Contours of equal perceived amplitude and equal perceived frequency for electrocutaneous stimuli

CLAYTON L. VAN DOREN
Case Western Reserve University, Cleveland, Ohio

Previous measurements of equal-sensation contours for electrocutaneous stimuli consisting of repeated bursts of biphasic pulses have shown that stimulus frequency has little effect on perceived amplitude, and that stimulus amplitude has no effect on perceived frequency. These earlier contours, however, were measured over a very restricted range of amplitude and frequency or for a single perceived amplitude or perceived frequency. Contours of equal perceived amplitude and equal perceived frequency were measured in the present study for stimuli covering most of the useable range of amplitudes and frequencies: 3–12 dB SL and 4–64 Hz. Eight naïve subjects generated contours of equal perceived amplitude at four reference amplitudes via Békésy tracking, and 8 additional subjects generated contours of equal perceived frequency at three reference frequencies. The contours of equal perceived amplitude declined slightly but significantly with increases in stimulus frequency, consistent with previous results. The shape of the contours was also slightly dependent on the amplitude of the reference stimulus. Contours of equal perceived frequency were unaffected by stimulus amplitude on the average, but the contour shape did vary modestly, though erratically, with reference frequency.

Electrical stimulation of cutaneous afferents is a convenient, flexible, and efficient method for providing sensory information to a person with impaired tactile, visual, or auditory sensation, or to the user of an insensate manipulator (Kaczmarek, 1995; Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991; Riso, Ignagni, & Keith, 1991; Szeto & Riso, 1990; Szeto & Saunders, 1982; Van Doren, Riso, & Milchus, 1991). Electrocutaneous sensations, like most sensory continua, can be modulated along more than one perceptual dimension by changing stimulus parameters. A repetitive train of discrete electrical stimuli has, among other qualities, a perceived amplitude and a perceived frequency. Perceived amplitude is determined primarily by the physical amplitude of the stimulus; and perceived frequency, by the physical frequency—but neither perceptual dimension depends wholly on a single physical dimension.

Interactions between the physical dimensions of amplitude and frequency occur at both sensory and cognitive levels. Interactions at the sensory level result in “distortion” (Poletto & Van Doren, 1995), so that perceived amplitude is changed (distorted) by changes in stimulus frequency and perceived frequency is distorted by changes in stimulus amplitude. In difference scaling, for example, increasing amplitude reduces perceived frequency differences and increasing frequency increases perceived

differences in amplitude (MacFie & Thomson, 1981). Cognitive interactions are manifest as changes in cognitive processing time when the subject is asked to attend to only one dimension while another dimension is changing (Garner, 1974; Garner & Felfoldy, 1970). Stimulus categorization along either the amplitude or the frequency dimension is slower if the other dimension is varied at random, but categorization is faster if the other dimension is varied in a deterministic, correlated fashion (Poletto & Van Doren, 1995). Similar results have been observed for vibrotactile (Melara & Day, 1992; Taylor, 1977; see also Sherrick, 1985; Summers et al., 1994) and auditory (Melara & Marks, 1990) stimuli, and they occur whether distortion is present or absent.

Both types of interactions present design problems for sensory communication devices. Cognitive interactions may be impossible to avoid, but systems can be designed to take advantage of improvements conferred by such interactions (Riso & Ignagni, 1986; Sherrick, 1985; Summers et al., 1994) or to accommodate impairments. Distortion, in contrast, can be eliminated by co-varying frequency and amplitude to produce unidimensional changes in sensation. In previous studies, researchers have attempted to measure the amount of electrocutaneous distortion (Menia & Van Doren, 1994; Szeto, 1985) and then compensate for it (Szeto & Farrenkopf, 1992). The results have been limited to single contours of equal perceived amplitude (i.e., the set of amplitudes and frequencies with the same perceived amplitude as a fixed standard), which appear to differ significantly across studies. Szeto (1985), Menia and Van Doren (1994), and Blamey and Clark (1987) found that the contour of equal perceived amplitude could be described by a power function of the form

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$$A = m \log(F) + b, \quad (1)$$

where A is the stimulus amplitude (charge, current, or pulsewidth, expressed in decibels) and F is the stimulus frequency. Whereas Szeto (1985) reported a steep slope of -2.48 dB/octave¹ from 5 to 100 Hz, Menia and Van Doren (1994) found a much weaker dependence, with a slope of only -0.137 dB/octave from 2 to 64 Hz (see Figure 6B). Blamey and Clark (1987) measured a contour of equal perceived amplitude at the "maximum comfortable level" for frequencies from 25 to 400 Hz, with a slope of -0.71 dB/octave.

Fewer data are available on the perceived frequency of electrocutaneous stimuli. Menia and Van Doren (1994) found no effect of amplitude on perceived frequency, but they tested only a single reference frequency (25 Hz) and a limited range of amplitudes (5–7 dB above threshold). Békésy (1957) reported some limited evidence (a stylized representation of the data from a single subject) that amplitude distorts perceived frequency for sinusoidal electrocutaneous stimuli, but he asked subjects to attend only to sensations of "mechanical vibration" while ignoring "localized pricks" and perceived "pushes and pulls" also evoked by the stimulus. Given the difficulty of the task and the scant data, it is difficult to conclude whether distortion of perceived frequency exists for electrocutaneous stimuli.

The purpose of the present study was to measure electrocutaneous distortion of both perceived frequency and perceived amplitude more completely, covering a wide range of amplitudes and frequencies. Contours of equal perceived amplitude for an electrocutaneous stimulus consisting of repeated bursts of biphasic pulses were measured at four levels, ranging from faint (3 dB above threshold) to intense (12 dB above threshold) over a four-octave range of frequencies (4–64 Hz). Contours of equal perceived frequency were measured using three reference frequencies (8, 16, and 32 Hz), over the same range of amplitudes. The results show that stimulus frequency had a small though significant effect on perceived amplitude and that the effect changed slightly with the amplitude of the reference stimulus. Amplitude, in contrast, had no overall effect on perceived frequency, but its effect did differ significantly at different reference frequencies.

METHOD

Some methods were common to all of the present experiments and have been described in detail previously (Menia & Van Doren, 1994; Poletto & Van Doren, 1995; Van Doren et al., 1991). All stimuli consisted of repeated bursts of 10 charge-balanced, constant-current, biphasic pulses, illustrated in Figure 1A. The pulses within each burst were presented at a frequency of 1000 Hz and were not discriminable. Bursts of pulses tend to be more comfortable than single pulses (Saunders, 1974) and provide a wider range of perceived amplitudes without causing pain (Kaczmarek, Webster, & Radwin, 1992). Pulse current and burst frequency were the experimental variables. Stimuli were applied via a surface electrode with a circular stainless steel cathode and an annular stainless steel anode separated by a slightly recessed plastic insulator (Figure 1B). The electrode was placed on the lateral surface of the upper arm a

Figure 1. (A) The electrocutaneous stimuli consisted of repetitive bursts of balanced, biphasic, constant-current pulses. Ten pulses were presented in each burst at a frequency of 1 kHz. The burst frequency F varied from 4 to 64 Hz. (B) Stimuli were delivered through a concentric bipolar electrode taped to the lateral surface of the upper arm. The central stainless steel cathode had an area of 0.32 cm^2 , and the area of the annular stainless steel anode was 1.2 cm^2 . (C) A typical Békésy tracking trial for a contour of equal perceived amplitude, with the amplitude (current) of the match stimulus plotted for each reversal in amplitude step direction. Four reversals, indicated by each set of open or closed points, were completed and averaged at each match frequency from 4 to 64 Hz in half-octave steps.

few centimeters proximal from the elbow. The site was cleaned with alcohol and moistened with water to hydrate the skin, stabilize the electrode-skin impedance, and prevent uncomfortable sensations (Kaczmarek et al., 1991; Mason & Mackay, 1976; Saunders, 1974). The actual stimulus site was chosen for each subject by applying a 16- or 25-Hz stimulus that felt "moderately strong" (subjective report) and moving the electrode until the subject felt tapping sensations without pricks or stings. The electrode was secured with an adhesive bandage after a suitable site was located. The electrode site was then "warmed up" for 5 min (see, e.g., Kaczmarek et al., 1991), using the site-mapping stimulus.

The threshold for detecting a single burst was measured following the warm-up in the preliminary tracking experiments, and the threshold for detecting a 1-sec stimulus with a burst frequency of 16 Hz was measured in the main experiments. In both cases, detection thresholds were measured with two-alternative, forced-choice (2AFC) tracking, following the method of Zwislöcki, Maire, Feldman, and Rubin (1958). The tracking rule decreased the amplitude after any three correct responses and increased the amplitude after any incorrect response, equilibrating on the average to the amplitude yielding 75% correct identification (Zwislöcki et al., 1958). The step size decreased from 2 to 0.25 dB during the early portions of the tracking, and 25 stimuli were presented and averaged once the step size reached its minimum value. Most threshold measurements had six to nine reversals, and measurements with four or fewer reversals were repeated.

Equal-sensation contours were measured in a Békésy tracking paradigm (Békésy, 1947). A reference stimulus with a fixed amplitude and burst frequency was presented in alternation with a vari-

able match stimulus. Both were 1 sec in duration and were separated by a 1-sec silent interval. Informal trials showed that tracking was more stable with the silent interval than without it, perhaps because of a reduction in the amount of adaptation (see also Van Doren & Menia, 1993; Van Doren et al., 1991). During tracking of perceived amplitude, the frequency of the match stimulus was under the control of the experimenter while the amplitude of the match stimulus was controlled by the subject via a push-button. The subject released the button when the match stimulus felt weaker than the reference, and the match amplitude increased at a fixed rate (0.5 dB per stimulus). The subject pressed the button when the match stimulus felt stronger than the reference, and the match amplitude decreased at the same fixed rate. Either a buttonpress or a release reversed the direction of the amplitude steps, and four such reversals were completed and averaged at each match frequency. A typical record of match amplitude (stimulus current) at each reversal is plotted in Figure 1C. During tracking of perceived frequency, the amplitude of the match stimulus was under experimental control and the subject controlled the stimulus frequency (which changed 0.25 octave per stimulus) in order to match the perceived frequency of the reference.

Effect of Session and Sweep Direction

A control experiment was conducted to determine whether contours of equal perceived amplitude measured under the Békésy tracking protocol (four reversals, tracking rate of 0.5 dB steps per stimulus) were stable across sessions, and whether they were affected by the direction of the frequency sweep. Each of 3 subjects completed two sessions on different days. Four contours were measured in each session, using nine match stimulus frequencies from 4 to 64 Hz in half-octave steps. The match frequency was swept up (*U*) from 4 to 64 Hz or down (*D*) from 64 to 4 Hz, alternating in consecutive contours (e.g., *UDUD*). The sweep order was reversed across sessions (e.g., *UDUD*, then *DUDU*). The reference frequency was 25 Hz (as in Menia & Van Doren, 1994), and its amplitude was fixed throughout the session. The 3 subjects each matched a different reference amplitude: 3, 7, or 12 dB above their single-burst threshold.

The average contour of matching at each reference amplitude is shown by the dashed lines in Figure 2A. The data are the averages of the match stimulus amplitude, in dB re the single-burst threshold, at each of the four reversals for each of the nine match stimulus frequencies. An analysis of variance (ANOVA) showed that match frequency, reference amplitude, and their interaction were all significant ($p < .05$). The contours in the figure are not flat, as was indicated by the significant frequency effect, and they have different shapes at different reference amplitudes, as was indicated by the significant amplitude $\times$ frequency interaction. Sweep direction and session did not exert significant main effects, but sweep direction had a small effect on contour shape, manifest as a significant frequency $\times$ sweep direction interaction ($p = .02$). The open circles in Figure 2A are the averages of all the *U* sweeps, and the filled circles are the averages of the *D* sweeps. The effect of sweep direction on contour shape was controlled in the main experiment by counterbalancing directions across sessions and averaging across sessions. Averaging across sessions is justified because session did not affect the contour shape ($p > .75$), nor did it affect the sweep direction $\times$ frequency interaction ($p > .85$).

Effect of Reference Frequency

A second control experiment was completed with the same 3 subjects in order to assess the effect of the reference frequency on the shape of the contours of equal perceived amplitude. If the shape depends on the reference frequency, the results obtained with any one reference frequency will not be generalizable, restricting the interpretation and application of the results. Contours were measured at a single reference amplitude for each subject, and the reference frequency was 4 Hz in one session and 64 Hz in another.

Figure 2. (A) Results from the first control experiment to assess the effects of session and the direction of the match stimulus frequency sweep on the shape of the contour of equal perceived amplitude. Each dashed contour represents the average of eight contours measured in two sessions from an individual subject matching a reference amplitude of 3, 7, or 12 dB re the threshold for detecting a single burst. The reference frequency was 25 Hz and the match frequency was swept from 4 to 64 Hz or the reverse. The points represent averages of all data for the upward ($\circ$) and downward ($\bullet$) sweeps. (B) Results from the second control experiment to assess the effects of reference frequency on the shape of the contour of equal perceived amplitude. Each of the 3 subjects matched a different reference amplitude: 3, 7, or 12 dB re the single-burst threshold. Points are averages across four sweeps (two in each direction), using a reference of 64 Hz ($\circ$) or 4 Hz ($\bullet$). Results for a 25-Hz reference (Δ) are replotted from (A).

Four sweeps in alternating directions were completed in each session. Data with a reference frequency of 25 Hz were collected in the first control experiment.

The results for each reference frequency are plotted in Figure 2B. The triangles are the 25-Hz data averaged across sweep direction and session from the first experiment. The open circles are the 64-Hz data, and the closed circles are the 4-Hz data. Match frequency and reference amplitude again exerted significant effects on the matching current ($p = .0001$). The shape of the contour varies with reference amplitude (frequency $\times$ amplitude interaction, $p = .04$); but the variation may be due to different subjects matching at each amplitude. More importantly, the reference frequency also affected contour shape, as was indicated by a significant reference frequency $\times$ match frequency interaction ($p = .0001$). In Figure 2B, the 25- and 64-Hz contours have similar shapes, whereas the 4-Hz contours are steeper at low match frequencies. The effect of reference frequency also changed with the amplitude (or subject), as was indicated by a significant three-way interaction ($p = .0001$) among reference frequency, match frequency, and reference amplitude.

The effects of reference frequency on the shape of the contours of equal perceived amplitude are probably the result of a matching bias or a context effect. Suppose that we measure a contour by using the

reference stimulus $A = (f_1, q_1)$, and the subject adjusts the amplitude of a match stimulus to get $B = (f_2, q_2)$. Suppose further that we measure a second contour by using B as the reference stimulus, and the subject makes a match $A^* = (f_1, q_1^*)$. If the contours are not identical, then $q_1^* \neq q_1$ even though there is no way to distinguish physically the sequence of stimuli in the first match from the sequence of stimuli in the second match. The only difference between the two cases is the context of the specific trial within the contour—that is, whether or not f_1 or f_2 was the same in preceding trials. Such context effects are not of primary interest here, so only one reference frequency (16 Hz) will be used in the main experiment.² Any conclusions will have to be tempered, however, by the possibility that contour shape might be different for different reference frequencies.

The results of the control experiments show that: (1) contours of equal perceived amplitude are stable and may be averaged across sessions; (2) sweep direction has a small but significant effect on contour shape, so both directions should be used and averaged; and (3) reference frequency has a significant effect on contour shape, though perhaps only at low frequencies. Reference amplitude may have changed contour shape, but the effect was confounded in the control experiment by testing a different subject at each amplitude. As a consequence, each subject in the main experiment was tested at all of the reference amplitudes. It was assumed that similar cautions regarding session, sweep direction, reference amplitude, and reference frequency applied to contours of equal perceived frequency.

Main Experiment

Two separate groups of 8 naïve subjects with no reported sensorimotor abnormalities matched perceived amplitude or perceived frequency in the main experiment. Two males and 6 females, ages 22–44, matched perceived amplitude; and 3 males and 5 females, ages 19–38, matched perceived frequency. Each subject completed four sessions. Equal-sensation contours were measured in the first and third sessions, and detection thresholds were measured at each of the match frequencies, using 2AFC tracking in the second and fourth sessions.

Contours of equal perceived amplitude were measured at four reference amplitudes (3, 6, 9, and 12 dB re the threshold of the 16-Hz reference stimulus), using one sweep direction in a given session. Contours of equal perceived frequency were measured at three reference frequencies (8, 16, and 32 Hz) as the match amplitude was swept in 1-dB steps from 3 dB to 12 dB (re the threshold at 16 Hz) or the reverse. Only three reference frequencies were used, because subjects could easily match the number of bursts in each stimulus at low frequencies (4 Hz) by counting, and subjects could not discriminate frequencies well enough to produce a contour at high frequencies (64 Hz). The presentation orders of reference amplitude or frequency and sweep direction were counterbalanced across subjects via a Latin square design. The data were averaged across subjects and sweep directions.

RESULTS

Thresholds

The average detection thresholds across all subjects and both sessions in the perceived amplitude experiment (closed circles) and perceived frequency experiment (open circles) are plotted in Figure 3 in absolute units. A repeated measures ANOVA with subject group (perceived amplitude or perceived frequency tracking) as the between factor, session (second or fourth) and frequency as the within factors, and all interactions, showed that only the frequency effect was significant ($p < .002$). The results show that threshold depends significantly (though

Figure 3. Detection thresholds in dB re 1 mA as a function of frequency, measured in the second and fourth sessions of the main experiment. Points are averages across the 8 subjects in the perceived amplitude (●) or (○) perceived frequency matching experiment. Error bars represent standard errors of the mean.

slightly) on burst frequency, but that the shape of the threshold contour is stable across the two groups of subjects.

The average thresholds within each group of subjects (Figure 3) were used to convert the match amplitudes from dB re the 16-Hz threshold to dB SL (sensation level; i.e., dB re the threshold at each frequency). The conversion is given by

$$I(\text{dB SL}) = 20 \log \left(\frac{i}{i_0} \right) = 20 \log \left(\frac{i}{i_{16\text{Hz}}} \cdot \frac{i_{16\text{Hz}}}{i_0} \right)$$

$$= I(\text{dB re 16 Hz}) - I_0(\text{dB re 16 Hz}), \quad (2)$$

where i_0 refers to the threshold current at each frequency in absolute units, and $i_{16\text{Hz}}$ refers to the threshold of the 16-Hz reference stimulus.

Contours of Equal Perceived Amplitude

Contours of equal perceived amplitude are shown in Figure 4. Figure 4A shows the contours from both sessions of a typical subject, with match amplitudes plotted in dB re the threshold of the 16-Hz reference stimulus (i.e., amplitudes are not corrected for changes in threshold with frequency). Each point is the average of the four reversals at each frequency. The open symbols represent data from the session with upward frequency sweeps, and the closed symbols represent downward sweeps. Figure 4B shows the contours averaged across all subjects and sessions, expressed in dB SL. Error bars are omitted for clarity, but standard errors at all points are 0.4 dB or less. Note that the conversion to dB SL imparts an inflection between 8.00 and 11.3 Hz to all of the perceived amplitude contours. The large symbols represent the actual contours, and the lines represent “nominal” contours. That is, the contours were averaged across all ref-

Figure 4. (A) Contours of equal perceived amplitude from a single subject plotted in dB re the threshold of the 16-Hz reference stimulus. Open symbols are averages of upward sweeps of match frequency, and closed symbols represent downward sweeps. (B) Contours averaged across all subjects and both sweep directions, plotted in dB SL. Standard errors were 0.4 dB or less. Large symbols are the actual contours, and the lines represent nominal contours passing through the coordinates of the reference stimuli (small symbols). The nominal contours have the shape of the average taken across all reference amplitudes.

erence amplitudes, and nominal contours with the average shape were drawn through each of the four reference amplitudes (3, 6, 9, and 12 dB SL) at 16 Hz. The coordinates of the reference stimuli are shown by the small symbols. A repeated measures ANOVA of average contours from each subject, with match amplitudes expressed in dB SL (relative to the thresholds for each subject) showed highly significant effects ($p < .0001$) of reference amplitude and match frequency, as expected. The interaction of frequency and reference amplitude was also significant ($p = .04$), but it produced only slight variations between the shapes of the actual and nominal contours shown in Figure 4B. In sum, the effect of frequency on perceived amplitude was small and was nearly independent of the stimulus amplitude—at least over the range of amplitudes examined here.

Contours of Equal Perceived Frequency

Contours of equal perceived frequency from both sessions of 1 subject are plotted in Figure 5A, where each point represents the geometric mean of four reversals in match frequency (D , open symbols; U , closed symbols). All match amplitudes are expressed in dB re the thresh-

old of the 16-Hz reference stimulus. The contours are repeatable for both sweep directions for amplitudes greater than 3 or 4 dB. Perception of frequency is very difficult for faint stimuli, resulting in poor matches and erratic contours across sessions for individual subjects. Contours averaged across sweep directions and subjects are plotted in Figure 5B (symbols). Error bars have been omitted for clarity, but standard errors are less than 0.15 octaves for amplitudes above 5 dB, and less than 0.25 octaves for smaller amplitudes. The amplitudes in Figure 5B have been converted to dB SL according to Equation 2. The conversion shifted amplitudes by -0.25 , 0.0 , and 0.05 dB at 8, 16, and 32 Hz, respectively. Because the shifts were quite small, the data from each uncorrected amplitude (3–12 dB) were pooled for subsequent analysis.

A repeated measures ANOVA was applied to the contours averaged geometrically across sweep direction from each subject, with reference frequency and match amplitude as factors. Match frequency, transformed to a loga-

Figure 5. (A) Contours of equal perceived frequency from a single subject plotted in dB re the threshold of the 16-Hz reference stimulus. Open symbols are geometric averages of upward sweeps of match amplitude, and closed symbols represent downward sweeps. Note that the independent variable is the match current, plotted on the vertical axis for consistency with previous figures. The dependent variable is match frequency, plotted horizontally. (B) Contours averaged across all subjects and both sweep directions, plotted in dB SL. Standard errors were 0.15 octaves or less for amplitudes greater than 5 dB. Matches at smaller amplitudes were more variable, with standard errors up to 0.25 octaves. Large symbols are the actual contours, and the lines represent nominal contours passing through the coordinates of the reference stimuli (small symbols).

rithmic scale (octaves), was the dependent variable. Reference frequency exerted the strongest effect ($p < .0001$), as expected. The average match frequencies across all conditions were 8.72, 17.5, and 32.2 for reference frequencies of 8, 16, and 32 Hz, respectively. Match amplitude did not have a significant effect on match frequency ($p = .88$), but it did interact significantly with reference frequency, showing that the contours had different shapes ($p = .01$). The differences are shown in Figure 5B by comparing the actual contours (symbols) to nominal contours (lines). The latter were constructed by creating an average contour across all subjects and reference frequencies, and shifting it to pass through each of the reference frequencies (small points). The 8-Hz contour is distorted toward higher frequencies at low amplitudes, whereas the 16-Hz contour diverges towards higher frequencies at high amplitudes.

DISCUSSION

The results from the main experiment are summarized in Figure 6A, where the thick lines are the average equal sensation contours replotted from Figures 4B and 5B. The thin lines pass through the coordinates of the reference stimuli and represent idealized, undistorted matches. In reality, frequency distorted perceived amplitude slightly but significantly, so that the physical amplitude necessary to maintain a fixed perceived amplitude decreased with increasing frequency. Put another way, the perceived amplitude at a fixed physical amplitude increased with increases in frequency. The frequency-induced distortion was nearly independent of the reference amplitude, but the subtle differences in the shapes of the contours of equal perceived amplitude were statistically significant. Amplitude, in contrast, did not significantly distort perceived frequency on the average—although the observed contours of equal perceived frequency were not parallel to each other.

The contours from the present experiment are similar to earlier results of Menia and Van Doren (1994), compared in Figure 6B. All data in that figure, including the contours from the present study (thick lines) are plotted in dB re the reference threshold, since detection thresholds were not measured at all match frequencies in the previous study. The purpose of the Menia and Van Doren experiment was to measure distortion over a range of electrocutaneous stimuli suitable for representing the surface texture of a set of grooved plates (Menia, 1993; Van Doren & Menia, 1993). Menia and Van Doren measured distortion by having subjects adjust the amplitude or frequency of a matching stimulus to match the perceived frequency or perceived amplitude of a 25-Hz, 7.5-dB reference. Subjects were permitted as many adjustments as they wanted in order to make a match, and they made three matches for each reference stimulus in each of four sessions. Regressions failed to show significant distortion of perceived amplitude (Figure 6B, large filled circles) or perceived frequency (open circles) over the narrow range of stimuli used, even though the different

Figure 6. (A) Thick lines are equal-sensation contours replotted from Figures 4B and 5B, with amplitudes in dB SL. Thin lines are orthogonal contours expected if distortion were absent. (B) Comparison of equal-sensation contours from the present study (thick lines), Menia and Van Doren (1994, $\circ$, $\bullet$, Δ), and Szeto (1985, $\blacktriangle$, ∇); all are expressed in dB re the particular reference stimulus used in the study. (C) Comparison of contours of equal perceived amplitude as replotted from (B), but with match amplitudes expressed in units of JNDs according to Equation 4. The contour from the present study (thick line) represents the average across all reference amplitudes.

physical frequencies and amplitudes were discriminable. Menia and Van Doren repeated the perceived amplitude matches over a wider range of frequencies (Figure 6B, small points), resulting in a small but significant reduction of match amplitude with increasing match frequency. The reduction is consistent with but smaller than the decrease measured in the present study (Figure 6B, thick lines).

Figure 6B (triangles) also shows contours of equal perceived amplitude from Szeto (1985), which seem to differ markedly from the others (see Menia & Van Doren, 1994). Szeto's subjects adjusted pulse width to equalize the perceived amplitude of two stimuli consisting of

trains of single, monophasic, capacitively coupled pulses presented at different rates. The reference stimulus had a pulse width of 200 μ sec and rates of 10 or 20 pulses per second (Figure 6B; downward and upward triangles, respectively). Menia and Van Doren attributed the discrepancy to differences in the stimuli (single pulses vs. bursts of pulses) or their timing (the presence or absence of a silent interval between the match and reference), but failed to acknowledge another possibility: differences in the sensitivity to changes in amplitude for the two types of stimuli.

The data can be normalized by expressing the stimulus amplitude (i.e., charge) q in units of Δq , the discrimination threshold or just noticeable difference (JND). As a rough approximation, we can assume that the Weber fraction ($w = \Delta q/q$) is constant (Weber's law) throughout the range of stimulus charges. The charge q_n that is n JNDs above the threshold q_0 is given by

$$q_n = q_0(1 + w)^n. \quad (3)$$

Therefore, the number of JNDs corresponding to a charge q_n is given by

$$n = \frac{\log\left(\frac{q}{q_0}\right)}{\log(1 + w)} = \frac{Q(\text{dB})}{20 \log(1 + w)}. \quad (4)$$

The average data from the present study, from Szeto (1985), and from Menia and Van Doren (1994) are all replotted in Figure 6C with amplitudes expressed in JNDs obtained with Equation 4 and previous measurements of the Weber fraction for each stimulus type: 0.40 for Szeto's stimuli (from Szeto, Lyman, & Pryor, 1979) and 0.033 for the stimuli in the present study (from Menia & Van Doren, 1994). The slopes are now commensurate, with the results of Szeto (1985) falling between those of the present study and those of Menia and Van Doren. The latter two studies used identical stimuli but different matching protocols (Békésy tracking and adjustment, respectively) and reference frequencies (16 vs. 25 Hz). The conversion to JNDs is approximate at best, but it does illustrate the possibility that discrepancies identified previously between contours of equal perceived amplitudes from different studies may vanish when physical amplitude is converted to units of discriminability. It appears that all of the contours drop by 3–4 JNDs over the range of frequencies tested.

It is tempting to presume that the poor discriminability of pulse durations near 200 μ sec, as used by Szeto (1985), is due to incomplete integration of stimulus charge. It is well known that below a certain critical duration, fiber activation is dependent only on the total charge, so that the product of pulse duration and current is nearly constant. Integration of charge becomes progressively incomplete above the critical duration until a minimum current, the rheobase, is reached, which is not reduced by any further increase in duration. A duration of 200 μ sec, however, appears to lie within the integration region, as is shown by four strength-duration curves (Figure 7) measured via

Figure 7. Strength duration curves for single monophasic, cathodic, constant-current pulses at threshold (●, Van Doren, 1996; ◇, Rollman, 1975; △, Friedli & Myer, 1984; □, Tachi, Tanie, & Abe, 1978), or above threshold (thick lines: Babkoff, 1978). The latter functions are drawn for magnitude estimates of 5, 10, 20, and 50. The bracket shows the range of pulse widths used by Szeto (1985), which fall within the range of nearly complete charge integration.

psychophysical detection of cathodic, monophasic, rectangular pulses. The closed circles are data from this laboratory and are averages of pairs of thresholds measured using the method of limits on the upper arm for 7 subjects. Thresholds were measured similarly on the forearm (Rollman, 1975, diamonds), and the index fingertip (Friedli & Meyer, 1984; triangles). The open squares are thresholds measured using a forced-choice method on the upper arm (Tachi, Tanie, & Abe, 1978). A variety of electrode shapes, sizes, and locations were used, but the strength duration functions are remarkably similar. Moreover, the shapes of suprathreshold strength duration functions for single pulses (Babkoff, 1978), shown by the thick lines in Figure 7, are not markedly different from the threshold functions. All of the functions have slopes near -1 over the range of pulsewidths used by Szeto's (1985) subjects (46–677 μ sec; note the bracket in Figure 7), indicating nearly complete integration of charge in this region. Perhaps the stimuli used by Szeto differed in some critical detail from the broad sampling represented in Figure 7, but the robust shape of these strength duration curves across studies, locations, electrodes, and methods argues against attributing the inefficiency at 200 μ sec simply to failure of integration.

No other explanation for the 12-fold difference in amplitude JNDs emerges readily. Adaptation might be suspected, since Szeto (1985; Szeto et al., 1979) presented the match and reference stimuli in alternation without an intervening silent interval, whereas the match and reference stimuli used in the present experiment and used by Van Doren and Menia (1993) were separated by 1 sec. However, two vibrotactile studies suggest that, had adaptation been more prevalent in Szeto's experiments, discrimination would have improved. (The comparison between sensations evoked by electrical and mechanical stimuli is appropriate, since they presumably activate

large, myelinated fibers or their terminal receptors, respectively; see, e.g., Rollman, 1974). Goble and Hollins (1993) measured detection and discrimination thresholds for 1-sec, 25-Hz sinusoids with and without a preceding 15-sec adapting stimulus. They found that the absolute detection threshold increased but the discrimination threshold decreased if the adapting stimulus had the same amplitude as did the standard test stimulus. Gescheider, Bolanowski, Verrillo, Arpajian, and Ryan (1990) found that intensity discrimination was best if the test stimuli were superimposed on a continuous pedestal—the condition that produced the most adaptation of the three paradigms tested in that study. It seems unlikely, then, that adaptation can account for the disparity between JNDs if electrocutaneous stimuli produce the same adaptation effects as do vibrotactile stimuli. Perhaps the disparity can be resolved by further study of electrocutaneous intensity discrimination.

It is also useful to compare vibrotactile and electrocutaneous equal-sensation contours. Contours of equal perceived amplitude for sinusoidal vibrations depend on stimulus amplitude, frequency (Verrillo, Fraioli, & Smith, 1969), and duration (depending on the frequency, Gescheider & Joelson, 1983; and contactor size, Verrillo, 1965). Frequency effects are largely due to the temporal tuning of the receptors. The pacinian corpuscle, for example, has a bandpass characteristic due to its neural low-pass and mechanical high-pass properties that yields U-shaped threshold functions (Bolanowski & Zwislocki, 1984; Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968) and suprathreshold contours of equal perceived amplitude (Verrillo et al., 1969). That is, lower stimulus amplitudes are needed to produce a given perceived amplitude for frequencies at the center of the passband than on the skirts. A repetitive train of mechanical pulses or taps, in contrast, has a uniform spectral envelope regardless of the pulse frequency, and changes in perceived amplitude with pulse frequency or number reflect central integration rather than peripheral filtering. Pulses applied through a large contactor (1.9 cm diameter) on glabrous skin apparently activate pacinian corpuscles, and perceived amplitude increases with both the frequency and the number of pulses as though passing through an energy integrator with a 200-msec time constant (Verrillo, 1965; although see Sherrick, 1985). In marked contrast, pulses delivered through a small contactor (diameter < 0.16 cm; Verrillo, 1965) or to hairy skin (Rothenberg, Verrillo, Zahorian, Brachman, & Bolanowski, 1977) show little or no integration at or above threshold, suggesting that they excite one or more of the non-pacinian receptor systems known to lack temporal integration (for reviews of receptor systems in glabrous and hairy skin, see Bolanowski, Gescheider, & Verrillo, 1994; Bolanowski, Gescheider, Verrillo, & Checkosky, 1988). Perhaps electrical stimuli also excite these non-pacinian receptors, resulting in relatively flat electrocutaneous contours of equal perceived amplitude, although the mechanism for such selectivity is uncertain (e.g., Blamey et al., 1990).

Electrocutaneous perceived frequency is distorted erratically by stimulus amplitude, with no average effect over the range of frequencies and amplitudes tested here. It is reasonable to hypothesize that an electrocutaneous stimulus at frequency F produces a neural response that is modulated at that same frequency, unless the stimulus is so weak that each of the component bursts evokes less than a single spike on the average. If periodicity is the substrate for perceived frequency, amplitude should have no effect, as has been observed here (on the average). Békésy (1957) argued, though, that the asynchronous firing of receptors at low amplitudes actually produces a “sort of white noise” (p. 1061) taken over the whole population, which has a perceived frequency that is higher than that associated with F . As the amplitude increases, the firing becomes more synchronized, and the perceived frequency drops. If that were the case, we would expect that the matching frequency would exceed the standard at low amplitudes and decrease to equal the standard at high intensities. Indeed, just that pattern was observed for matches made to the 8-Hz reference (Figure 5B); but the relatively high match frequencies observed at low amplitudes are the least certain, and the pattern was not apparent in the contours at 16 and 32 Hz. Moreover, Békésy’s own data (Békésy, 1957, Figure 4) fail to follow the pattern, with match frequencies equal to the standard at low amplitudes and above the standard at high amplitudes. The distortions reported by Békésy were also small, and he presented data from a single subject in a stylized plot. There is little evidence, then, to conclude that stimulus amplitude affects the perceived frequency of electrocutaneous stimuli.

The results of the present experiment, in sum, suggest that frequency distortion of perceived amplitude and amplitude distortion of perceived frequency are present for electrocutaneous stimuli, but that the sizes of the effects are modest. Contours of equal perceived amplitude dropped by 2–4 JNDs as frequency increased over a four-octave range, and the effect was nearly independent of the reference amplitude. To a first approximation, then, it is possible to correct for frequency-induced distortions with a single equation of the form given in Equation 1, varying only the intercept to adjust perceived amplitude. Amplitude-induced distortions of perceived frequency are not corrected as easily. Since there was no average effect of amplitude on perceived frequency across the three reference frequencies, it may be reasonable to ignore amplitude effects in practice. However, the differences in the shape of the contours of equal perceived frequency suggest that corrections should vary with the perceived frequency, complicating such procedures in real devices. It should be noted, in conclusion, that the equal-sensation contours reported here were measured at a single, carefully chosen electrode site, using a particular method (Békésy tracking), a particular stimulus timing, and a single reference frequency (16 Hz) or a single reference amplitude (7.5 dB). The results represent only a first approximation to the effects that might manifest themselves

in a sensory communication device. Moreover, it will be both interesting and necessary to determine whether such distortions, regardless of their magnitude, lead to functional deficits in the use of communicative or sensory substitution devices.

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2. 16 Hz was chosen for the main experiment because it falls at the logarithmic midpoint of the overall frequency range of 4-64 Hz. 25 Hz was chosen for the middle frequency in the control experiments to match the reference stimulus used in an earlier study (Menia & Van Doren, 1994).

NOTES

1. Szeto (1985) actually reported his slope as -0.412 decades pulse width per decade pulse rate. The slope in dB per octave is $-0.412(20 \text{ dB/decade})/(3.32 \text{ octaves/decade}) = -2.48 \text{ dB/octave}$.

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