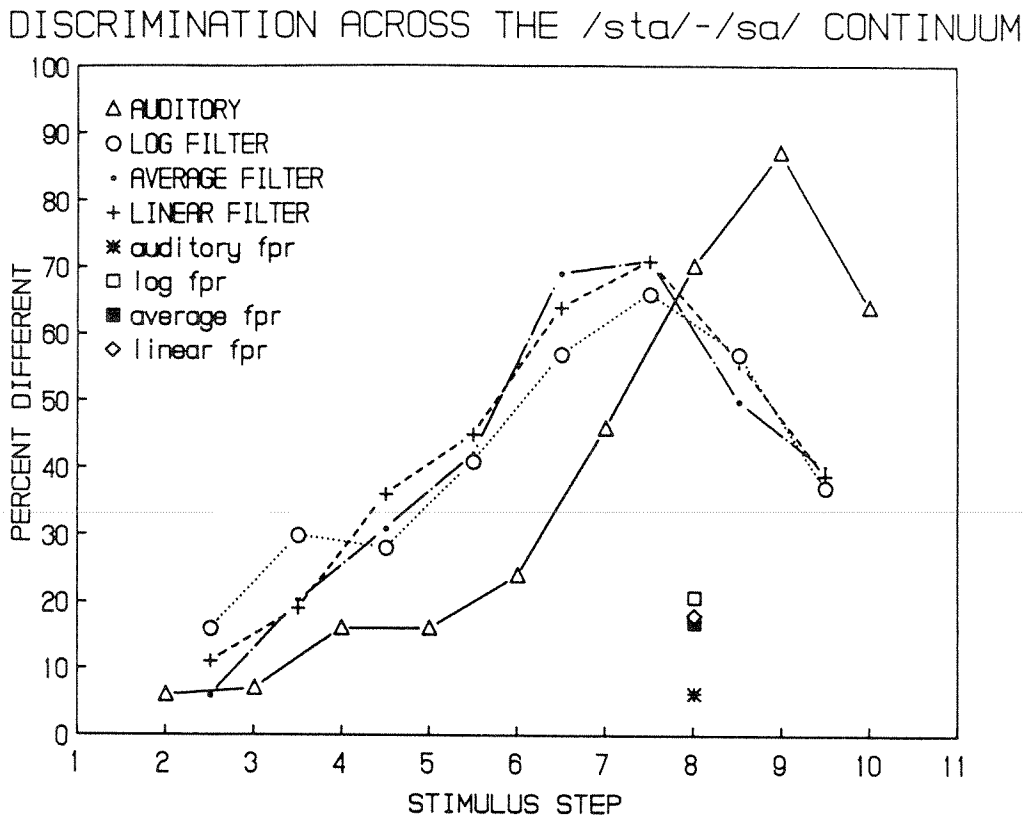

Figure 4a.
Pair-wise discrimination across the /sa/-/sta/ continuum.

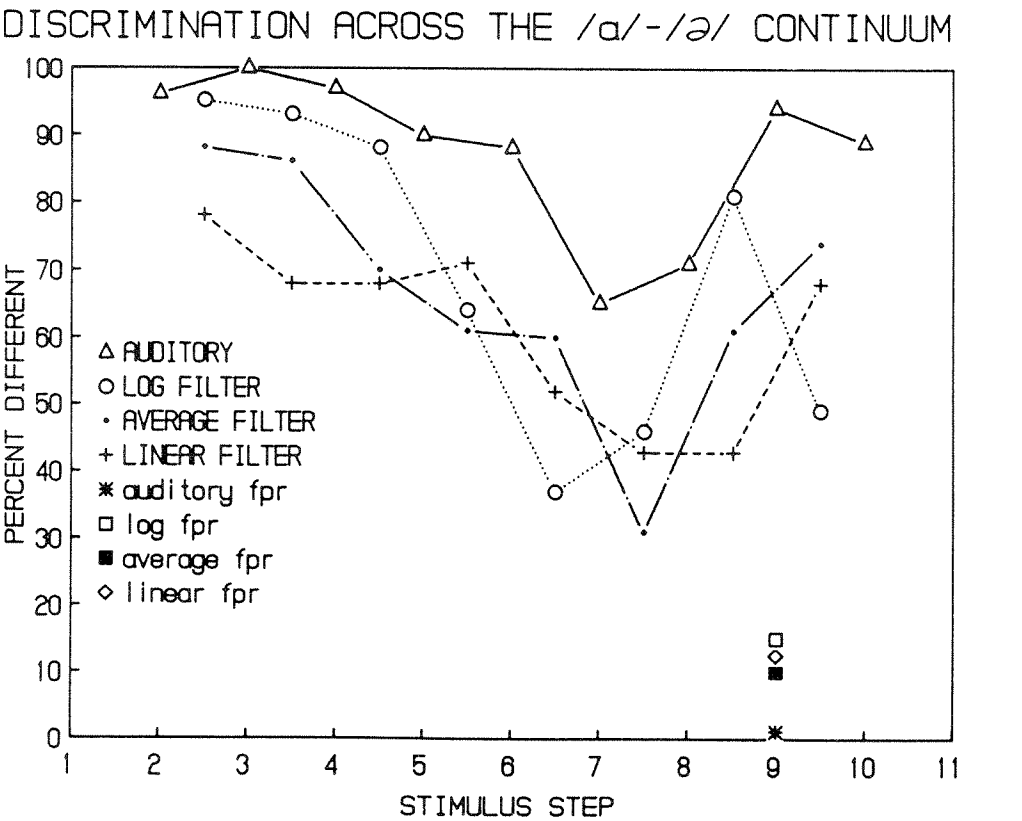

Figure 4b.
Pair-wise discrimination across the /a/-/ə/ continuum.

and vowel continua did not have significantly different shapes as a function of configuration type.

Discrimination functions for the two continua are shown in **Figures 4a** and **4b**. It is apparent from **Figure 4a** that the /sa/-/sta/ continuum yielded an auditory peak in the discrimination function near the phonemic auditory category boundary, the region in which subjects split the continuum by using different labels to define adjacent stimuli. The boundary was defined as the value in steps at an ordinate value of 50 percent. Within-category discrimination was, in general, poor. The labelling functions for each of the three tactual filter configurations showed tactual /sa/ falling steeply between steps 10 and 6, while the discrimination peak for all configurations was located between steps 9 and 6. In both modalities for all filter conditions, discrimination peaks occurred in the region of category labelling boundaries and discrimination within categories was relatively poor. This pattern of results was consistent both tactually and auditorially with the results of Eilers *et al.* (8) and fit a model of categorical perception for the consonantal continuum. In contrast to the consonant functions, discriminative performance on the vowel continuum (**Figure 4b**) was well above chance at each stimulus interval for both modalities and all tactual filter configurations. A region of relative discriminative sensitivity coincided with the steeply falling region of the labelling function. The middle of the continuum showed the poorest discriminability in both modalities. The high discriminability, both auditorially and tactually, on the right-hand side of the vowel continuum is indicative of the presence of another phonemic (or potentially phonemic) boundary between the step 11 vowel [ə], as in the word "just" pronounced with low stress and a fairly high central vowel in the sentence, "He's j*u*st a man," and the intermediate step mid-central vowel [ʌ], as in, "He's a j*u*st man." A comparison of **Figures 4a** and **4b** indicates the stronger tendency toward categorical perception of consonants than of vowels for both the auditory and tactual modalities irrespective of the filter configuration considered.

To assess potential differences among the three filter configurations, two separate analyses of variance were conducted, one for each continuum. These analyses had two factors, Filter Configuration (log, linear, and average) and Pairs (eight). These analyses yielded significant effects only for Pairs [$F(7,21) = 13.30$, $p < 0.0001$ for /sa/-/sta/; $F(7,21) = 7.10$, $p < 0.0002$ for /a/-/ə/]. The differences between filter configurations were not significant. It was not possible to assess the statistical significance of differences between the auditory and tactual modality, since the number of steps between contrasting stimuli differed across modality. Nevertheless, it is clear that tactual discrimination functions differed somewhat from auditory discrimination functions of the same stimuli.

DISCUSSION

Both labelling and discrimination functions for two continua, one consonantal and one vocalic, were similar in two sensory modalities, tactual and auditory. Furthermore, the similarities between the modalities did not seem to depend upon the filter configuration used in the tactual presentation system, since three different configurations all showed the similarity with audition. While the log and average filter configurations simulate cochlear function to a greater extent than linear arrays, evidence was not found to suggest that a linear filter configuration limits or distorts perception of the consonantal and vocalic continua studied here. It appears that as long as the filter configuration does not eliminate critical, spatial, or temporal cues (analogous to spectral and temporal cues in audition), there is considerable flexibility in the tactile system for perception of speech-like events represented by a broad array of potential patterns.

The labelling and discrimination functions were similar but not identical for the tactual and auditory modalities. In particular, they differed in the realm of discriminatory precision or sensitivity. Auditory discrimination was superior, yielding higher hit rates, lower false positive rates, and discrimination of smaller step sizes. These differences were observable in the height of the /sa/-/sta/ discrimination peak, and in the poorer overall tactual discrimination of the vowel continuum.

Factors responsible for better auditory than tactual perception may include superior auditory sensitivity, greater auditory experience in perception of speech sounds, and limitations in the designs of tactual vocoders in current use. While important differences between filter configurations have not been apparent with the stimuli studied in the present

experiments, it is possible that alternative filter designs may yield improved performance in coding some speech information. In particular, fundamental frequency has been shown to be difficult to transmit by other than log configurations (23). In addition, improved tactual performance may be dependent on developing more adequate coding schemes for intensity. At the present time, it is not possible to evaluate independently the contributions of auditory experience, auditory sensitivity, and adequacy of current vocoder design.

In summary, the experiments showed that speech perception through the skin is similar in important ways to perception through audition, and that the similarities occur with various spectral coding schemes employed in tactual vocoders. In the present experiments, this was true for two speech continua, one spectrally varying, and one temporally varying. This research, however, should not be construed to suggest that modifications of spectral characteristics of vocoders is unimportant; but rather, that additional research with additional speech contrasts is warranted. For example, it may be that log or average filter configurations or modifications of these configurations are necessary for successful formant tracking or fundamental frequency perception. These results do suggest that a variety of filter configurations may be useful and that tactual perception is relatively robust through a spectrally-oriented display. Regardless of filter configuration, labelling functions reflected phonologically appropriate parsing of two speech continua and appropriate peaks and valleys in discrimination functions. These data suggest that perception in both modalities is at least partially dependent on pattern recognition, though the details of the patterns can vary somewhat. As long as acoustic information can be adequately coded, it appears that it can be interpreted in similar ways by both auditory and tactual systems.

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REFERENCES

1. **Brooks PL, Frost BJ:** Evaluation of a tactile vocoder for word recognition. *J Acoust Soc Am* 74:34-39, 1983.
2. **Brooks PL, Frost BJ, Mason JL, Gibson DM:** Continuing evaluation of the Queen's University tactile vocoder. I: Identification of open set words. *J Rehabil Res Dev* 23(1):119-128, 1986.
3. **Brooks PL, Frost BJ, Mason JL, Gibson DM:** Continuing evaluation of the Queen's University tactile vocoder. II: Identification of open set sentences and tracking narrative. *J Rehabil Res Dev* 23(1):129-138, 1986.
4. **Bull D, Eilers RE, Oller D, Mandalia B:** The effect of frequency on discrimination of pulse bursts in an electrocutaneous tactual vocoder. *J Acoust Soc Am* 77:1192-1198, 1985.
5. **Buchsbaum G:** The possible role to the cochlear frequency-position map in auditory signal coding. *J Acoust Soc Am* 77:573-576, 1985.
6. **Craig JC:** Vibrotactile letter recognition: The effect of a masking stimulus. *Percept Psychophys* 20:317-326, 1976.
7. **Craig JC:** Vibrotactile masking: A comparison of energy and pattern maskers. *Percept Psychophys* 31:523-529, 1982.
8. **Eilers RE, Özdamar Ö, Oller DK, Miskiel E, Urbano R:** Similarities between tactual and auditory speech perception. *J Speech Hear Res* 31:124-131, 1988.
9. **Eilers RE, Widen J, Oller DK:** Assessment techniques to evaluate tactual aids for hearing-impaired subjects. *J Rehabil Res Dev* 25(2):33-46, 1988.
10. **Eldredge D, Miller J, Bohne BA:** A frequency-position map for the chinchilla cochlea. *J Acoust Soc Am* 69:1091-1095, 1981.
11. **Engelmann S, Rosov RJ:** Tactual hearing experiment with deaf and hearing subjects. *Except Child* 41:243-253, 1975.
12. **Gilson RD:** Vibrotactile masking: Effects of multiple maskers. *Percept Psychophys* 5:181-182, 1969.
13. **Gilson RD:** Vibrotactile masking: Some spatial and temporal aspects. *Percept Psychophys* 5:176-180, 1969.
14. **Greenwood D:** Critical bandwidth and the frequency coordinates of the basilar membrane. *J Acoust Soc Am* 33:1344-1356, 1961.
15. **Klatt D:** Software for a cascade/parallel formant synthesizer. *J Acoust Soc Am* 67:971-995, 1980.
16. **Levitt H:** Transformed up-down methods in psychoacoustics. *J Acoust Soc Am* 49:467-477, 1971.
17. **Liberman M:** The cochlear frequency map for the cat. Labelling auditory-nerve fibers of known characteristic frequency. *J Acoust Soc Am* 72:1441-1449, 1982.
18. **Lynch MP, Eilers RE, Oller DK, LaVoie L:** Speech perception by congenitally deaf subjects using an electrocutaneous vocoder. *J Rehabil Res Dev* 25(3):41-50, 1988.
19. **Lynch MP, Eilers RE, Oller DK, Cobo-Lewis A:** Multisensory speech perception by profoundly hearing-impaired children. *J Speech Hear Res* 54:57-67, 1989.
20. **Oller DK, Eilers RE, Vergara K, LaVoie E:** Tactual vocoders in a multisensory program training speech production and reception. *Volta Rev* 88:21-36, 1986.
21. **Oller DK, Eilers RE:** Tactual artificial hearing for the

deaf. In *Hearing Impairment in Children,* F. Bess (Ed.). Parkton, MD: York, 1988.

22. **Özdamar Ö, Eilers RE, Oller DK:** Tactile vocoders for the deaf. *IEEE Eng Med Biol Mag* 6(3):37-42, 1987.
23. **Özdamar Ö, Oller DK, Miskiel E, Eilers RE:** Computer system for quantitative evaluation of an electrocutaneous tactile vocoder. *Comp Biomed Res* 21:85-100, 1988.
24. **Rosner BS:** Neural factors limiting cutaneous spatio-temporal discriminations. In *Sensory Communication,* W. A. Rosenblith (Ed.). New York: John Wiley & Sons, 1961.
25. **Saunders F:** Wearable multichannel electrotactile sensory aids. Presented at the Second Tactual Communications Conference, Wichita, KS, 1985.
26. **Schmid E:** Temporal aspects of cutaneous interaction with two-point electrical stimulation. *J Exp Psychol* 61:400-409, 1961.
27. **Weisenberger JM, Miller JD:** The role of tactile aids in providing information about acoustic stimuli. *J Acoust Soc Am* 82:906-916, 1987.
28. **Weisenberger JM, Potts SM, Saunders FA:** Evaluation of two multichannel tactile aids for the deaf: Phoneme and syllable identification. *J Acoust Soc Am* (in press).