Frequency and amplitude discrimination along the kinesthetic-cutaneous continuum in the presence of masking stimuli[a]

Ali Israr[b] and Hong Z. Tan
Haptic Interface Research Laboratory, Purdue University, 465 Northwestern Avenue, West Lafayette, Indiana 47907

Charlotte M. Reed
Research Laboratory of Electronics, Room 36-751, 77 Massachusetts Avenue, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 14 January 2006; revised 27 May 2006; accepted 16 August 2006)

Frequency and amplitude discrimination thresholds along the kinesthetic to cutaneous continuum were evaluated on the left index fingerpad using a multifinger tactual display. Target stimuli were presented either in isolation (no-masker condition) or in the presence of masking stimuli (one- or two-masker conditions). Six reference target signals in the frequency range 2–300 Hz (two each from low-, medium-, and high-frequency regions) and at an amplitude of either 20 or 35 dB sensation levels (SL) were used. In the no-masker condition, the range of frequency Weber fraction was 0.13–0.38 and 0.14–0.28, and the range of amplitude discrimination threshold was 1.82–2.98 dB and 1.65–2.71 dB, at 20 and 35 dB SL, respectively. In the masking conditions, average frequency Weber fractions rose to 0.60 and 0.46, and average amplitude thresholds rose to 3.63 and 3.72 dB, at 20 and 35 dB SL, respectively. In general, thresholds were largest in the two-masker condition and lowest in the no-masker condition. Although the frequency and amplitude thresholds generally increased in the presence of masking stimuli, there was some indication of channel independence for low- and high-frequency target stimuli. The implications of the results for tactual communication of speech are discussed. *© 2006 Acoustical Society of America.*
[DOI: 10.1121/1.2354022]

PACS number(s): 43.66.Fe, 43.66.Gf, 43.66.Dc, 43.66.Ts, 43.66.Wv [RAL] Pages: 2789–2800

I. INTRODUCTION

The present study is motivated by issues related to the development of artificial aids designed for the communication of acoustic signals through the sense of touch for persons with profound hearing impairment. A multifinger tactual display capable of simultaneously stimulating the thumb, index, and middle fingers, the TACTUATOR, has been developed recently to broaden the spectrum of tactual stimulation from the tactile/cutaneous region (small-amplitude high-frequency vibrations) that is commonly used by most artificial tactile aids to the kinesthetic region (large-amplitude low-frequency movements) (Tan and Rabinowitz, 1996). The idea of presenting movement signals in addition to vibrations in a tactual communication aid was inspired by a means of natural tactual speech communication called the Tadoma method where a deaf-and-blind receiver places one hand or both hands on the face of a talker and monitors the tactual signals (e.g., laryngeal vibration, mouth opening, lip movements, air flow at the lips, etc.) associated with the articulatory process (Reed *et al.*, 1985). One hypothesis for the success of the Tadoma method is that Tadoma users have access to a rich set of signals including both cutaneous and kinesthetic stimulation. The TACTUATOR is uniquely suited for evaluating such a hypothesis because unlike other tactual displays (such as a minishaker) that can generate signals at very low frequencies but can only do so at near-threshold intensity levels, the TACTUATOR is capable of delivering slow motions at a peak-to-peak displacement of up to 25 mm.

Previous research conducted with the TACTUATOR shows high-information transmission capability with stimulus sets composed of kinesthetic movements, cutaneous vibrations, signals with intermediate frequencies, and their combinations. For example, a static information transfer (IT) of 6.5 bits and a dynamic IT rate of 12 bits/sec were achieved in one study (Tan *et al.*, 1999) and an IT rate of 21.9 bits/sec was reported in another (Tan *et al.*, 2003). These static IT and dynamic IT rates are among the highest reported for any artificial tactual display and are comparable to those of the natural Tadoma method used by deaf-and-blind individuals for speech communication (Reed and Durlach, 1998).

A subsequent study using the TACTUATOR evaluated temporal onset-order discrimination with a 50-Hz sinusoidal signal delivered to the thumb and a 250-Hz sinusoidal vibration to the index finger (Yuan, Reed, and Durlach, 2005a). The average temporal onset-order threshold was found to be 34 msec. The same authors then used amplitude envelope information from two spectral regions of speech to transmit consonant voicing information through the TACTUATOR (Yuan, Reed, and Durlach, 2005b). The amplitude envelope of the high-frequency band was used to modulate a 250-Hz vibration at the index finger and the amplitude envelope of

---

[a] A preliminary version of this work was presented as a poster at the *International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Alexandria, VA, March 25–26, 2006.

[b] Electronic mail: israr@purdue.edu

the low-frequency band was used to modulate a 50-Hz vibration at the thumb. Results indicated that noise-masked normal-hearing subjects were highly successful in discriminating voiced from unvoiced sounds at the segmental level and that the display provided a substantial benefit to lipreading alone in closed-set consonant identification tasks. Results of sentence recognition tasks, however, revealed that the tactual cues were not beneficial for lip reading. This lack of benefit may have reflected the user's inability to integrate tactual and visual cues and therefore may have been the result of insufficient training.

Recently, a 2-DOF (degree of freedom) controller has been developed for the TACTUATOR that preserves the relative intensities of the spectral components of input waveforms in terms of perceived intensity (Israr, Meckl, and Tan, 2004). Consider the case where the input signal to the TACTUATOR contains two spectral components at 50 and 250 Hz at equal voltage levels. The 2-DOF controller compensates for both the frequency response of the TACTUATOR hardware and the difference in human detection threshold at the respective frequencies such that the two signal components are perceived at roughly the same sensation levels (SL). With this controller, a low-pass filtered broadband acoustical speech signal can be directly applied as the input to the TACTUATOR to transmit, for example, pitch information. The use of such an encoding scheme for speech obviously requires that the user be able to discern variations in frequency and/or amplitude in the presence of other masking signals occurring before, after, or simultaneously with the target. In order for speech signals to be transmitted successfully through the TACTUATOR, it is important to characterize frequency and amplitude discrimination thresholds associated with the use of the TACTUATOR in the presence of masking stimuli delivered to the same or neighboring digits of the hand.

Previous studies have examined frequency and amplitude discrimination thresholds through the tactual sense. Frequency discrimination thresholds, typically expressed in the form of Weber fractions (WFs), computed as $(\Delta F)_0/F_{\mathrm{ref}}$ where $(\Delta F)_0$ is the frequency discrimination threshold in hertz and F_{ref} the reference frequency, have been found to be in the range 0.02 to 0.72 on fingertips, forearm, thenar eminence, and sternum using sinusoidal or pulselike waveforms over a frequency range of 1 to 512 Hz and an amplitude range of 14 to 35 dB SL (Franzen and Nordmark, 1975; Globe and Hollins, 1994; Goff, 1967; Horch, 1991; Knudsen, 1928; LaMotte and Mountcastle, 1975; Rinker, Craig, and Bernstein, 1998; Rothenberg *et al.*, 1977). Variability in the size of frequency WFs across studies has been attributed to differences in experimental conditions, methodology, and stimulus artifacts (Bensmaia *et al.*, 2005; Hnath-Chisolm and Medwetsky, 1988; Rothenberg *et al.* 1977; Verrillo and Gescheider, 1992).

Amplitude discrimination thresholds are typically expressed in decibels in amplitude change. Previous studies of just-noticeable-differences (JNDs) in intensity for tactile stimulation have employed a variety of experimental methods (continuous versus gated methods, pulses versus pure sinusoids, forced-choice method versus method of adjustment, method of limits versus adaptive procedures) using stimuli that varied in frequency, amplitude, body site, and contact area. Amplitude-discrimination thresholds in $(\Delta A)_0$ have been reported in the range of roughly 0.4 to 6 dB; for example, 0.8 dB (Geldard, 1957), 1.5–2.5 dB (Craig, 1972), 1.5–6 dB (Craig, 1974), 0.4–2 dB (Fucci, Small, and Petrosino, 1982), 0.5–4 dB (Gescheider *et al.*, 1990), 0.8–5 dB (Gescheider, Zwislocki, and Rasmussen, 1996), 0.8–3 dB (Globe and Hollins, 1993), and 0.8–1.5 dB (Rinker *et al.*, 1998). Despite differences in experimental conditions, it is generally agreed that amplitude-discrimination thresholds tend to decrease with an increase in stimulus intensity when the intensity is close to detection threshold, and then stay constant when stimulus intensity is above 14 to 20 dB SL (see, for example, Craig, 1972; Craig, 1974; Gescheider *et al.*, 1990).

Despite all existing data, there have been relatively few studies concerned with the masking properties of kinesthetic signals on vibrations and vice versa, presumably because, until very recently, no displays existed that could deliver signals over a wide range of frequencies that spanned the kinesthetic-cutaneous continuum.[1] The TACTUATOR provides a unique opportunity for studying frequency and amplitude discrimination thresholds using both kinesthetic and cutaneous signals in the presence of masking stimuli. In an earlier study, experiments were conducted to examine the temporal masking properties for recognition of tactual stimulation patterns using forward masking, backward masking, and sandwiched masking (in which the target was presented between two maskers) paradigms (Tan *et al.*, 2003). In the present study, frequency and amplitude discrimination experiments were performed in the presence of masking stimuli that occurred *simultaneously* with the target. The results from the present and previous studies will shed light on the design of multidimensional tactual signals for speech communication.

II. METHODS

A. Apparatus

The experimental apparatus (the TACTUATORII[2]) consists of three independent, point-contact (with a contact area of approximately 70 mm^2), one-degree-of-freedom actuators interfaced individually with the fingerpads of the thumb, the index finger, and the middle finger [Fig. 1(a)]. The motion trajectory for the thumb is perpendicular to that of the index and middle fingers, thereby maintaining an approximately natural hand configuration with the wrist resting in its neutral position. The range of motion for each digit is about 25 mm. All motions begin and end with each of the three digits at the middle of its respective range of motion. Each digit can thus be moved either outward (extension) or inward (flexion).

Each actuator utilizes a disk-drive head-positioning motor augmented with angular position feedback from a precision rotary variable differential transformer that has a response bandwidth (−3 dB) of 1 kHz and a theoretically unlimited resolution[3] due to electromagnetic coupling [Fig. 1(b)]. The overall system performance is well suited for the present study for several reasons. First, each movement channel has a *continuous* frequency response from dc to 300 Hz (the disk-drive motor ceases to move beyond about

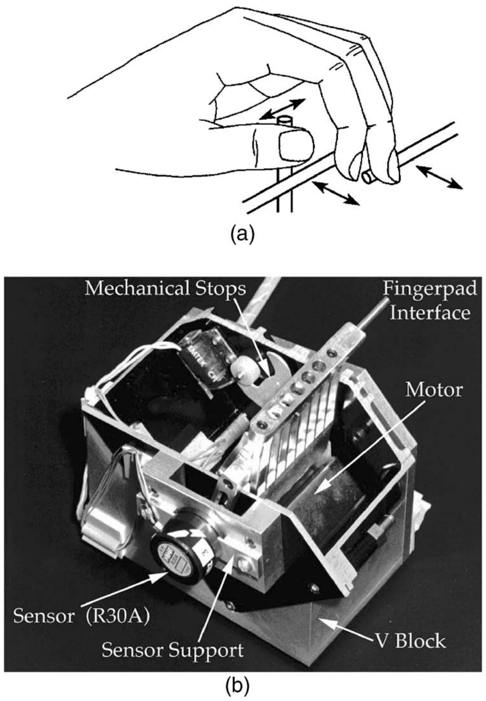


FIG. 1. The TACTUATOR. (a) Schematic drawing illustrating finger placement on the TACTUATOR and the motion trajectories of the thumb, index, and middle fingers. (b) Photograph of one of the three motor assemblies with its components labeled. The participant rests the fingerpad on the rod labeled “finger interface” in (b).

400 Hz). Therefore, stimulation can be delivered in the kinesthetic (i.e., low-frequency gross motion) and cutaneous (i.e., high-frequency vibration) ranges as well as in the mid-frequency range. Stimuli with any desired spectral components can be realized within the frequency range of dc to 300 Hz. Second, across the frequency range of dc to 300 Hz, amplitude of 0 dB SL to at least 47 dB SL can be achieved at each frequency.[4] This stimulus range is well matched to the dynamic range of tactual perception in that stimulation levels exceeding 50–55 dB SL tend to induce discomfort and fatigue (Verrillo and Gescheider, 1992). Third, measurements with single and multiple frequency inputs at various amplitude levels indicate that each channel is highly linear, harmonic distortion is low, and interchannel crosstalk is small. These characteristics permit high-fidelity delivery of waveforms of arbitrary frequency content and stimulation level (e.g., a 20 dB SL high-frequency vibration superimposed on a 35 dB SL low-frequency motion) simultaneously to all fingers. Fourth, “loading” a movement channel (i.e., resting a finger lightly on the actuator’s moving bar) does not significantly alter the intended stimuli. Selected measurements indicate that loading reduces the magnitude of stimulation by an average of 1.5 dB at 2 Hz, 2.7 dB at 20 Hz, and 0.1 dB at 200 Hz. These minor alterations due to loading do not pose a significant problem for the experiments reported here because the stimuli are generally strong (i.e., at least 20 dB SL).

Real-time positional control is provided by a digital 2-DOF controller implemented on a floating-point digital signal processing (DSP) system with 16-bit analog-to-digital and digital-to-analog converters. The controller shapes the frequency response of the closed-loop TACTUATORII assembly to that of the human detection-threshold function, thus preserving the relative amplitude of spectral components in terms of their perceived intensity by human observers. The current system can therefore be driven with a broadband signal (up to 300 Hz) while preserving the relative intensity of different spectral components in terms of the relative sensation levels delivered by the TACTUATORII (Israr *et al.*, 2004). The nominal threshold function values for six target frequencies are shown in Table I (see last column). These thresholds are averages of measurements obtained by Israr *et al.* (2004) on three experienced observers.

B. Participants

Four participants (2 females and 2 males; age 21 to 28 years old; average age 24 years old) took part in the experiments. *S*1 was highly experienced with the TACTUATORII device. *S*2 and *S*4 had not felt the device prior to the present study. *S*1 and *S*3 were research staff and had previous experience in other haptic perception experiments. *S*2 and *S*4, who had no prior experience with psychophysical experiments, were paid on an hourly basis. None of the participants reported any known tactual impairments of their hands.

C. Stimuli

The present study employed a stimulus set applied only to the left index finger. The duration of each stimulus was fixed at 250 msec throughout the experiments. The independent stimulus attributes were frequency and amplitude of sinusoidal signals. The entire frequency range of the TACTUATORII (0–300 Hz) was divided into three regions (low, medium, and high) as in previous studies with the TACTUATOR device (Tan *et al.*, 1999; Tan *et al.*, 2003). Two target frequencies were tested in each frequency region at two amplitudes of 20 and 35 dB SL (sensation level; decibels above nominal detection threshold at the same frequency). A 250-ms Hanning window (with 25-ms rise and fall time) was used so that each stimulus began and ended in the middle of the finger’s range of motion. All stimuli started in the finger extension direction. A complete list of the test stimuli is provided in Table I. Also shown are the nominal detection threshold levels measured from three participants (one of whom was *S*1) in our previous study (Israr *et al.*, 2004) from which signal amplitudes in decibels SL are derived for the present study. The sensation levels reported in Table I are

TABLE I. Listing of stimuli used in the frequency and amplitude discrimination experiments.

Frequency Region	Frequency (Hz)	Amplitude (dB SL)	Nominal Detection Threshold (dB re 1 μm peak)
Low	2	20 & 35	38
	4	20 & 35	34
Medium	15	20 & 35	25
	30	20 & 35	16
High	80	20 & 35	−8
	200	20 & 35	−18

nominal and representative, but not individualized for each participant (see the Appendix).

Different perceptual attributes are associated with the stimuli within each region. The 2- and 4-Hz low-frequency signals are perceived as movements that extend the index finger and bring it back to its resting position. The 15- and 30-Hz mid-frequency signals give rise to a mixed flutter/rough sensation. The 80- and 200-Hz high-frequency signals are perceived as smooth and penetrating vibrations. Within each of the three frequency regions, the two test stimuli can be easily discriminated in isolation.

1. Stimuli for Frequency Discrimination

For frequency discrimination, the participant was presented with either the *reference* frequency F_{ref}, or the *test* frequency $F_{\text{ref}}+\Delta F$, where ΔF was a variable frequency increment. Each F_{ref} was presented with either $A_1=20$ dB SL or $A_2=35$ dB SL. During an experimental run, the same amplitude (in sensation level) was used for F_{ref} and $F_{\text{ref}}+\Delta F$. The *target* stimuli (F_{ref} or $F_{\text{ref}}+\Delta F$) were presented either in isolation (no-masker condition $C1$) or in the presence of a *masker* that occurred simultaneously with the target (one-masker conditions $C2$ and $C3$, and two-masker condition $C4$). $C1$ served as a baseline condition against which the effect of masking stimuli could be measured. For $C2$, a single masker was selected from the lower one of the two frequency regions of which F_{ref} was not a member. For $C3$, a single masker was selected from the other (i.e., higher) frequency region that did not include F_{ref}. For example, if $F_{\text{ref}}=2$ Hz, then the masker in $C2$ was selected from the mid-frequency region, and the masker in $C3$ from the high-frequency region. For $C4$, two maskers were selected, one from each of the two frequency regions that did not include the target F_{ref}. In any of the masking conditions ($C2-C4$), the frequency of the masker was selected randomly from ten values linearly spaced between the two frequency values listed for that frequency region as shown in Table I. For example, the frequency of a masker in the mid-frequency region assumed values in the range of 15 to 30 Hz. The amplitude of the masker was also selected at random on each trial. In order that the intensity of the masker did not overwhelm the perception of the target signal, the masker amplitude for a target presented at $A_1=20$ dB SL was randomly selected from ten levels linearly spaced between 10 and 20 dB SL. The masker amplitude for a target presented at $A_2=35$ dB SL was randomly selected from ten levels between 20 and 35 dB SL. For any of the masking conditions, the masker frequency and amplitude were randomly selected on each presentation.

2. Stimuli for Amplitude Discrimination

The stimuli for amplitude discrimination were very similar to those used in frequency discrimination. The participant was presented with either the *reference* amplitude A_{ref}, or the *test* amplitude $A_{\text{ref}}+\Delta A$, where ΔA was a variable amplitude increment. During an experimental run, the same frequency was used for A_{ref} and $A_{\text{ref}}+\Delta A$. Two values of A_{ref} were tested: 20 and 35 dB SL. Six values of frequency were employed in the amplitude-discrimination tests consisting of two values from each of the three frequency regions as listed in Table I. As described above for the frequency discrimination experiment, the target stimuli were presented either in isolation ($C1$) or in the presence of masking stimuli ($C2-C4$). The amplitude-discrimination experiments also employed randomized values of masker frequency and amplitude on each presentation using the procedure described above for the frequency-discrimination experiments.

D. Procedures

The same experimental procedure was used in both the frequency and amplitude discrimination experiments. A three-interval forced-choice (3IFC) paradigm with a one-up three-down adaptive procedure (Leek, 2001; Levitt, 1971) was used. On each trial, the participant received three stimulus presentations. One randomly selected interval contained the test stimulus ($F_{\text{ref}}+\Delta F$ or $A_{\text{ref}}+\Delta A$) while the remaining two intervals contained the reference stimulus (F_{ref} or A_{ref}). During the masking conditions ($C2-C4$), the frequency and amplitude of the masker were randomly selected for each of the three intervals. The participant's task was to indicate the "odd" interval that contained $F_{\text{ref}}+\Delta F$ or $A_{\text{ref}}+\Delta A$ by pressing "1", "2", or "3" on the keyboard. The initial value of ΔF or ΔA was selected to be sufficiently above the expected discrimination threshold. The value of ΔF (or ΔA) changed by 2/3 octave (or 4 dB) initially (for faster convergence), and then by 1/6 octave (or 1 dB) after the first three reversals (for better resolution of threshold estimate). The experimental run terminated after 12 reversals at the smaller step size, which typically took 60–80 trials. After each experimental run, a plot of ΔF or ΔA as a function of trial number was generated. If it appeared that the stimulus frequency (or amplitude) did not converge, the participant was asked to repeat the same run again. Each run lasted about 4–6 min. Participants typically completed four experimental runs (one reference stimulus with all four conditions $C1-C4$) in one session.

For frequency discrimination, there were 12 possible reference signals (3 frequency regions × 2 frequencies per region × 2 amplitudes per frequency). The order of the reference signals was randomized for each participant. Given each reference signal, however, the four conditions $C1-C4$ were always tested in the same order as follows. The no-masker condition $C1$ was tested first, followed by either one of the one-masker conditions $C2$ or $C3$ (randomly chosen for each reference stimulus), then the remaining $C2$ or $C3$ that had not been tested yet, and finally the two-masker condition $C4$. Participants were required to complete all four conditions associated with one reference stimulus in one session. Assuming that a typical adaptive run terminated after 70 trials, each participant completed a total of 3360 trials (12 references × 4 conditions per reference × 70 trials per condition) for the frequency discrimination experiment. For amplitude discrimination, there were also 12 possible reference signals. Again, the order with which the reference signals were presented was randomized, and participants always went through $C1-C4$ in the same order for each reference

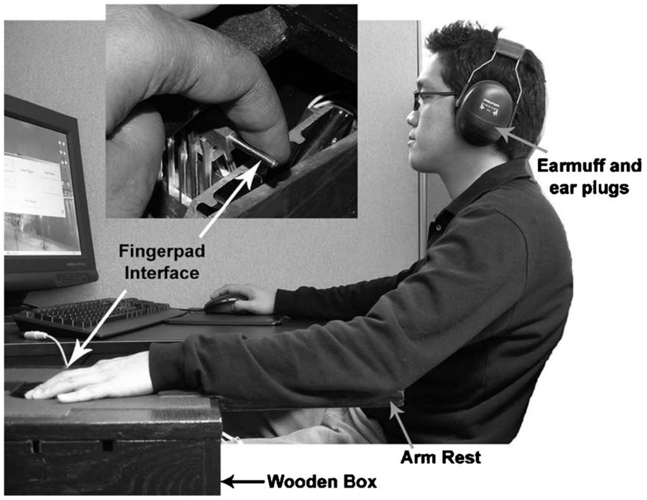


FIG. 2. Experimental setup. The apparatus was placed to the left of the participant's torso in a wooden box. The participant sat in front of the computer screen and placed the left index finger on the finger rest of the TACTUATORII as shown in the inset. The left elbow was supported by the arm rest. The participant wore earmuffs and ear plugs.

signal as in the frequency discrimination experiment.[5] Data were collected on a total of 48 conditions in both the frequency and the amplitude discrimination experiments. Thus, each participant completed a total of 96 experimental runs which required roughly 6,720 trials.

During the experiments, the TACTUATORII was placed to the left of the participant's torso as shown in Fig. 2. It was covered by a padded wooden box that served as an armrest for the participant's left forearm. The top of the box had an opening that allowed the participant to place the left index finger on the "fingerpad interface" rod as shown in Figs. 1(b) and 2. Earmuff (Twin-Cup type, H10A, NRR 29, Peltor, Sweden) and pink noise (presented at roughly 80 dB SPL) were used to eliminate possible auditory cues. No correct-answer feedback was provided during the experiments.

Training was provided before each run. During training, the participant could click on the appropriate buttons on a computer screen to feel the reference (F_{ref} or A_{ref}) or the test stimulus ($F_{\mathrm{ref}}+\Delta F$ or $A_{\mathrm{ref}}+\Delta A$). For the masking conditions $C2-C4$, the participant could either feel the target stimulus (reference or test signal) in isolation or in the presence of a masker (as would be the case during the actual experiment). The participant could terminate the training whenever she/he was ready. Training typically lasted only a few minutes. Data collection followed immediately after the training.

E. Data analysis

From the six pairs of peaks and valleys of stimulus intensities (ΔF or ΔA) obtained during the last 12 reversals at the smaller step size, six estimates of thresholds were obtained by averaging each peak-valley pair. The frequency and amplitude detection thresholds, $(\Delta F)_0$ in hertz and $(\Delta A)_0$ in decibels, respectively, were then estimated by averaging the six threshold estimates. The corresponding standard errors were also obtained from the six threshold estimates. The threshold so obtained corresponds to the 79.4-percentile point on the psychometric function (Levitt, 1971), and a d' value of 1.63 assuming no response bias (Hacker and Ratcliff, 1979).

III. RESULTS

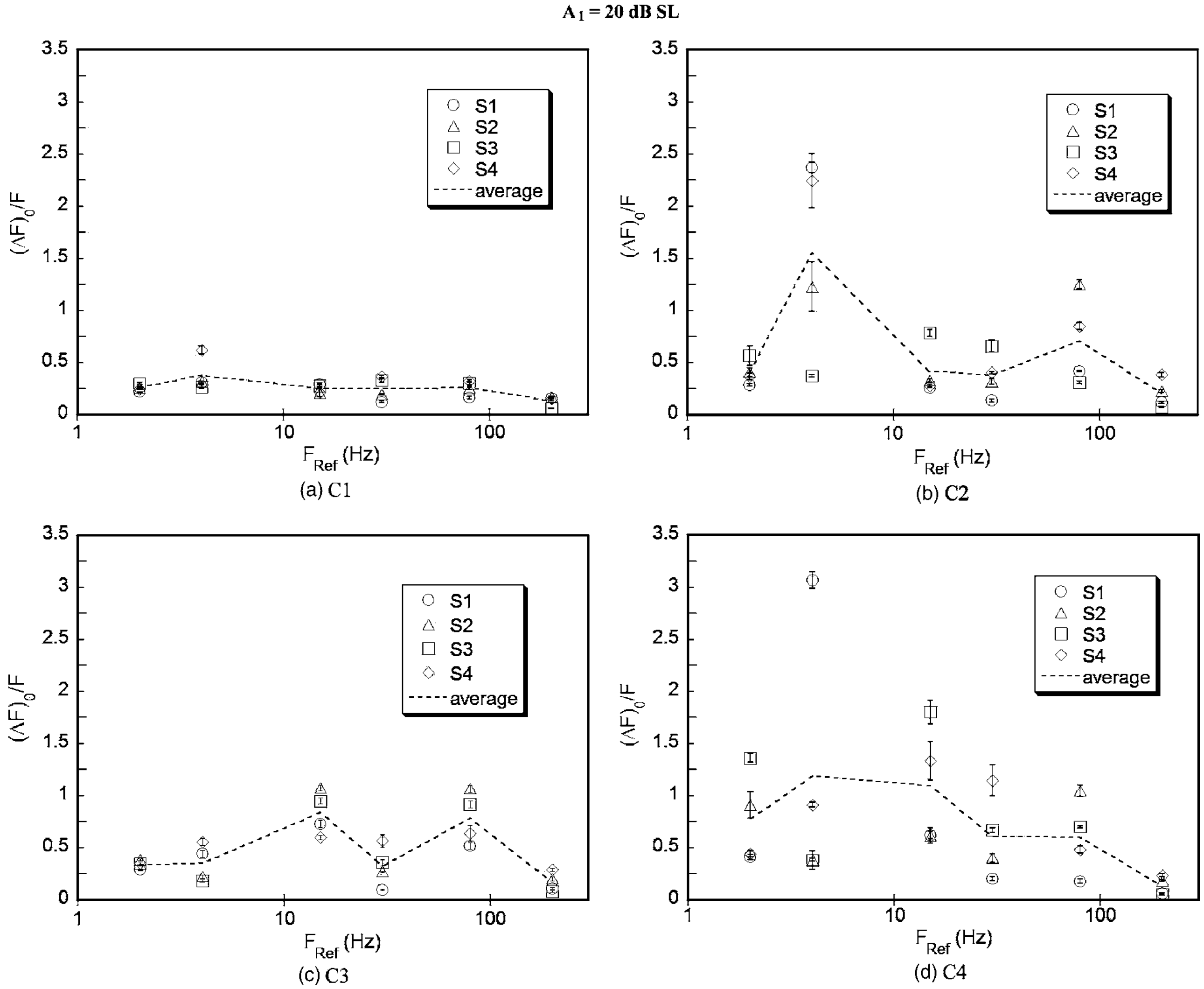
A. Frequency discrimination thresholds

Under the no-masker baseline condition ($C1$), the frequency discrimination threshold, $(\Delta F)_0$ in hertz, increased with the reference frequency F_{ref}. The linear regression model was $(\Delta F)_0=0.13\cdot F_{\mathrm{ref}}+2.7$ ($r^2=0.7142$) at 20 dB SL, and $(\Delta F)_0=0.15\cdot F_{\mathrm{ref}}+0.7$ ($r^2=0.8415$) at 35 dB SL. The average Weber fractions, $\mathrm{WF}=(\Delta F)_0/F_{\mathrm{ref}}$, are shown for each condition (in four separate panels) in Fig. 3 for 20 dB SL and in Fig. 4 for 35 dB SL. A visual inspection of both Figs. 3 and 4 revealed large interparticipant differences (particularly for the three masking conditions $C2-C4$), confirmed by a four-way (participant, frequency, amplitude, condition) analysis-of-variance (ANOVA) ($p<0.0001$). The Scheffe *post hoc* multirange test indicated two participant groups: $S1$ and $S3$ (experienced, with lower thresholds), and $S2$ and $S4$ (inexperienced, with higher thresholds). Despite the significant differences among participants, however, all participants' data displayed similar trends along frequency, amplitude, and masking conditions. Therefore, we discuss the general trends demonstrated by the pooled data and point out individual exceptions when they are significant.

The frequency WFs from the no-masker condition [$C1$; see Figs. 3(a) and 4(a)] averaged 0.25 and 0.18 at 20 and 35 dB SL, respectively. A two-way (amplitude, frequency) ANOVA showed that both frequency and amplitude were significant ($p<0.001$). Specifically, the WFs were significantly lower at 35 dB SL than at 20 dB SL, and they generally decreased as F_{ref} increased. The interaction term was also significant ($p<0.001$) indicating mixed trends along frequency and amplitude. For low-frequency targets ($F_{\mathrm{ref}}=2$ and 4 Hz), the WFs were significantly lower at 35 dB SL than at 20 dB SL. For targets at $F_{\mathrm{ref}}=200$ Hz, however, the opposite trend was observed. The trends were mixed for targets at $F_{\mathrm{ref}}=15$, 30, and 80 Hz.

When frequency WFs from all conditions ($C1-C4$; see Figs. 3 and 4) were considered, it was found that the average WF at 35 dB SL (mean = 0.39) was significantly lower than that at 20 dB SL (mean = 0.52) by a four-way (participant, frequency, amplitude, condition) ANOVA ($p<0.001$). As expected, the WFs for the no-masker condition ($C1$) were no greater than those for the one-masker conditions ($C2$ or $C3$), which in turn were no greater than those for the two-masker condition ($C4$), as confirmed by the four-way ANOVA ($p<0.001$). The average WFs decreased significantly in the order $C4$, $C2$, $C3$, and $C1$ (average WFs were 0.70, 0.49, 0.40, and 0.22, respectively). All the interaction terms of the four-way ANOVA were significant ($p<0.001$) implying mixed trends along frequency, amplitude, and masking conditions.

To visualize the masking effects ($C2-C4$), the average frequency WFs for $C1$ were subtracted from the corresponding WFs for $C2-C4$. The differences are shown in Fig. 5 for stimuli presented at (a) 20 dB SL and (b) 35 dB SL, respec-



(a) C1 (b) C2 (c) C3 (d) C4

FIG. 3. Frequency discrimination Weber fractions $(\Delta F)_0/F_{\mathrm{ref}}$ for the four participants as a function of reference frequency F_{ref} at 20 dB SL. Panel (a) shows the thresholds in the no-masker condition C1. Panels (b), (c), and (d) show thresholds for the one- and two-masker conditions C2, C3, and C4, respectively. Shown are individual participant's data (open symbols), the average (dashed lines), and standard errors.

tively. An asterisk indicates that the corresponding data column is significantly different from 0 ($p < 0.05$). A four-way ANOVA analysis (participant, frequency, amplitude, condition) applied to the data in Fig. 5 showed that there were more masking effects at 20 dB SL than at 35 dB SL ($p < 0.001$). All interaction terms were again significant ($p < 0.001$). The WFs for low-frequency targets ($F_{\mathrm{ref}}=2$ and 4 Hz) increased in the presence of mid-frequency maskers ($C2-C1$), but the WFs for mid-frequency targets ($F_{\mathrm{ref}}=15$ and 30 Hz) were generally not affected by low-frequency maskers ($C2-C1$). The WFs for low-frequency targets were not affected by high-frequency maskers ($C3-C1$), yet the WFs for high-frequency targets ($F_{\mathrm{ref}}=80$ and 200 Hz) were affected by low-frequency maskers ($C2-C1$). The interference between mid-frequency and high-frequency targets/maskers appeared to depend on both frequency and amplitude.

B. Amplitude discrimination thresholds

The average amplitude thresholds $(\Delta A)_0$ in dB are plotted against reference frequency (F_{ref}) for all four masking conditions ($C1-C4$) in Fig. 6 for 20 dB SL and Fig. 7 for 35 dB SL. Each of the four panels presents amplitude thresholds for one of the four conditions. Similar to the results of frequency discrimination experiments, interparticipant variability was observed in these results. A four-way ANOVA (participant, frequency, amplitude, condition) confirmed a significant interparticipant difference ($p < 0.0001$). A Scheffe *post hoc* multirange test indicated that lower thresholds were obtained for participants $S1$ and $S3$ (experienced), and higher thresholds were obtained for participants $S2$ and $S4$ (inexperienced). Despite the significant differences among participants, however, all participants displayed similar trends along frequency, amplitude, and background conditions. Therefore, we discuss the general trends demonstrated by the pooled data and point out individual exceptions when they are significant.

The amplitude discrimination thresholds in the no-masker condition [$C1$; see Figs. 6(a) and 7(a)] averaged 2.5 dB and 2.17 dB at 20 and 35 dB SL, respectively. A two-way ANOVA (frequency, amplitude) of the data showed that both frequency and amplitude were significant (p

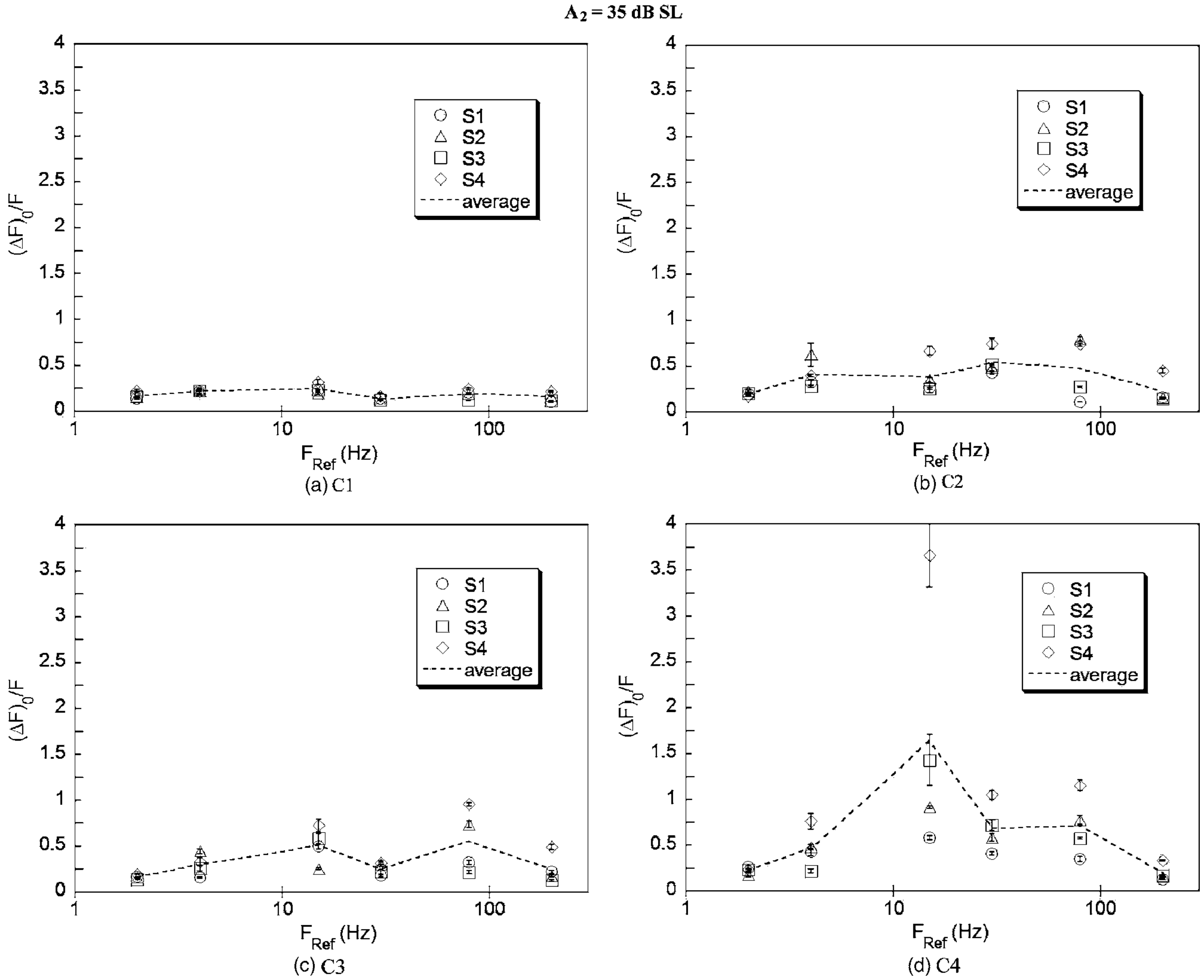


FIG. 4. Frequency discrimination Weber fractions $(\Delta F)_0/F_{\text{ref}}$ for the four participants as a function of reference frequency F_{ref} at 35 dB SL. Panel (a) shows the thresholds in the no-masker condition C1. Panels (b), (c), and (d) show thresholds for the one- and two-masker conditions C2, C3, and C4, respectively. Shown are individual participant's data (open symbols), the average (dashed lines), and standard errors.

< 0.001). The interaction term was also significant ($p < 0.001$) indicating mixed trends along frequency and amplitude. Unlike frequency discrimination data that exhibited a scattered pattern, an orderly transition of amplitude discrimination thresholds from low- to high-frequency regions was observed at both amplitude levels [see Figs. 6(a) and 7(a)]. A Scheffe multirange test at the two amplitudes (20 and 35 dB SL) separated the target frequencies into two groups. The thresholds for the low-to-mid-frequency group ($F_{\text{ref}}=2$, 4, and 15 Hz) were found to be significantly higher than those for the mid-to-high-frequency group ($F_{\text{ref}}=30$, 80, and 200 Hz) at 20 dB SL, and the opposite was true at 35 dB SL. The analysis also showed that the thresholds for the low-to-mid-frequency group were significantly lower at 35 dB SL than at 20 dB SL, but the thresholds for the mid-to-high-frequency group were similar at the two amplitude levels.

Unlike the results obtained in the frequency discrimination experiments, the average amplitude discrimination thresholds (see Figs. 6 and 7) were not significantly different at the two amplitude levels, as indicated by a four-way (participant, frequency, amplitude, condition) ANOVA ($p > 0.05$). Similar to the frequency discrimination thresholds, masking stimuli had a significant effect on amplitude discrimination ($p < 0.001$). The average amplitude discrimination threshold was significantly different in all test conditions ($C1-C4$) and differed in the same order as in the frequency discrimination experiment (4.08 dB for $C4$, 3.60 dB for $C2$, 3.35 dB for $C3$, and 2.33 dB for $C1$). As expected, the amplitude thresholds for the no-masker condition ($C1$) never exceeded those for the one-masker condition ($C2$ or $C3$), which in turn were smaller than those for the two-masker condition ($C4$).

Changes in the amplitude discrimination thresholds due to masking are shown in Fig. 8. The average $(\Delta A)_0$ for $C1$ is subtracted from those for $C2-C4$ at the same reference frequency and the differences are plotted as bar graphs. The statistical significance ($p < 0.05$) of the difference in $(\Delta A)_0$ is indicated by an asterisk. The masking effects were slightly more pronounced at 35 dB SL than at 20 dB SL ($p < 0.01$). For both the low-frequency targets ($F_{\text{ref}}=2$ and 4 Hz) and the mid-frequency targets ($F_{\text{ref}}=15$ and 30 Hz), the effect of high-frequency maskers ($C3-C1$) was generally smaller than that in the other one-masker conditions ($C2-C1$). For

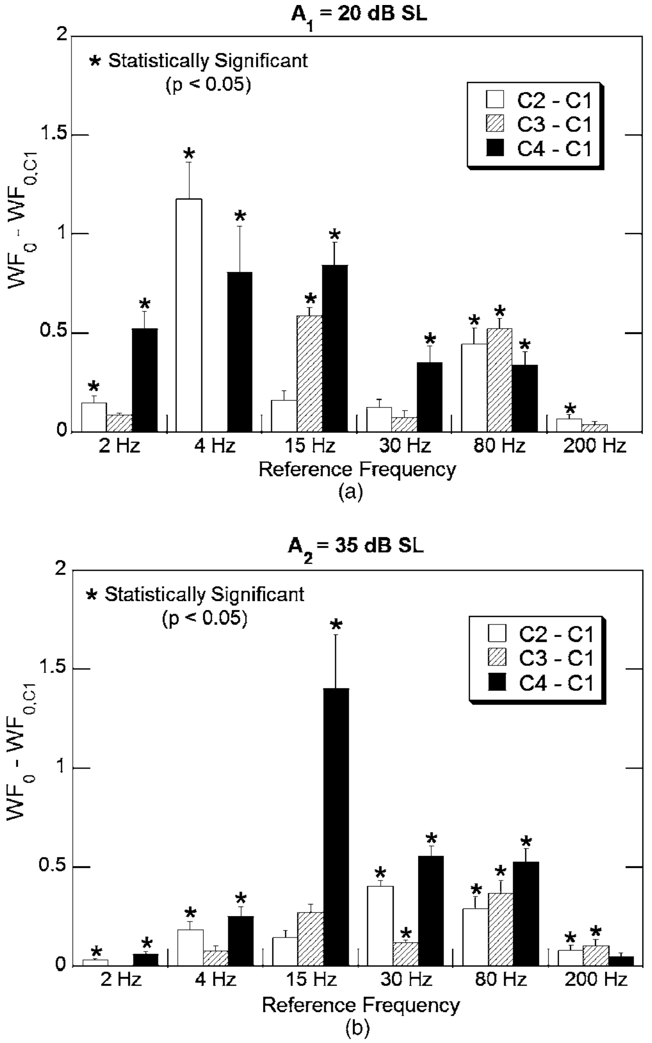


FIG. 5. Increase in frequency Weber fractions under the one- and two-masker conditions (C2–C4) for stimuli presented at (a) 20 dB SL and (b) 35 dB SL. WF_0 is the Weber fraction for the one- and two-masker conditions (C2–C4) and $WF_{0,C1}$ is the Weber fraction for the no-masker condition (C1). Differences are shown in a bar graph for each reference frequency. An asterisk indicates statistical significance ($p < 0.05$). Also shown are the standard errors.

the high-frequency targets ($F_{\text{ref}} = 80$ and 200 Hz), all the masking conditions affected the amplitude thresholds except for the 200-Hz targets at 20 dB SL for which the one-masker conditions ($C2-C1$ and $C3-C1$) did not significantly increase the amplitude threshold.

IV. DISCUSSION

The present study measured frequency and amplitude discrimination thresholds in the absence and presence of masking stimuli over a wide range of frequencies. In this section, we first compare our results from the no-masker condition to those in the literature, and then summarize the general effects of masking on frequency and amplitude discrimination thresholds. We also discuss the implications of our results in the context of tactile speech communication.

The frequency WFs in the no-masker condition (0.13–0.38 and 0.14–0.28 at 20 and 35 dB SL, respectively) are comparable to those reported by Goff (1967) (0.20–0.55 and 0.18–0.38 at 20 and 35 dB SL, respectively) and Rothenberg *et al.* (1977) (0.15–0.30 at 14 dB SL). The current data, however, do not show an increasing trend in WF with frequency as was apparent in the data of Goff (1967) and Rothenberg *et al.* (1977), although Rothenberg *et al.* (1977) did comment that some of their participants achieved very low WFs at high frequencies (0.05 and 0.03 at 150 and 200 Hz, respectively). As far as signal amplitude is concerned, the frequency WFs from the present study generally confirm the expected trend that WFs decrease with an increase in signal amplitude, presumably due to an increased signal-to-noise ratio in afferent signals at higher signal amplitudes (see Goff, 1967; LaMotte and Mountcastle, 1975). The one exception from the present study was that the frequency WFs for 200 -Hz targets were significantly lower at 20 dB SL than at 35 dB SL. According to the psychophysical model proposed by Bolanowski Jr., *et al.* (1988); Gescheider *et al.*, (2002); and Gescheider, Bolanowski, and Verrillo (2004), only the P channels respond to 200-Hz targets at 20 dB SL, and both the P and NP II channels are sensitive to 200-Hz targets at 35 dB SL. Our results at 200 Hz are consistent with previous studies that reported better tactual performance with high-frequency targets at intensities that activated only the P channels (Bensmaia *et al.*, 2005; Horch, 1991; Summers *et al.*, 1997). It is therefore possible that the activation of the NP II channels at 35 dB SL can somehow elevate frequency discrimination thresholds, although an explanation for such a phenomenon has yet to be discovered (although see Bensmaia *et al.*, 2005; Bensmaia and Hollins, 2000; Summers *et al.*, 1997; Verrillo and Gescheider, 1992).

The amplitude-discrimination thresholds obtained from the no-masker condition of the present study are similar to those reported in previous studies and vary with reference frequency and amplitude. The trend exhibited by the data depended on whether the target frequency was in the low-to-medium (2, 4, and 15 Hz) or medium-to-high (30, 80, and 200 Hz) regions. The amplitude discrimination thresholds in the lower frequency region were significantly higher at 20 dB SL than at 35 dB SL. This is consistent with the trend reported by Rinker *et al.* (1998) in that amplitude discrimination thresholds of 1-Hz waveforms decreased from roughly 1.3 to 0.8 dB as the waveform amplitude increased from 6.3 to 19.2 mm (a change of approximately 10 dB). The amplitude discrimination thresholds in the higher-frequency region did not change with amplitude in the present study. Several earlier studies have also reported that amplitude discrimination thresholds remained constant at amplitude levels above about 15 dB SL for mid- and high-frequency reference signals (Craig, 1972; Fucci *et al.*, 1982; Gescheider *et al.*, 1990; Knudsen, 1928; LaMotte and Mountcastle, 1975).

Although overall trends in the data were similar across participants, individual differences in threshold values were noted, particular for the masked conditions ($C2-C4$). For frequency discrimination, no one subject stands out as consistently exhibiting the highest values of WF [e.g., see panel (d) of Fig. 4]; for amplitude discrimination, on the other hand, the performance of S4 is consistently worse than that of the other three participants [e.g., see panels (b) and (d) of

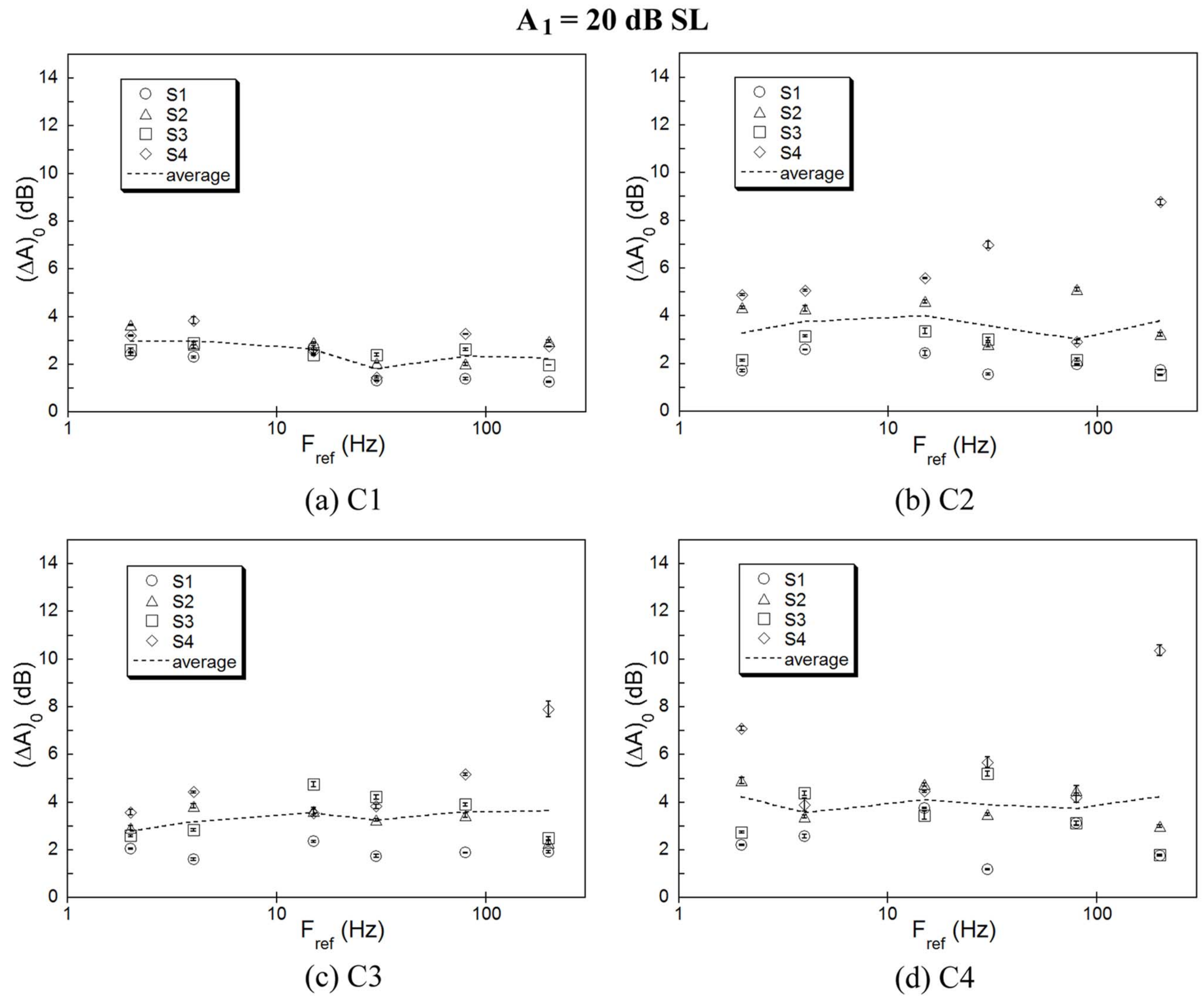
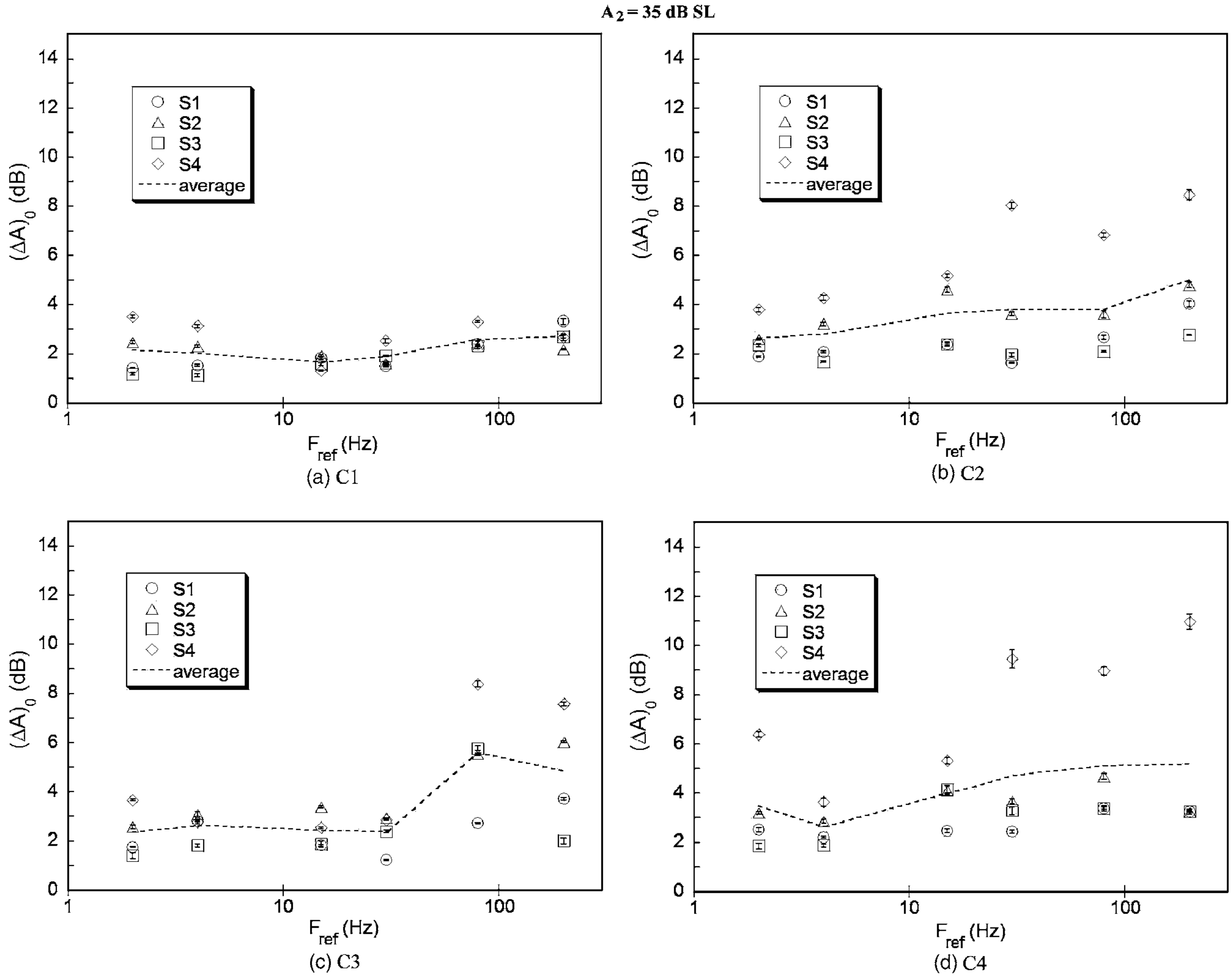


FIG. 6. Amplitude discrimination thresholds $(\Delta A)_0$ in decibels for the four participants as a function of reference frequency F_{ref} at 20 dB SL. Panel (a) shows the thresholds in the no-masker condition C1. Panels (b), (c), and (d) show thresholds for the one- and two-masker conditions C2, C3, and C4, respectively. Shown are individual participant's data (open symbols), the average (dashed lines), and standard errors.

Fig. 7]. One issue that could have potentially contributed to the significant interparticipant differences observed in the present study was the use of nominal detection threshold values for estimating the sensation levels of tactual signals. As mentioned earlier, the detection thresholds used in the present study were representative of three participants in Israr *et al.* (2004). Post detection thresholds of three participants in the present study showed that measured detection thresholds were within 6 dB from the nominal detection thresholds except for high-frequency targets where the thresholds varied up to 13 dB from the nominal detection thresholds (see the Appendix). From existing data in the literature, it appears that a small variation in the sensation level of tactual signals should not have a strong effect on discrimination thresholds. For example, Horch (1991) showed that the capability of humans to discriminate vibrations between 168 and 226 Hz did not change when the amplitude of the stimulus was varied from −4.6 dB to 3 dB relative to the reference. LaMotte and Mountcastle (1975) also demonstrated that frequency discrimination thresholds obtained at 30 Hz with roving amplitudes (24–36 dB SL) were identical to those evaluated with equal subjective intensities, for both humans and monkeys. Therefore, the significant interparticipant differences were likely due to other factors such as familiarity with the experimental apparatus and training, and is not uncommon in psychophysical studies involving threshold testing (see, for example, Brisben, Hsiao, and Johnson, 1999). Previous studies have shown that training can lead to improved tactile discrimination performance, especially with new participants (Hnath-Chisolm and Medwetsky, 1988; Horch, 1991).

The detrimental effects of masking stimuli on frequency and amplitude discrimination found in the present study are consistent with similar findings from numerous earlier studies (Craig, 1972, 1974; Gescheider *et al.*, 1990; Gescheider, Verrillo, and Van Doren, 1982; Verrillo and Gescheider, 1992). In general, compared to the thresholds obtained in the no-masker condition, discrimination thresholds increased more under the two-masker condition (*C*4) than under the one-masker conditions (*C*2 and *C*3), and masking effects decreased as the frequency separation between the target and the maskers increased. The latter is consistent with findings



(a) C1

(b) C2

(c) C3

(d) C4

FIG. 7. Amplitude discrimination thresholds $(\Delta A)_0$ in decibels for the four participants as a function of reference frequency F_{ref} at 35 dB SL. Panel (a) shows the thresholds in the no-masker condition C1. Panels (b), (c), and (d) show thresholds for the one- and two- masker conditions C2, C3, and C4, respectively. Shown are individual participant's data (open symbols), the average (dashed lines), and standard errors.

from other studies (Gescheider *et al.*, 2004; Hollins *et al.*, 1990; Summers *et al.*, 2005; Tan *et al.*, 1999, 2003). From the point of view of developing coding schemes for transmitting speech through a tactual display, one of the most important findings of the present study is that the discrimination of low-frequency targets is hardly affected by high-frequency maskers, and vice versa.

No definite model of frequency and amplitude discrimination is available, presumably due to the complex mechanisms underlying mechanical touch. Bolanowski Jr., *et al.* (1988) proposed a four-channel psychophysical model for the mechanical nature of touch in the dynamic range of about dc–400 Hz and 0–55 dB SL. According to this model for the glabrous skin of the thenar eminence, the detection thresholds of mechanoreceptors are contributed by four neural channels (NP I, NP II, NP III, and P) that partially overlap in their absolute sensitivity. In addition, each channel exhibits its own temporal and spatial characteristics (Verrillo and Gescheider, 1992). A similar psychophysical model was obtained at the fingertip by the same research group (Gescheider *et al.*, 2002, 2004). It is likely that suprathreshold stimuli activate more than a single channel (if not all four channels) as frequency and amplitude vary. The reference and masker stimuli of the present study covers approximate the entire dynamic range of useful mechanical touch, in that the low-frequency targets are sensed by the NP I and NP III channels and also activate receptors for kinesthetic sensations at larger amplitudes, and the 200-Hz targets are sensed by the P channels as well as the NP II channels at higher amplitudes. Our results contribute to future studies of a model for frequency and amplitude discrimination in the presence of masking stimuli.

The present study was a continuation of our effort to use the tactual sense as a channel for speech communication. Despite decades of intense research efforts, performance with artificial hearing aids is still shadowed by that of natural methods such as the Tadoma method. Inspired by the Tadoma method, the TACTUATOR was developed to deliver both high-frequency low-amplitude vibrations and low-frequency high-amplitude movements to enrich the amount of speech information that can be transmitted through the tactual sense. Building on the author's previous studies using the TACTUATOR, the present study focused on user's ability to detect small variations in frequency or amplitude in the presence of a broadband speech signal. In this context, the main conclusions to be drawn from the present study are that low-

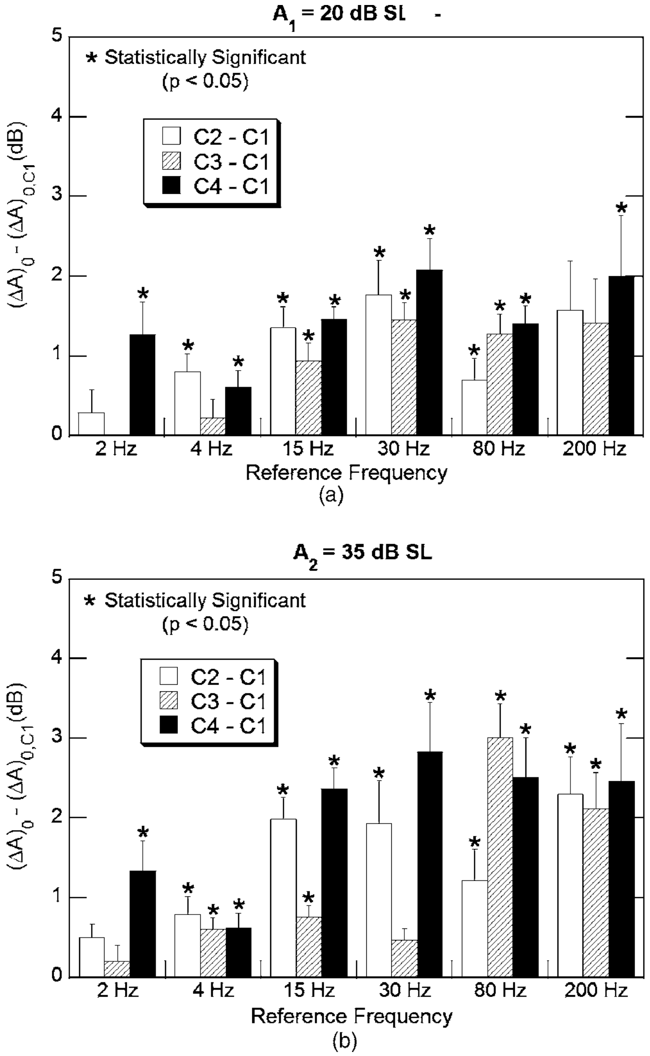


FIG. 8. Increase in amplitude discrimination thresholds in (decibels) under the one- and two-masker conditions (C2–C4) for stimuli presented at (a) 20 dB SL and (b) 35 dB SL. $(\Delta A)_0$ is the amplitude discrimination threshold for the one- and two-masker conditions (C2–C4) and $(\Delta A)_{0,\mathrm{C1}}$ is the amplitude discrimination threshold for the no-masker condition (C1). Differences are shown in a bar graph for each reference frequency. An asterisk indicates statistical significance ($p < 0.05$). Also shown are the standard errors.

TABLE II. Nominal and individual detection thresholds for S1, S2, and S3.

Frequency (Hz)	Detection thresholds (dB re 1 μm peak)			
	Nominal	*S*1	*S*2	*S*3
2	38	39	41	33
4	34	34	35	32
15	25	29	26	24
30	16	19	22	21
80	−8	−16	5	4
200	−18	−22	−9	−12

and high-frequency tactual signals do not interfere with each other, that experience with the apparatus or task improved discrimination performance, and that tactual discrimination thresholds appear to be too large for encoding more than a few speech features. The relative independence of the low- and high-frequency tactual channels will be exploited in the near future to improve the transmission of one speech cue: place of articulation. Previous studies on tactile aids were able to provide manner and voicing distinctions, but failed to transmit the place of articulation cue (Bernstein *et al.*, 1991; Carney *et al.*, 1993; Clements, Braida, and Durlach, 1982, 1988; Weisenberger, Craig, and Abbott, 1991; Weisenberger and Percy, 1995). Place of articulation is well correlated with the frequency values of the first two formats *F*1 and *F*2 and their transitions (see, for example, Ainsworth, 1968; Ali, Van der Spiegel, and Mueller, 2001a, 2001b; Jongman and Miller, 1991; Jongman, Wayland, and Wong, 2000; Sharf and Hemeyer, 1972; Stevens and Klatt, 1974). Based on the frequency and amplitude discrimination thresholds found in the present study, the human hand does not have the resolution required for discriminating changes in high-frequency vibrations in the *F*1 and *F*2 region. A direct presentation of vibration signals associated with *F*1 and *F*2 is therefore expected to lead to poor speech reception performance. We will use a low-frequency motional signal to supplement the *F*1 and *F*2 vibrations. The direction (extension versus flexion of a finger) and the extent of the motional signals will be used to indicate to a user whether the formats increase or decrease and how fast they are changing. We hope to demonstrate that the strategy of redundantly encoding place of articulation cues via the simultaneous use of low- and high-frequency signals will eventually contribute toward improved speech transmission through the sense of touch.

ACKNOWLEDGMENTS

This research was supported by research Grant No. R01-DC00126 from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health. The authors wish to thank the reviewers for their detailed and thoughtful comments.

APPENDIX

To check the validity of the threshold levels shown in Table I, detection thresholds for *S*1, *S*2, and *S*3 were measured after the main experiments and are presented in Table II. S4 was no longer available for the additional testing.

---

[1] There exists another device that can display both high-frequency vibrations and low-frequency motions with appreciable amplitude (Eberhardt *et al.*, 1994). However, it either operates closed loop under 20 Hz or open loop above 100 Hz, but does not deliver signals in the frequency range 20–100 Hz.

[2] The first TACTUATOR was developed at MIT (Tan and Rabinowitz, 1996). A second device, the TACTUATORII, was then developed at Purdue University with essentially the same hardware, but a new two degrees-of-freedom controller (Israr *et al.*, 2004).

[3] The actual noise level of the sensor (due to mechanical and electrical noises) can be found in Fig. 8 of Tan and Rabinowitz (1996).

[4] To estimate the displacements associated with the sensation levels discussed in this paragraph, please see Table I for the detection thresholds at six frequencies tested in the present study.

[5] To examine training effects, participants *S*1 and *S*2 completed two runs of experimental conditions. For both subjects, frequency-discrimination thresholds improved in the second run. In the amplitude discrimination experiments, thresholds for *S*1 were not significantly different across the two runs, while those of *S*2 were better in the first run. The better of the two runs was used in the final data analyses. Because of the mixed training trends observed here, *S*3 and *S*4 completed only one set of runs.

Ainsworth, W. A. (**1968**). “First formant transitions and the perception of synthetic semivowels,” J. Acoust. Soc. Am. **44**(3), 689–694.

Ali, A. M. A., Van der Spiegel, J., and Mueller, P. (**2001a**). “Acoustic-phonetic features for the automatic classification of fricatives,” J. Acoust. Soc. Am. **109**(5), 2217–2235.

Ali, A. M. A., Van der Spiegel, J., and Mueller, P. (**2001b**). “Acoustic-phonetic features for the automatic classification of stop consonants,” IEEE Trans. Speech Audio Process. **9**(8), 833–841.

Bensmaia, S. J., and Hollins, M. (**2000**). “Complex tactile waveform discrimination,” J. Acoust. Soc. Am. **108**(3), 1236–1245.

Bensmaia, S., Hollins, M., and Yau, J. (**2005**). “Vibrotactile intensity and frequency information in the pacinian system: A psychophysical model,” Percept. Psychophys. **67**(5), 828–841.

Bernstein, L. E., Demorest, M. E., Coulter, D. C., and O’Connell, M. P. (**1991**). “Lipreading sentences with vibrotactile vocoders: Performance of normal-hearing and hearing-impaired Subjects,” J. Acoust. Soc. Am. **90**(6), 2971–2984.

Bolanowski Jr., S. J., Gescheider, G. A., Verrillo, R. T., and Checkosky, C. M. (**1988**). “Four channels mediate the mechanical aspects of touch,” J. Acoust. Soc. Am. **84**(5), 1680–1694.

Brisben, A. J., Hsiao, S. S., and Johnson, K. O. (**1999**). “Detection of vibration transmitted through an object grasped in the hand,” J. Neurophysiol. **81**, 1548–1558.

Carney, A. E., Osberger, M. J., Carney, E., Robbins, A. M., Renshaw, J., and Miyamoto, R. T. (**1993**). “A comparison of speech discrimination with cochlear implants and tactile aids,” J. Acoust. Soc. Am. **94**(4), 2036–2049.

Clements, M. A., Braida, L. D., and Durlach, N. I. (**1982**). “Tactile communication of speech: II. Comparison of two spectral displays in a vowel discrimination task,” J. Acoust. Soc. Am. **72**(4), 1131–1135.

Clements, M. A., Braida, L. D., and Durlach, N. I. (**1988**). “Tactile communication of speech: Comparison of two computer-based displays,” J. Rehabil. Res. Dev. **25**(4), 25–44.

Craig, J. C. (**1972**). “Difference threshold for intensity of tactile stimuli,” Percept. Psychophys. **11**, 150–152.

Craig, J. C. (**1974**). “Vibrotactile difference thresholds for intensity and the effect of a masking stimulus,” Percept. Psychophys. **15**, 123–127.

Eberhardt, S. P., Bernstein, L. E., Barac-Cikoja, D., Coulter, D. C., and Jordan, J. (**1994**). “Inducing dynamic haptic perception by the hand: System description and some results,” *Proceedings of the American Society of Mechanical Engineers: Dynamic Systems and Control*, Vol. **55**, (The American Society of Mechanical Engineers, NY), pp. 345–351.

Franzen, O., and Nordmark, J. (**1975**). “Vibrotactile frequency discrimination,” Percept. Psychophys. **17**(5), 480–484.

Fucci, D., Small, L. H., and Petrosino, L. (**1982**). “Intensity difference limens for lingual vibrotactile stimuli,” J. Magn. Reson. **1**, 54–56.

Geldard, F. A. (**1957**). “Adventures in tactile literacy,” Am. Psychol. **12**, 115–124.

Gescheider, G. A., Bolanowski, S. J., and Verrillo, R. T. (**2004**). “Some characteristics of tactile channels,” Behav. Brain Res. **148**(1), 35–40.

Gescheider, G. A., Bolanowski, S. J., Pope, J. V., and Verrillo, R. T. (**2002**). “A four-channel analysis of the tactile sensitivity of the fingertip: Frequency selectivity, spatial summation, and temporal summation,” Somatosens Mot Res. **19**(2), 114–124.

Gescheider, G. A., Bolanowski Jr., S. J., Verrillo, R. T., Arpajian, D. J., and Ryan, T. F. (**1990**). “Vibrotactile intensity discrimination measured by three methods,” J. Acoust. Soc. Am. **87**(1), 330–338.

Gescheider, G. A., Verrillo, R. T., and Van Doren, C. L. (**1982**). “Prediction of vibrotactile masking functions,” J. Acoust. Soc. Am. **72**(5), 1421–l426.

Gescheider, G. A., Zwislocki, J. J., and Rasmussen, A. (**1996**). “Effects of stimulus duration on the amplitude difference limen for vibrotaction,” J. Acoust. Soc. Am. **100**(4), 2312–2319.

Globe, A. K., and Hollins, M. (**1993**). “Vibrotactile adaptation enhances amplitude discrimination,” J. Acoust. Soc. Am. **93**(1), 418–424.

Globe, A. K., and Hollins, M. (**1994**). “Vibrotactile adaptation enhances frequency discrimination,” J. Acoust. Soc. Am. **96**(2), 771–780.

Goff, G. D. (**1967**). “Differential discrimination of frequency of cutaneous mechanical vibration,” J. Exp. Psychol. **74**(2), 294–299.

Hacker, M. J., and Ratcliff, R. (**1979**). “A revised table of d’ for M-alternative forced choice,” Percept. Psychophys. **26**(2), 168–170.

Hnath-Chisolm, T., and Medwetsky, L. (**1988**). “Perception of frequency contours via temporal and spatial tactile transforms,” Ear Hear. **9**(6), 322–328.

Hollins, M., Globe, A. K., Whitsel, B. L., and Tommerdahl, M. (**1990**). “Time course and action spectrum of vibrotactile adaptation,” Somatosens Mot Res. **7**(2), 205–221.

Horch, K. (**1991**). “Coding of vibrotactile stimulus frequency by Pacinian corpuscle afferents,” J. Acoust. Soc. Am. **89**(6), 2827–2836.

Israr, A., Meckl, P. H., and Tan, H. Z. (**2004**). “A two DOF controller for a multi-finger tactual display using a loop-shaping technique,” *Proceedings of the 2004 ASME International Mechanical Engineering Congress*, Anaheim, CA, Nov. 13–19 (The American Society of Mechanical Engineers, NY), pp. 1083–1089.

Jongman, A., and Miller, J. D. (**1991**). “Method for the location of burst-onset spectra in the auditory-perceptual space: A study of place of articulation in voiceless stop consonants,” J. Acoust. Soc. Am. **89**(2), 867–873.

Jongman, A., Wayland, R., and Wong, S. (**2000**). “Acoustic characteristics of english fricatives,” J. Acoust. Soc. Am. **108**(3), 1252–1263.

Knudsen, V. O. (**1928**). ““Hearing” with the sense of touch,” J. Gen. Psychol. **1**, 320–352.

LaMotte, R. H., and Mountcastle, V. B. (**1975**). “Capacities of humans and monkeys to discriminate vibratory stimuli of different frequency and amplitude: A correlation between neural events and psychological measurements,” J. Neurophysiol. **38**(3), 539–559.

Leek, M. R. (**2001**). “Adaptive procedures in psychophysical research,” Percept. Psychophys. **63**(8), 1279–1292.

Levitt, H. (**1971**). “Transformed up-down methods in psychoacoustics,” J. Acoust. Soc. Am. **49**(2), 467–477.

Reed, C. M., and Durlach, N. I. (**1998**). “Note on information transfer rates in human communication,” Presence—Teleoperators & Virtual Environments **7**(5), 509–518.

Reed, C. M., Rabinowitz, W. M., Durlach, N. I., Braida, L. D., Conway-Fithian, S., and Schultz, M. C. (**1985**). “Research on the tadoma method of speech communication,” J. Acoust. Soc. Am. **77**(1), 247–257.

Rinker, M. A., Craig, J. C., and Bernstein, L. E. (**1998**). “Amplitude and period discrimination of haptic stimuli,” J. Acoust. Soc. Am. **104**(1), 453–463.

Rothenberg, M., Verrillo, R. T., Zahorian, S. A., Brachman, M. L., and Bolanowski Jr., S. J. (**1977**). “Vibrotactile frequency for encoding a speech parameter,” J. Acoust. Soc. Am. **62**, 1003–1012.

Sharf, D. J., and Hemeyer, T. (**1972**). “Identification of place of consonant articulation from vowel formant transitions,” J. Acoust. Soc. Am. **51**(2), 652–658.

Stevens, K. N., and Klatt, D. H. (**1974**). “Role of formant transitions in the voiced-voiceless distinction for stops,” J. Acoust. Soc. Am. **55**(3), 653–659.

Summers, I. R., Cooper, P. G., Wright, P., Gratton, D. A., Milnes, P., and Brown, B. H. (**1997**). “Information from time-varying vibrotactile stimuli,” J. Acoust. Soc. Am. **102**(6), 3686–3696.

Summers, I. R., Whybrow, J. J., Gratton, D. A., Milnes, P., Brown, B. H., and Stevens, J. C. (**2005**). “Tactile information transfer: A comparison of two stimulation sites,” J. Acoust. Soc. Am. **118**(4), 2527–2534.

Tan, H. Z., Durlach, N. I., Reed, C. M., and Rabinowitz, W. M. (**1999**). “Information transmission with a multifinger tactual display,” Percept. Psychophys. **61**(6), 993–1008.

Tan, H. Z., and Rabinowitz, W. M. (**1996**). “*A new multi-finger tactual display*,” *Proceedings of the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, edited by K. Danai, Vol. **58** (The American Society of Mechanical Engineers, NY), pp. 515–522.

Tan, H. Z., Reed, C. M., Delhorne, L. A., Durlach, N. I., and Wan, N. (**2003**). “Temporal masking of multidimensional tactual stimuli,” J. Acoust. Soc. Am. **114**(6), 3295–3308.

Verrillo, R. T., and Gescheider, G. A. (**1992**). “*Perception via the sense of touch*,” *Tactile Aids for the Hearing Impaired*, edited by I. R. Summers (Whurr Publishers, London), pp. 1–36.

Weisenberger, J. M., Craig, J. C., and Abbott, G. D. (**1991**). “Evaluation of a principal-components tactile aid for the hearing-impaired,” J. Acoust. Soc. Am. **90**(4), 1944–1957.

Weisenberger, J. M., and Percy, M. E. (**1995**). “The transmission of phoneme-level information by multichannel tactile speech perception aids,” Ear Hear. **16**(4), 392–406.

Yuan, H., Reed, C. M., and Durlach, N. I. (**2005a**). “Temporal onset-order discrimination through the tactual sense,” J. Acoust. Soc. Am. **117**(5), 3139–3148.

Yuan, H., Reed, C. M., and Durlach, N. I. (**2005b**). “Tactual display of consonant voicing as a supplement to lipreading,” J. Acoust. Soc. Am. **118**(2), 1003–1015.