Vibrotactile frequency for encoding a speech parameter

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Frequency of vibration has not been widely used as a parameter for encoding speech-derived information on the skin. Where it has been used, the frequencies employed have not necessarily been compatible with the capabilities of the tactile channel, and no determination was made of the information transmitted by the frequency variable, as differentiated from other parameters used simultaneously, such as duration, amplitude, and location. However, several investigators have shown that difference limens for vibration frequency may be small enough to make stimulus frequency useful in encoding a speech-derived parameter such as the fundamental frequency of voiced speech. In the studies reported here, measurements have been made of the frequency discrimination ability of the volar forearm, using both sinusoidal and pulse waveforms. Stimulus configurations included the constant-frequency vibrations used by other laboratories as well as frequency-modulated (warbled) stimulus patterns. The frequency of a warbled stimulus was designed to have temporal variations analogous to those found in speech. The results suggest that it may be profitable to display the fundamental frequency of voiced speech on the skin as vibratory frequency, though it might be desirable to recode fundamental frequency into a frequency range more closely matched to the skin's capability.

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INTRODUCTION

The concept of using the skin as a surrogate sensory input for the ears or eyes is not new. Recorded efforts to do so date from the sixteenth century, when Gaspara Tagliacozzi devised a tactile communication system (Gnudi and Webster, 1950). Rousseau in 1762 suggested that the skin could be used to supplement sight and substitute for hearing (Geldard, 1960). The Braille system is perhaps the most familiar example of sensory substitution in language processing.

Formal efforts to develop a tactile speech encoder date from the attempts of Gault (1924, 1926) and Gault and Crane (1928), who first impressed upon the skin the vibratory outputs of speech signals via a microphone, amplifier, and a single vibrator. Following these early efforts, numerous attempts have been made to encode speech signals into vibratory stimuli in order to help the profoundly deaf to communicate. These attempts range from minimally processed microphone signals presented directly to a single vibrator (Gault, 1924, 1926; Gault and Crane, 1928; and, in some more recent examples, Boothroyd, 1970; Erber and Cramer, 1974; Schulte, 1970) to complex vocoder or feature extraction systems employing a spatio-temporal vibratory code (Engelman and Rosov, 1975; Goldstein and Stark, 1976; Guelke and Huyssen, 1959; Keidel, 1974; Kirman, 1974; Kringlebotn, 1968; Miller, Engebretson, and De Filippo, 1974; Pickett, 1963; Pickett and Pickett, 1963; Willemain and Lee, 1972; for a comprehensive review, see Kirman, 1973).

In all such attempts to date, either the frequency of the stimulus has not been used for encoding information or it has been used in conjunction with amplitude or location on the skin, so that the contribution of the frequency parameter was not made clear. The lack of attention to frequency as an information-bearing parameter is due in part to the limited frequency range of the skin when compared to the ear. The skin has a usable bandwidth of about 700 Hz compared to the 2–3 kHz in which most speech information is encoded. In addition, the skin is a relatively poor frequency analyzer compared to the ear.

On close examination, the perception of frequency emerges as a rather complex function. This is due to the interaction of frequency and amplitude in pitch discriminations. As amplitude of vibration increases, the pitch (subjective vibrotactile frequency) of the signal decreases dramatically, especially at high frequencies (von Békésy, 1957, 1959). Furthermore, pitch as a function of frequency changes with the neural density over different parts of the body (von Békésy, 1962). For regions of high neural density (fingers), pitch rises more sharply with frequency than for regions of low neural density (arm). Geldard (1960) has cautioned that frequency must be used with great discretion as a stimulus variable in a tactile communication system.

In the absence, however, of any better estimate of what might be the "natural" encoding parameters for a vibrotactile stimulus at one body site, it is reasonable to examine first the stimulus parameters of frequency, amplitude, and waveform. We emphasize the role of frequency in these investigations because of the importance of frequency information in the speech signal. Where the possibility exists, converting frequency information to a frequency variable might facilitate the integration of tactile sensations with information from any residual hearing, or reduce the relearning task of a prelingually deaf person who has some hearing restored later in life. For the postlingually deaf, learning to interpret an analogous tactile sensation might be easier than learning to interpret a nonanalogous sensation such as amplitude or movement. Using a stimulus which is "natural" may also be important in motivating an infant in the initial language learning years. Of course, the use of a frequency variable for encoding a specific speech parameter does not preclude the simultaneous use of other stimulus parameters for encoding the same or other parameters of speech.

One speech parameter which might be well suited for encoding into vibrotactile frequency is the fundamental frequency of voicing, the primary physical determinant of vocal pitch, since the range in normal speech, roughly 70–500 Hz (Fairbanks, 1940), overlaps the frequency range of tactile sensitivity. It is, indeed, likely that any success achieved by Gault and others in the direct coupling of speech signals to the skin, or in the use of high degrees of amplification with the profoundly deaf, has been at least partially due to the tactile perception of fundamental frequency.

In the few systematic studies of frequency discrimination, estimates reported for the difference limen have varied from approximately 30% of the reference frequency (Goff, 1967) to about 3% (Franzén and Nordmark, 1975). The situation is clouded by variations between experiments in the vibration site, the waveform used, and the experimental procedure. The limen for the discrimination of frequency of a sinusoidal vibrotactile stimulus at the fingertip was found by Goff (1967) to be comparatively large, using a two stimulus, forced-choice procedure. Within the frequency range where the skin is most sensitive, between 200 and 400 Hz (Verillo, 1963), Goff found the difference limen to be over 100 Hz. However, at lower frequencies the limen was as low as 5 Hz.

Mowbray and Gebhard (1957), using repetitive, pulse-like stimuli delivered to a rod held between the fingertips, and a method of adjustment, reported considerably better discriminations ranging from a difference limen of 0.02 Hz at a reference frequency of 1 Hz, to a difference limen of 24.4 Hz at 320 Hz, with a roughly linear relationship between difference limen and reference frequency. They made no attempt to control for the pitch-intensity interaction as Goff (1967) had, but claim that the interaction had no effect on their results, at least at low frequencies. The smaller difference limens obtained by Mowbray and Gebhard may be related to the fact that they stimulated two fingertips simultaneously, or to their use of a method of adjustment rather than a forced-choice procedure. Since a forced-choice procedure more closely models the task of the user of a speech reception aid, it may be that the smaller difference limens, if due to the use of a method of adjustment, may not be useable in speech reception.

The most recent attempt to determine vibrotactile frequency discrimination systematically is that of Franzén and Nordmark (1975), who measured the discrimination of pulse frequencies between 1 and 384 Hz using a method of adjustment. They report difference limens of only about 3% of the reference frequency over the entire range of frequencies tested. However, since they allowed the subject to bracket the reference frequency on a dial with visible dial graduations, their measure of difference limen was, in effect, the standard deviation of data points, each of which was the average of an estimate of the minimum detectable increase in frequency and an estimate of the minimum detectable decrease in frequency. If the difference limen is considered the minimum detectable difference in frequency, then the method of Franzén and Nordmark yields not the difference limen itself, but the subjects' uncertainty about the difference limen (or, more precisely, the uncertainty divided by $\sqrt{2}$, since each data point they record is really the average of two independent estimates, namely of the upper and lower difference limens). Since in the method they used, the subject was free to put considerable time and effort into each estimate, one would expect the uncertainty (standard deviation) of the estimate to be considerably smaller than the quantity estimated. Hence we would expect that the procedure used by Franzén and Nordmark would result in "difference limens" that are much smaller than those obtained using more standard techniques.

The experiments presented here were designed to measure vibrotactile frequency discrimination for pulse and sinusoidal waveforms over a wide range of frequencies. Measurements were made on the left hand at the thenar eminence or the distal pad of the middle finger, or at a site on the left volar forearm midway between the medial epichondile and the furrow marking the midcarpal articulation (between palm and wrist). We have emphasized the forearm in these experiments. Although not as richly endowed with mechanoreceptors as the hand, the forearm would be a more convenient location for an eventual vibrotactile encoder.

I. APPARATUS AND PROCEDURE

Vibrotactile stimuli were delivered through an Electrodyne AV-6 vibrator. We designed and constructed a capacitance-type displacement monitor with wide linear dynamic range to monitor the vibratory stimuli at the time of stimulation. The faithful reproduction of the nonsinusoidal waveforms used in this study required a vibrator response that was flat to over 400 Hz. To accomplish this, the unsatisfactory electrodynamic response characteristic of the vibrator was corrected by a specially constructed "inverse filter" having a transfer function that was the inverse of that of the vibrator. This filter was located between the input waveform and the power amplifier driving the vibrator. The inverse filter had a pair of complex-conjugate zeros (an antiresonance) to compensate for the mechanical resonance of the armature assembly, and a real zero to compensate for the real pole caused by the inductance of the armature coil. The frequency and damping of the complex-conjugate zeros and the frequency of the real zero were adjusted by making the displacement waveform match the waveform of the input, when the input was an approximately Gaussian shaped pulse about 1 msec wide. With the standard AV-6 suspension, the adjustments were affected only slightly by the loading of the skin, and could normally be made without the arm in place (though they could be easily retouched at any time during the testing). Most of the testing was done with a modified suspension, in which one of the two $\frac{1}{64}$-in.-thick flexures in the suspension was replaced with a $\frac{1}{32}$-in.-thick flexure of the same type, to increase the stiffness. With the modified suspension, the effect of skin loading

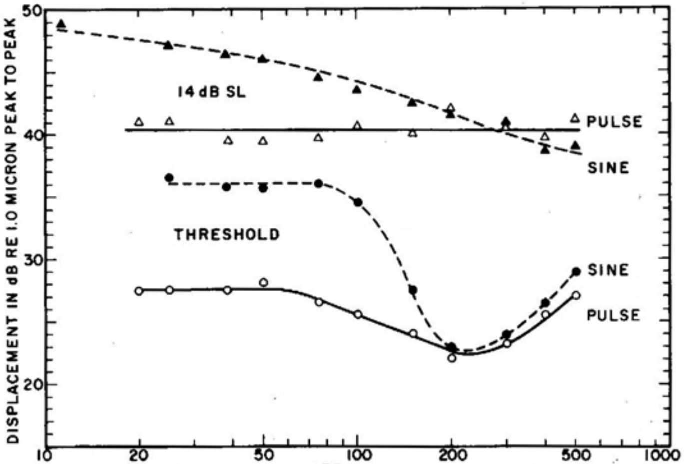

FIG. 2. Sensitivity of the volar forearm to sinusoids and 1-msec Gaussian pulses, at threshold and at 14 dB SL.

C. Pulse width and pulse shape

To estimate the optimum pulse width for the frequency discrimination experiments, the threshold and the suprathreshold subjective magnitude were measured on four subjects as a function of pulse width. The pulses were Gaussian shaped, and formed by passing a narrow, rectangular pulse of fixed width through a six-pole Bessel low-pass filter having a variable cutoff frequency. The pulse width could be varied from 0.30 to 4.0 msec by changing the cutoff frequency of the Bessel filter. A pulse repetition rate of 50 Hz was used, at a sensation level of 16 dB. Measurements were made both on the thenar eminence and on the forearm. Figure 3 shows that as the pulse width is reduced from 4.0 msec, the pulse becomes subjectively stronger down to a pulse width of about 1.0 msec for the thenar and 0.8 msec for tne forearm. For yet narrower pulses the sensitivity remains approximately constant. Using these results, a pulse width of about 1 msec was chosen for the frequency discrimination experiments reported below.

The foregoing experiment was done with Gaussian-shaped pulses in which, for a given amplitude, the rise-fall time varied with pulse width. The effect of rise-fall time on tactile sensitivity was investigated by comparing the thresholds of Gaussian pulses of various widths with those of flat-topped pulses having the same widths, but a fixed rise–fall time of 1 msec, 10%–90%. The shape of the non-Gaussian pulse is shown in Fig. 4. It was formed by passing a rectangular pulse of variable width through a six-pole Bessel low-pass filter, −3 dB at 400 Hz. The results shown in Fig. 4 are the median values for five subjects. Pulse widths of 0.30–4.0 msec and 0.65–20 msec were tested for the Gaussian and non-Gaussian pulses, respectively, at a pulse repetition rate of 50 Hz. Threshold measurements were made on the forearm and thenar eminence using the Békésy tracking method. The results (Fig. 4) show that unlike Gaussian pulses, the sensitivity to the non-Gaussian pulse remains constant within the range of pulse widths used in the experiment. Thus the rise–fall time of the pulses appears to be the primary determinant of vibrotactile sensitivity, and not the pulse width, *per se*.

From another point of view, the results for the flat-topped pulses give the impression that the response was due to the peak amplitude of the time derivative of the displacement, or probe velocity, which varied little with the pulse width. However, the derivative hypothesis is only partially supported by the Gaussian pulse data since it would lead to a 6 dB/octave change in sensitivity for the Gaussian pulses at larger pulsewidths, a value somewhat higher than the actual slopes shown in Fig. 3.

One would expect the Gaussian and non-Gaussian data to conincide for pulse widths below about 1 msec, since the waveshapes are very similar. This occurred with the forearm data, however, the thenar data showed an unexplained difference of about 3 dB. One possible explanation for the discrepancy is learning, since the non-Gaussian experiment followed the Gaussian one.

The results also suggest that the use of pulses of differing width or with a time-varying pulse width may be useful in transmitting information to the skin, if the variation in width is accomplished by varying the rise-fall time. The changing rise–fall time may provide an additional cue that can be utilized by the cutaneous sensory system. This is supported by observations from the subjects that variations in pulse width, for Gaussian pulses, can be felt as a parameter clearly different from pulse amplitude or frequency, over a wide range of frequencies. If pulse frequency were made analogous to voice fundamental frequency, variations in pulse width would be analogous to variations in the harmonic content of the speech wave, or in other words, to the spectral variations that are primarily responsible for signaling differences between the various vowels and voiced-sonorant consonants. Though preliminary experiments indicate that there are only a few discriminable levels of spectral quality produced by changes of pulse width at a given pulse frequency, it is conceivable that some

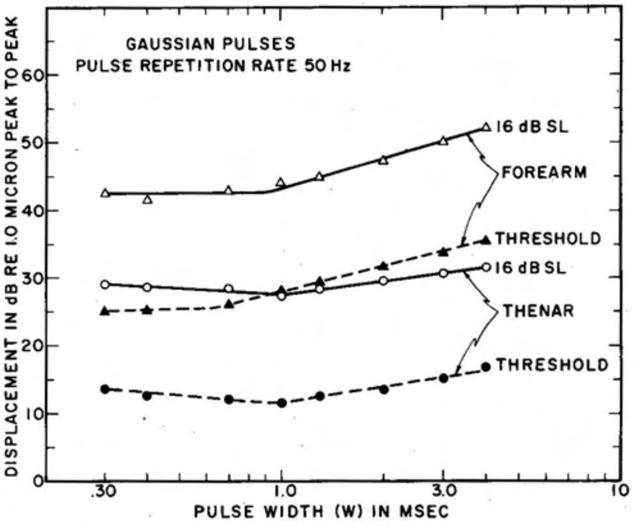

FIG. 3. Sensitivity of the volar forearm and thenar eminence as a function of pulse width for Gaussian pulses of width *W* at the half-power points.

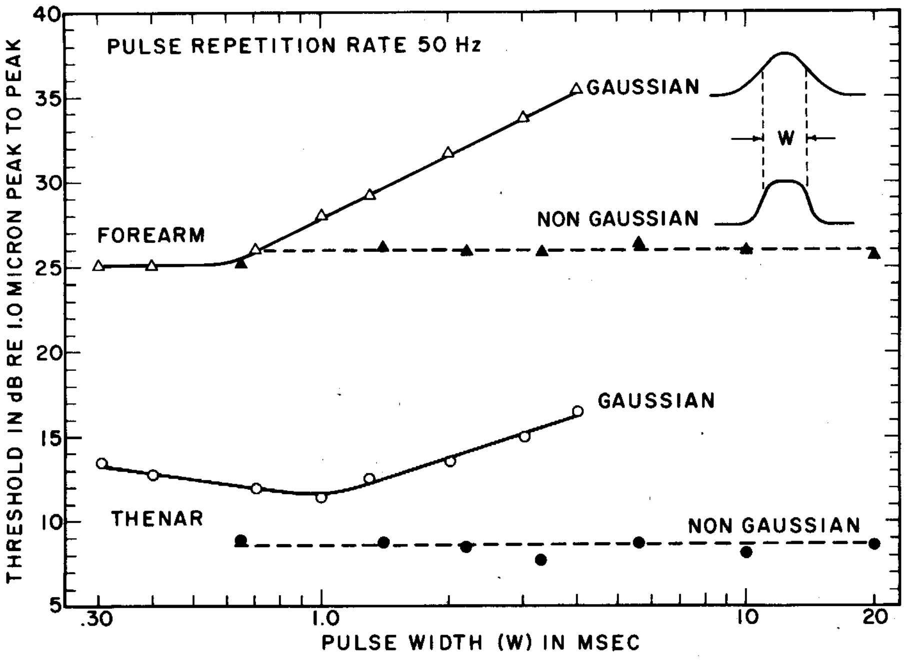

FIG. 4. Sensitivity of the volar forearm and thenar eminence as a function of pulse width for Gaussian pulses, compared with the sensitivity for pulses having the same pulse width but a fixed rise and fall time.

gross spectral structure variations, such as the differences between harmonic-rich vowels and harmonic-poor sonorant consonants could be encoded into this dimension.

D. Frequency discrimination

The ability of subjects to make frequency discriminations with vibrotactile stimuli was investigated using two types of experiments. In the first type, subsequently referred to as the constant-frequency method, the subject was asked to compare two vibratory bursts of different frequencies. The frequency was held constant during each burst. In the second type, subsequently referred to as the warble-tone method, the subject compared a burst of constant frequency with one of time-varying or "warbled" frequency. For each experiment, measurements were made using both sinusoids and 1-msec-wide Gaussian pulses.

1. Constant-frequency method

Using the constant-frequency stimuli, subjects were presented with a 1-sec sample of a standard frequency followed by a 1-sec sample of a test frequency, and asked to judge whether the frequency of the test stimulus was higher or lower than that of the standard, using a forced-choice procedure. Measurements were made on the forearm with both sinusoids and pulse trains, using five subjects for each waveform. Only one subject was common to both groups, so that a total of nine subjects were tested. Pulses were Gaussian shaped and 1.1 msec wide, as measured at the half-power points. These pulses are hereafter referred to as 1-msec pulses. The amplitudes were normalized for equal subjective magnitude at 14 dB SL. As is customary, the difference limen (DL) was considered to be one-half the difference between the frequency which was called "greater" than the standard 75% of the time, and that which was called "smaller" 75% of the time, when the data was fit with a normal distribution function. For each standard frequency, each subject was tested 15 times at each of six values of the test frequency, three higher than the standard and three lower. The test frequencies were spaced evenly on a log scale, with the spacing from the highest to the lowest chosen from the results of preliminary experiments to be about five or six times the difference limen of an average subject at that standard.

Since the difference limen tends to vary directly with frequency, the results (Fig. 5) are plotted as the Weber fraction $\Delta f/f$, that is, the difference limen divided by the reference frequency. Our results are represented by the solid lines in Fig. 5. As would be expected, the sine results and pulse results tend to merge at high frequencies where the pulses tend to merge into a sinusoid. At low frequencies the pulse trains seem to be more discriminable in frequency by a factor of about 2. Intersubject variability was generally within about ±20% of the median, except for sinusoids at 150 and 200 Hz, where the deviations from the median increased to about 40%, with two subjects registering a difference limen just under 5% of the reference frequency at 150 Hz and one of those two subjects reaching 3.2% of the reference frequency at 200 Hz. The increased variability at these frequencies may have been due to the small number of subjects used, but also may be related to the changing nature of the sensation above about 100 Hz, as discussed below.

In comparing our results to the other frequency DL's reported in the literature, as shown in Fig. 5, we find a somewhat better frequency discrimination than Goff (1967), especially considering that Goff measured on the fingers while we used the less sensitive forearm. The even better discrimination reported by Mowbray and Gebhard (1957) for pulses applied to a rod held between the fingertips could be at least partially explained by their method of double stimulation and the use of a meth-

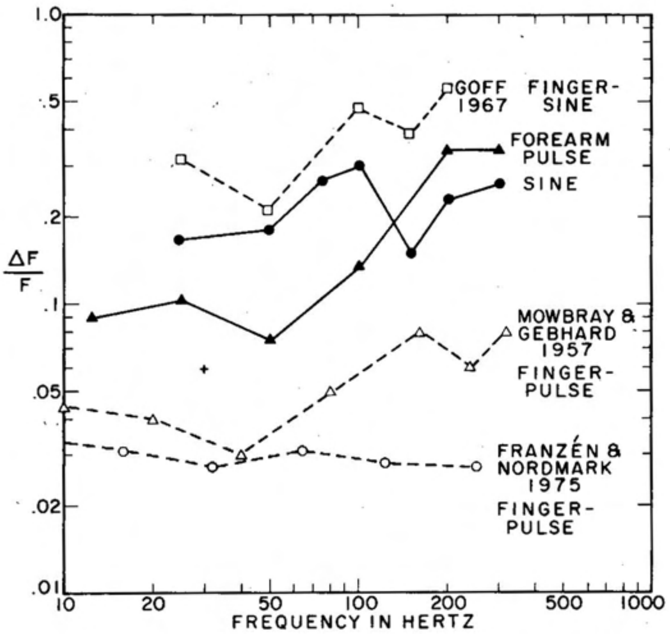

FIG. 5. Difference limen for frequency discrimination for pulses and sinusoids on the forearm, when identifying a frequency difference between successive constant frequency vibrotactile tone bursts (solid lines). Results are plotted as the Weber fraction $\Delta f/f$. The dashed lines and the cross at 30 Hz show the results of other laboratories. The cross is from LaMotte and Mountcastle (1975), for sinusoids on the thenar eminence.

od of adjustment. The cross in the figure shows the result reported by LaMotte and Mountcastle (1975), who measured the frequency DL for sinusoids at 30 Hz using the thenar eminence of highly trained subjects and a two interval forced-choice procedure similar to that used by Goff and ourselves. As mentioned above, the very low DL's reported by Franzén and Nordmark were obtained by a nonstandard method.

2. Warble-tone method

Another standard method in auditory psychophysics for measuring the difference limen for frequency presents the subject with a tone of constant frequency followed or preceded by one with a time-varying or "warbled" frequency. The subject is asked to identify the order of presentation. The amount of frequency variation in the warbled stimulus for 75% correct identification is considered the difference limen. An important advantage of this technique is that the stimulus frequency is presented in a manner much closer to the way it would be presented when encoding a speech-derived variable such as, for example, the fundamental frequency during voiced speech. This technique does not appear to have been used previously in cutaneous experiments.

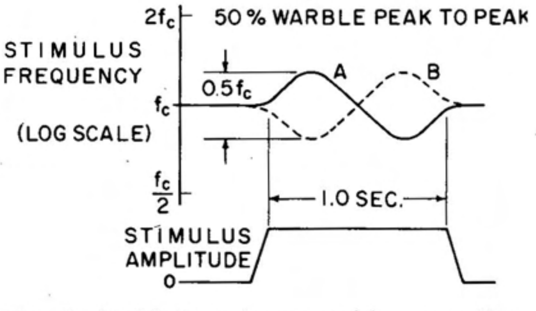

FIG. 6. Modulation patterns used for generating a warbled vibrotactile burst at a center frequency f_c.

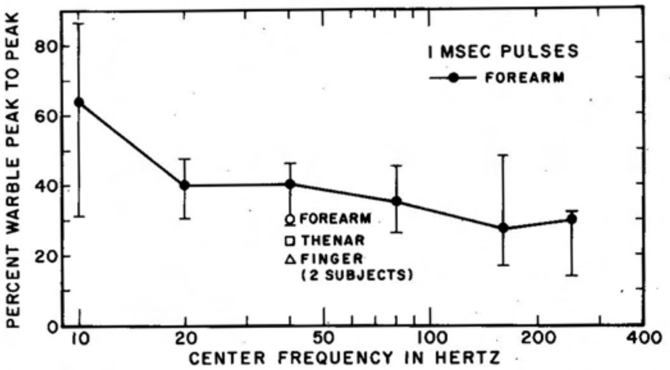

FIG. 7. Warble-tone measurements of the frequency discrimination threshold for pulses on the forearm (filled circles). The vertical bars are the interquartile ranges. The unfilled points at 40 Hz show a comparison for two of the subjects between their forearm results and measurements on the thenar eminence and the finger.

In applying the technique to vibrotaction we used a pattern for the warble shown in Fig. 6. On a logarithmic scale, the time variation of the stimulus frequency (pulse repetition rate for pulses) was roughly that of a 1.0-Hz sinusoid. The time constants in a 1-Hz sinusoid are similar to those of the articulatory movements in speech and, therefore, of many speech-derived parameters. For the parameter fundamental frequency of voicing, in particular, the grosser variations associated with sentence intonation tend to occur at a rate of roughly 1 Hz. Thus 1 Hz approximates the slowest warble rate that still simulates fundamental frequency variations in natural speech.

Either pattern A in Fig. 6 (solid curve), or pattern B (dashed curve), was used for the warble. A counterbalanced presentation produced no significant difference between patterns. Pulse trains were presented at 20 dB SL. Subjects were tested 24 times at each of seven values of percent warble for each center frequency. The values of percent warble were logarithmically spaced, with a spacing at each center frequency determined from preliminary experiments. In a forced-choice format, subjects were presented with two 1-sec pulse trains separated by a 1-sec interval, and asked to identify which one was warbled in frequency. The nonwarbled pulse train was set at a constant frequency equal to the center frequency on a logarithmic scale (f_c) of the warbled train.

The results are shown in Fig. 7, where the percent warble (peak-to-peak) for 75% correct performance is plotted as a function of the center frequency. Nine subjects were tested on the forearm, except at 250 Hz, where data was obtained from only five subjects. Two subjects were retested at 40 Hz on the thenar eminence and distal pad of the middle finger. Median values are

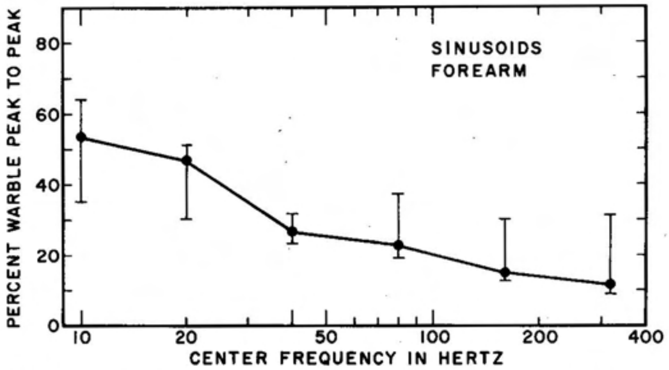

FIG. 8. Warble-tone measurements of the frequency discrimination threshold for sinusoids on the forearm. The vertical bars are the interquartile ranges.

plotted, with vertical bars indicating the interquartile range.

It should be noted that these subjects had been doing frequency discrimination tasks two or three times a week for about three months and so were quite familar with the stimuli, but they did not undergo lengthy training procedures. The subjects were only trained until it was felt that they understood the task and were answering consistently and confidently. The training consisted of providing feedback as to the correct response for about 20 min at each center frequency. At no time was feedback given during the experiments.

The results in Fig. 7 indicate that the ability to discriminate the warbled pulse trains, as measured by the percent warble, deteriorated for frequencies below about 20 Hz. However, as indicated by the large variance at 10 Hz, this poor low-frequency performance may be due to the relation between the center frequency and the length of the test signal. At a 10-Hz center frequency, for example, there would be only ten pulses, on the average, in the entire test signal. Some subjects apparently had difficulty detecting the warble with so few pulses in the total stimulus. A longer test signal and slower warble rate might have resulted in an improved performance for these subjects.

The variance was largest at 160 Hz, with the two smallest difference limens at this frequency being 8.5% and 12% warble. As noted above, the variance between subjects was also found to be high at the 150- and 200-Hz data points for constant-frequency sinusoidal bursts. The large variances at these frequencies may be related to changes in the nature of the sensation above about 100 Hz. Below 100 Hz subjects generally reported a sensation of periodicity or "buzz" that may have been more analogous to the auditory sensation of pitch at those frequencies than the more diffuse tactile sensation experienced at higher pulse frequencies. Thus, as frequency varies between approximately 100 and 200 Hz there may be a change in the quality of the sensation which some subjects learned quickly to associate with frequency variation but which others had more difficulty discriminating.

In order to compare our results with tests at other sites, two of the more consistent subjects were also tested on the thenar eminence and on the finger using a center frequency of 40 Hz. The stimulus intensity was again 20 dB SL. The points in Fig. 7 represent the average performance for the two subjects. It can be seen that there was a small improvement of performance from forearm to thenar to finger. These differences may help explain some of the variation between the results of different laboratories shown in Fig. 5.

To test for the effect of the stimulus waveform, the same warble-discrimination procedure was used with a sinusoidal stimulus, using five of the nine subjects tested with pulses. (The other four subjects were no longer available.) The median performance for these five subjects on the pulse experiment was similar to the group results. To compensate for the variation of subjective magnitude with frequency for sinusoids, a specially constructed electronic filter was used having a frequency response that would result in an approximately constant subjective magnitude as frequency was varied. An equal-subjective-magnitude contour at 16 dB SL was constructed for each subject using the method of matching by adjustment, with an 80-Hz standard. The filter was then set to this contour at the start of each test session and tested by manually sweeping through the range of frequencies to be used. Adjustments were made if any significant changes in subjective magnitude were reported.

The warble-tone results for sinusoids, as shown in Fig. 8, were similar to those for pulses. While the medians for sinusoids were generally lower, the interquartile ranges for pulses and sinusoids show a significant overlap.

Figure 9 shows the warble-tone data replotted in term of $\Delta f/f$ (solid lines) and superimposed on the comparison

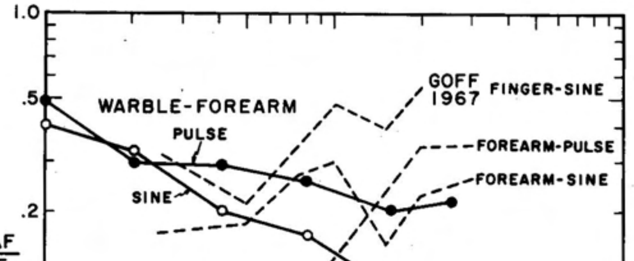

FIG. 9. Measurements of frequency DL on the forearm using the warble-tone method (solid lines) compared with the measurements of frequency DL from Fig. 5, in which a constant-frequency method was used (dashed lines and cross).

of frequency DL's from Fig. 5. To make the comparison more meaningful, we have estimated that the detection of the warble is equivalent to comparing constant frequencies separated by about three-quarters of the peak-to-peak warble. In other words, we are assuming that at a 1-Hz warble rate the peak-frequency excursions cannot be sensed, and that a frequency change must be at least about $\frac{1}{4}$ sec in duration to be detectable. However, this figure should be considered a subjective estimate, since no direct measurements were made of the averaging time required for frequency discriminations on the skin.

Considering the differences in vibration site, and the high intersubject variability, Fig. 9 shows that below about 100 Hz our warble-tone measurements are at least consistent with the measurements of Goff, and our own constant-frequency results. However, above 100 Hz the warble-tone method appears to yield a comparatively smaller difference limen than does the constant-frequency method. This may be related, at least in part, to our previous observation that the sensation above 100 Hz is less tonal than that below 100 Hz. The constant frequency method requires that the subject identify correctly the direction of the frequency change, while the warble-tone method only requires the detection of a variation in frequency. It is possible that above 100 Hz it is much easier to detect a change or difference in frequency than to identify the direction of the change or difference.

Warble-tone frequency discrimination experiments were also attempted with two profoundly deaf subjects, one age 11 and one a young adult college student, and with one other college student with a severe-to-profound hearing loss. All had a prelingual impairment, but otherwise apparent normal sensory capabilities. In each case we had considerable difficulty in locating difference limens for frequency within the range found for the normal hearing subjects. The subjects generally appeared to grasp the task briefly after some instruction and examples, only to have their performance deteriorate during repeated trials without feedback as to the correctness of the response. Even though a signing interpreter was used with the two profoundly deaf subjects, and the third subject had good oral communication, the communication of instructions may have been a contributing factor. However, with each subject there seemed to be an underlying problem stemming from a relative lack of experience in interpreting vibratory frequency. Though it was decided to discontinue testing with deaf subjects until there was time for a better control of subject history, communication ability, and learning of the task, these preliminary results are included here because of the possible significance of the findings. As pointed out by Kirman (1973), an initial advantage by hearing persons in interpreting a given dimension of a vibratory stimulus may indicate a natural association by the central nervous system between the sensation associated with that dimension and a similar auditory sensation.

The frequency discrimination experiments reported thus far employing sinusoids utilized the compensatory filter that provided an equalization of subjective magnitude for stimuli at different frequencies. In order to assess the effect of adding a subjective magnitude cue to the frequency-discrimination task, the warble-tone experiment was repeated on the forearm of five subjects using sinusoids at a center frequency of 40 Hz, both with and without the compensatory filter. Removal of the compensatory filter introduces cues of subjective magnitude that are related to frequency. Addition of the amplitude cue was found to improve the performance for each subject, with the average difference limen decreasing from 25% of the center frequency to 17.5%. This result illustrates the need to control for subjective magnitude when measuring frequency discrimination.

III. CONCLUSIONS

The frequency-discrimination experiments may be summarized in the following way. First, we may conclude that Goff's (1967) estimate of the frequency-discrimination ability of the skin may have been overly pessimistic by a factor of at least 2. On the other hand, the lowest reported estimates of frequency DL (Franzén and Nordmark, 1975) were obtained using a definition of difference limen that we feel results in estimates that are unrealistically small. The low estimates of frequency DL obtained by Mowbray and Gebhard (1957) may be related to their method of stimulation or to the method of adjustment they used. The somewhat low DL at 30 Hz reported by LaMotte and Mountcastle (1975) is not inconsistent with our results, considering that their measurements were made on the thenar eminence, and that their subjects received considerable training before testing. Since practice can have a marked effect on auditory threshold (Zwislocki, Maire, Feldman, and Rubin, 1958) it is reasonable to believe that it would also reduce the DL for the more ambiguous variable, vibrotactile frequency. It should also be noted that frequency DL's in the nonwarbled mode may not provide a realistic estimate of the discrimination potential when encoding the typical variations in a speech-derived parameter.

For speech movements occurring at roughly a 1-Hz rate, as assumed here, the lowest vibratory frequency useable for encoding a speech-derived parameter would be about 10 or 15 Hz. Using the results of the warble-tone experiments, we could estimate that in the region of clearest sensation of buzz or tonality, up to, say, 80 or 90 Hz, there are at least seven potentially differentiable steps in frequency on the forearm, and perhaps ten on the finger. A discriminability of seven to ten steps indicates that vibrotactile frequency could be used to encode at least the stronger variations in the speech parameter fundamental frequency of voicing. However, in such an encoding, some normalization between speakers may be needed, since there may not be enough resolution to encode the entire range for men, women, and children (70–500 Hz) by a simple monotonic transformation, such as dividing fundamental frequency by four or five. For example, it may be desirable to employ a variable scaling that would encode the total fundamental frequency range for each speaker (a span of roughly 100 Hz) into the vibrotactile frequency range of 15–90 Hz.

However, if the apparently less tonal vibrotactile sensations produced by frequencies above 100 Hz also proved usable in encoding a speech-derived parameter, the number of potentially differentiable steps would be approximately doubled, and it might be possible to encode voice fundamental frequency using one scale factor for most voice ranges. A small increase in the number of differentiable steps may also be obtained by raising the stimulus amplitude. Those studies in which the stimulus level was a variable generally indicate that a reduction in the frequency DL of up to 30% or 40% may be possible if the stimulus level could be increased by about 20 dB over the range used in this study (Goff, 1967; Rösler, 1957).

If the stimuli are pulses of width 1 msec or less, moderate vibration amplitudes could be used, with the same amplitude at all frequencies. However, the use of smoother functions, such as sinusoids, should not be discounted; and, in fact, our results suggest that the degree of smoothness of the pulse may be useable as an information-bearing variable, simultaneous with the pulse frequency.

Though a spatial variable, such as the locus of vibration, could be used to replace or augment vibration frequency for the encoding of voice fundamental frequency, it may be more fruitful to reserve the tactile spatial variables for encoding those more complex dimensions of the speech signal which are related to articulation. For example, in a tactile vocoder, a one or two dimensional spatial array of vibrators is usually used to encode spectral structure. The vibrators of the spatial array could be excited at a frequency derived from voice fundamental frequency during voiced speech segments, instead of the one fixed frequency generally used. Such a scheme would make the encoding of fundamental frequency alone with a single vibrator compatible with its use in the vocoder array.

In a tactile vocoder, it is also possible to encode spectral information simultaneously into vibration frequency and a spatial variable, as occurs along the basilar membrane of the cochlea. Fundamental frequency could then be encoded into the frequency of a separate vibrator. Some form of encoding of spectral information into vibration frequency can be found in the schemes proposed by Edmundson (1974), Guelke and Huyssen (1959), Keidel (1974), Kringlebotn (1968), and Traunmüller (1975).

In conclusion, it should be pointed out that in the work reported here there has been a tacit assumption that a fixed and simple waveform was important to the tactile encoding of vibration frequency. This assumption was explored only so far as simultaneous variations of subjective magnitude ware concerned. We expect that fundamental frequency variations in a much more complex periodic waveform, as might be present in a low-pass filtered or a frequency reduced version of the raw speech waveform, may be less discriminable than for the simple waveforms tested here, since the skin would not be expected to have the ability of the ear to extract the periodicity of complex waveforms. However this assumption has yet to be tested.

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