Equal-onset contours of vibrotactile stimuli*

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Characteristic sensations of "surge" occur at onset of vibratory stimulation, analogous to the experience of musical "attack" in the auditory modality. Such a cutaneous sensation may have a phenomenal reality that is discriminable from the sensitivity to either of its physical determinants of time and intensity. Contours of equal-onset sensation obtained by the method of adjustment permitted the assessment of the relative contributions of these two parameters. Both rise time and intensity were found to be significant factors in the determination of contours of equal-onset sensation obtained by either time adjustment or adjustment of vibratory intensity. Equating onset by intensity adjustment was found to be more difficult than equating onset by time adjustment.

The interaction of the physical variables of a stimulus can produce a greater number of parameters of sensory attributes than there are physical variables involved (Boring, 1935). For example, from the two physical attributes of intensity and frequency, at least four attributes can be obtained in the auditory modality—pitch, loudness, volume, and density (Stevens, 1934a). In the cutaneous modality, the ability of man to discriminate in the four primary dimensions of tactile sensitivity—duration, intensity, locus, and frequency—has been systematically investigated (Craig, 1972; Diespecker, 1970; Goff, 1967; Howell, 1956; Sherrick, 1950; Spector, 1954).

Onset and "phi" are examples of secondary dimensions created by appropriate combinations of the primary dimensions. Cutaneous "phi" refers to the feeling of apparent movement resulting from the interaction of the temporal and spatial conditions of the stimuli; cutaneous onset refers to the characteristic sensation of "surge" that is dependent on the temporal and intensive dimensions of the stimulus. The sensory attribute of cutaneous onset is analogous to the sensation of musical "attack" in the auditory modality. For audition, onset has been the topic of considerable investigation (Békésy, 1933; Hirsh & Zérlin, 1965; Liberman, Harris, Kinney, & Lane, 1961; Pollack, 1963; Tenney, 1962).

In the cutaneous modality, Howell (1958) studied the discriminability of the right index finger for onset and offset of vibratory stimuli, using a 60-Hz signal with a sigmoidal onset envelope. Working with rise times that ranged from 20 to 1,420 msec, Howell found 6 jnds for a terminal signal amplitude of 480 microns, 3 jnds for a terminal amplitude of 4 microns, and intermediate results for a terminal amplitude of 8 microns. Because of

these differences in discriminability at various intensity levels, Howell suggested that slope (i.e., the rate of signal growth) determines onset judgment rather than rise time per se. Sticht (1968; Sticht & Foulke, 1966) studied the effect of rise time upon threshold (RL) and reaction time for electrocutaneous stimuli. He reported that the RL was slightly elevated for onset times of less than 50 msec, but that it was not affected by longer durations of onset. RT was found to be directly related to the rise time, for those times longer than 50 msec. Geldard (1964) obtained magnitude estimates for onset of electrocutaneous stimuli whose rise times ranged from 25 to 402 msec with a sigmoidal envelope. Geldard found a power function for onset that had an exponent of about unity and was independent of the frequency and intensity of the stimuli. Whereas no intensive effect was evident, coupled with the fact that the power function for the estimation of electrical duration also is about 1.0, Geldard concluded that rise time rather than slope might well be the basis for the judgment of electrical onset.

Establishing jnds for vibrotactile onset demonstrates capability for discrimination of onset, but does not indicate the relative contributions of the dimensions of time and intensity to this attribute. In preliminary investigation, the author obtained magnitude estimates of onset and determined the power function for vibrotactile onset for an assortment of covarying rise times and intensity levels, and thus indicated the importance of both of these primary dimensions to the judgment of onset (1965).

The relationship of the two primary dimensions to the sensation at stimulus onset can be accurately determined by the method of average error, using the technique employed by Stevens (1934b) for his dimensional analysis of the auditory modality. It is possible, by this method, to equate a comparison signal to a standard value of onset. Matching of sensory magnitudes across the two dimensions of intensity and frequency has been successfully accomplished for vibrotactile stimuli (Goff, 1967; Stevens, 1966; Verillo, Fraioli, & Smith, 1969). If

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Fig. 1. Block diagram of the apparatus for producing adjustable onsets of vibratory stimuli.

the value of either the rise time or the terminal intensity of the comparison were fixed, the O could adjust the other value until the sensations at onset for comparison and standard were judged to be equal. The purpose of the present study was to determine such equal-onset contours for vibrotactile stimuli by this procedure.

EXPERIMENT I ONSET MATCHING BY TIME ADJUSTMENT

Method

Apparatus

A diagram of the apparatus is shown in Fig. 1. Two separate channels provided for independent control of the standard and adjustable signals. In the circuit of the standard signal, the 200-Hz output of a Hewlett-Packard 200 AB audio oscillator was connected to an electronic switch¹ to generate transientless onsets with a linear envelope over a range of 1 to 1,000 msec. The output of the electronic switch passed through a Triad HSM-85 impedance-matching transformer to a Langevin 128X 20-W amplifier, and thence to a Hewlett-Packard 5-W attenuator. The attenuated signal was mixed with the output from a similar circuit for the adjustable signal, and was then sent through a UTC CVL-1 impedance-matching transformer to a Goodmans V-47 vibrator with a 3-ohm coil, which converted the electrical signal into movement of the 17-mm-diam stimulus tip.

The circuit that developed the adjustable signal differed from the foregoing description in a few details. A General Radio GR-1304-A beat-frequency oscillator was connected to an electronic switch of the same type used for the standard but with a range of onset times of 1,700 msec. External controls for O's use were added to this circuit; intensity was controlled by a 10-revolution CIT 500-ohm T-pad inserted after the Hewlett-Packard attenuator, and onset time was controlled by a General Radio 50,000-ohm rheostat (330-deg revolution) connected to the ramp circuit of the onset generator.

Calibration of the physical amplitude of vibration for any given input voltage was obtained with an MB Mfg. Co. Model M3 vibration meter and pickup. Voltage on the V-47 vibrator was measured with a Ballantine Model 300 VTVM, while rise time was monitored on a Tektronix Type 503 oscilloscope. The oscilloscope pattern for an onset of 100 msec is depicted in

Fig. 2. The picture was obtained from the integrated velocity output of a velocity pickup directly sensing the output of a Goodmans V-47, using apparatus described by Craig and Sherrick (1969) and Geldard and Sherrick (1966).

Procedure

The four Os were psychologists employed in a laboratory for cutaneous research who were experienced in making psychophysical judgments of vibrotactile stimuli. O placed his right arm and palm on a comfortable horizontal support of foam rubber so that the ball of the index finger rested on the stimulator tip of the vibrator. The weight of the finger and the compliance of its relaxed musculo-tendinous system assured constant, firm coupling to the contactor. Prior to each session, O's absolute threshold for 2.0 sec of vibrotactile stimulation was determined by the method of limits. At all times, O received white noise through headphones in order to mask any auditory cues produced by the equipment. The program of vibratory presentation was controlled by microswitches operated by a synchronous motor. A low-voltage condenser discharge of a local circuit proximal to the Goodmans V-47 coil generated a brief dc pulse to the vibrator, thus producing a low-level warning signal. The resultant waveform for this vibrator has been described by Sherrick (1964). Sixteen hundred milliseconds later (a time determined to be well beyond the integration time), the standard signal was turned on for 2,200 msec; this was followed by a 1,200-msec pause, after which the adjustable signal was given for 2,400 msec. The remainder of the 10-sec program was a rest period before the start of the next cycle. Intensity of the standard signal was fixed at 40 dB SL, while onset time of the standard was set at one of four values, ranging from 100 to 1,000 msec in duration. The adjustable signal was set at one of seven levels of intensity, ranging from 25 to 55 dB SL, while O could set the duration of onset of the adjustable signal anywhere from 30 to 1,700 msec. Two time ranges were used with O's control (30-435 msec and 115-1,700 msec); the shorter adequately served the two shorter time standards, and the longer served the longer time standards. O could switch between ranges if he so desired, but this very rarely occurred. It was possible with the apparatus to present a range of onset times wider than listed here, but the Os did not find such values to be of much use. The position of O's control could not be distinguished by sight or touch, and E always shifted its setting randomly from the true value before O started to match any new pair. The total of 28 different time and intensity combinations was presented in random order to O, who was instructed to make the "growth" or "surge" at the onset of the standard and comparison signals as much alike as possible. Each O completed this total in random sequence twice over the course of four sessions. Each session lasted a little under 1 h, including a 10-min break midway through the session. On the average, Os required 10 repetitions of the stimulus sequence to achieve a satisfactory match.

Results and Discussion

Results are shown in Fig. 3 for onset matches of 20 different standard signals, with each point based on the median value for eight judgments. Representation of the extreme intensity values (25 and 55 dB) is not included, since Os consistently reported difficulty in comparing these intensity levels to the standard, and forced comparisons produced inconsistent results. Curves obtained by the method of least squares showed slopes that ranged from .25 to .30. Since these slopes differ significantly from zero ($p < .05$), it follows that both rise time and intensity were contributing factors to the

Fig. 2. Picture of the oscilloscope pattern for the resultant displacement of a Goodmans V-47 vibrator with an input signal of 100 msec rise time.

judgment of sensory onset. None of the slopes of individual Os, in either this experiment or the one following, exhibited a trend in disagreement with the data for the entire group. Figure 3 illustrates how a proportionally small adjustment in onset time had an effect on onset matching equivalent to that produced by a much greater change in intensity. For example, when the standard onset took 100 msec rise time to reach 40 dB SL, E's altering the intensity of the variable stimulus by a factor of 10 could be balanced by O's adjusting the rise time by a factor of 2.

There was an apparent constant error such that the time setting of the 40-dB adjustable signal was set shorter than the actual value (100, 200, 500, 1,000 msec) of the standard signal at 40 dB. This could be attributable to the lack of complete counterbalancing of the order of stimulus presentation, since the fixed standard always preceded the adjustable signal. A more likely factor can be seen in the fact that one of the four Os produced significantly briefer rise times ($p < .01$ by the median test) than the other Os. Table 1 shows mean rise time settings of individual Os taken across all the intensity levels for any standard value of rise time.

EXPERIMENT II ONSET MATCHING BY INTENSITY ADJUSTMENT

Experiment I demonstrated that reliable equal-onset matching could be obtained by the adjustment of rise time. It remained to be shown whether reliable matching of vibrotactile onset could be obtained in the contrasting case, in which rise time was fixed and O adjusted the intensity of a comparison signal for equal-onset matching with a standard.

Apparatus and Procedure

The apparatus and Os were the same as in Experiment I. The procedure differed only in that O adjusted intensity rather than rise time. The range of available intensities spanned 25 to 60 dB SL and was more than ample for O's needs. There were five different values of rise time for the 40-dB standard, each compared to five different values of rise time for the signal of adjustable intensity. The fixed rise times for the signal of adjustable intensity were derived from the results for the signals of adjustable rise time in Experiment I. A standard value of 40 dB with 50-msec onset time was added in this experiment, since Experiment I had demonstrated that an onset time of 100 msec was not too brief for effective observation. In the case

Fig. 3. Contours of equal-onset sensation established by adjustment of rise time of vibratory stimuli. (The abscissa and ordinate identify the fixed intensity of the comparison stimulus and Os' setting of rise time for the comparison stimulus, respectively. Rise time of the standard signal is indicated by the choice of symbol; intensity was 40 dB. The symbols Δ , $\square$, $\times$, + depict the actual value of the standard signal for 100, 200, 500, and 1,000 msec, respectively.)

of the 50-msec standard, for which no previous data existed from Experiment I, rise times for the signal of adjustable intensity were established by a hypothetical curve extending through 50 msec at 40 dB with a slope equal to that obtained empirically in the preceding experiment. Each O matched the total of 25 pairs of stimuli twice over the course of six sessions. A session lasted a little under 1 h, including a 10-min break midway through the session.

Results and Discussion

The results are shown in Fig. 4 for onset matches of 24 different pairs (due to a technical error, one value for the 50-msec standard is omitted). Results obtained for the shorter rise times were not statistically significant. For the longer rise times of 500 and 1,000 msec, curves calculated by the method of least squares showed slopes of 1.1 and 0.9, respectively. Since these slopes differ

significantly from zero ($p < .05$), it follows that both rise time and intensity were contributing factors to the judgment of sensory onset. This is in general agreement with the results in Experiment I, although in the present case Os reported their task to be more difficult. This observational difficulty was particularly evident for the briefer values of rise time (i.e., 50- and 100-msec standards). If the one situation were the exact obverse of the other, then the slope in the present case would be the reciprocal of that for Experiment I. Instead, the slope obtained for Experiment II was about one-quarter of what would have been predicted from the previous results. For example, when the standard intensity took 500 msec to reach 40 dB SL, E's altering the duration of the variable stimulus by a factor of 2 could be balanced by O's adjusting the intensity by a factor of 2. It is pertinent to ask what caused this difference between the results of Experiment I and Experiment II. In both experiments, O had available an ample range of response values and so was not restricted in that respect by the apparatus. It is possible that the different ratios of control movement in the two experiments (1 revolution in Experiment I, 10 revolutions in Experiment II) may have influenced O. As stated previously, Os reported the second experiment to be more demanding than the first. This difficulty in judgment, combined with the relatively large span of control movement, could produce a regression toward the standard intensity of Experiment II, and thus may be the reason for the different slopes in the two experiments.

There was an apparent constant error such that the intensity setting of the adjustable signal was set higher than the actual value of the 40-dB standard when the two signals were of the same rise time. This error could be attributed to the same factors described in Experiment I concerning constant error: the lack of complete counterbalancing and the significantly higher values ($p < .01$ by the median test) given by one of the Os (the same individual as mentioned in Experiment I). Table 1 shows mean intensity settings of each O taken across all the given rise times for the standard rise times of 500 and 1,000 msec. The constant error in both experiments was in the same direction, in that O increased the rate of onset (i.e., the physical slope) for an adjustable signal in relation to a preceding standard.

Table 1
Mean Rise Times (Experiment I) and Intensities (Experiment II) for Each of Four Os Taken Across the Range of Given Intensities (Experiment I) or Rise Times (Experiment II) for the Distinct Onset Times of the 40-dB SL Standard Signal

Individual Os	Onset Time of the Standard (Msec)					
	Experiment I				Experiment II	
	100	200	500	1000	500	1000
O1	121.8	193.7	471.5	951.0	44.05	43.95
O2	97.9	175.7	692.0	971.5	41.05	42.15
O3	143.6	223.5	584.1	705.3	43.40	42.05
O4	53.7	139.5	391.5	896.0	44.45	45.40

Fig. 4. Contours of equal-onset sensation established by adjustment of intensity of vibratory stimuli. (The abscissa and ordinate identify the fixed rise time of the comparison stimulus and Os' setting of intensity for the comparison stimulus, respectively. Rise time of the standard signal is indicated by the choice of symbol; intensity was 40 dB. The symbols +, x, •, ⊗, ⊘ depict the actual value of the standard signal for 50, 100, 200, 500, and 1,000 msec, respectively.)

CONCLUSIONS

In these experiments, it was possible to manipulate the physical conditions of a stimulus such that contours of equal onset were obtained for different values of intensity and rise time. These results indicate that the sensory experience of cutaneous onset may be distinguishable as a unique phenomenal quality, analogous to the tonal dimensions described by Stevens (1934a).

Results of these experiments may be applied also to the practical situation of a cutaneous communication system. Cutaneous signaling systems generally rely upon distinguishing the separate stimulus dimensions, and Os try to avoid confounding their task with combinations of these dimensions. It may be, however, that if these stimulus combinations are properly handled they offer an opportunity for providing an O with usable information.

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NOTE

1. Constructed and lent by the Auditory Research Laboratories, Princeton University, Princeton, New Jersey.

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