Electrocutaneous stimulation

GARY B. ROLLMAN
University of Western Ontario, London, Ontario, Canada

Reprinted from F. A. Geldard (Ed.) *Conference on vibrotactile communication.* Austin, Tex.: The Psychonomic Society, 1974.

Electrocutaneous stimulation*

GARY B. ROLLMAN
University of Western Ontario, London, Ontario, Canada

Many of the cutaneous communication systems previously described in the literature (e.g., 3, 7, 27, 28) transmitted information by means of mechanical impact on the skin. While the engineering advances which made it possible to present a high density of vibrators against a relatively small skin area are laudatory, maximally useful devices must be portable enough to be taken out of the laboratory and worn by freely moving subjects. Major constraints on such systems are the power required to activate a large number of independent electromechanical units and the relatively small amplitude range obtainable with piezoelectric transducers or small solenoids. Compact, lightweight, yet powerful systems will be needed for communicating to subjects whose attention is focused elsewhere, who are operating in noisy environments, and who require placement of the transducers on relatively insensitive body regions.

It is quite possible that such problems can be overcome by electromechanical devices yet to be developed. In this paper, I would like to discuss one other avenue which deserves further investigation because of its potential for better meeting the needs of dynamic communication systems. I refer to the use of electrical rather than mechanical stimulation of the skin. This paper will review some basic psychophysical data obtained with electrocutaneous stimuli, compare these to the results of some similar experiments with mechanical stimulation, and suggest different mechanisms underlying the neural transduction of the two forms of cutaneous activation. It will also review some of the literature concerning pain associated with electrical stimulation.

Stimulation Techniques

It might be instructive to begin with two elementary questions: how does one present carefully controlled electrical pulses and what are the resulting sensations? In our laboratory, observers are seated comfortably, and two Grass EEG electrodes, filled with a conducting cream, are taped to the well-washed skin about 2 cm apart. Other laboratories have used single bipolar electrodes with very satisfactory results (72, 73). Our electrodes are attached to the output of a constant current stimulator (actually, a circuit which approximates constant current output, despite fluctuations in skin impedance, by incorporating a very high output resistance), with the more proximal electrode connected to the cathode. Suitable pulse and waveform generators permit control over the stimulus characteristics.

The sensations produced depend upon the physical parameters employed, but it should be emphasized that an electrical pulse need not be painful. A brief stimulus somewhat above threshold feels much like a tap with a dull pencil, localized in the vicinity of the cathodal electrode. Strong currents or pulses beyond 30-50 msec in duration may give rise to reports of pain, but, in general, electrical stimuli of moderate intensity and duration, singly or in trains, yield an experience which is described as tactile rather than painful in quality.

Psychophysical studies of any modality look for relationships between behavior and carefully controlled stimulus variables. The critical parameters which can be studied include the intensity, duration, and waveform of single pulses, the repetition rate and total number or duration of a train of pulses, the area of the stimulating electrodes, the bodily locus where they are attached, the system's state of adaptation, the effects of other stimuli in spatial or temporal proximity, and the motivational state of the observer. Space will not permit discussion of some of these variables, and data are sparse on others, so that the view I present is admittedly a selective one.

INTENSITY

Thresholds

The paper deals first with intensity, both at the threshold range and at suprathreshold levels. Figure 1 shows typical results of an experiment (51) in which stimuli of seven different intensities were presented in random order and subjects were required to indicate whether the pulse was detected. Yes-no methods are susceptible to many problems (33), but similar results have been obtained in forced-choice sessions.

Such a curve is labeled a psychometric function, and, as it has been shown for other modalities, the frequency of detection increases with stimulus intensity. What makes this curve remarkable, however, is its very steep slope. To describe relative steepness, I have adopted (51, 54) the coefficient of variability–the ratio of the standard deviation to the mean of the underlying normal

*This research was supported by Grant APA-392 from the National Research Council of Canada. I am grateful for the assistance of Barbara Barnett and Lawrence Starr in the conduct of these studies.

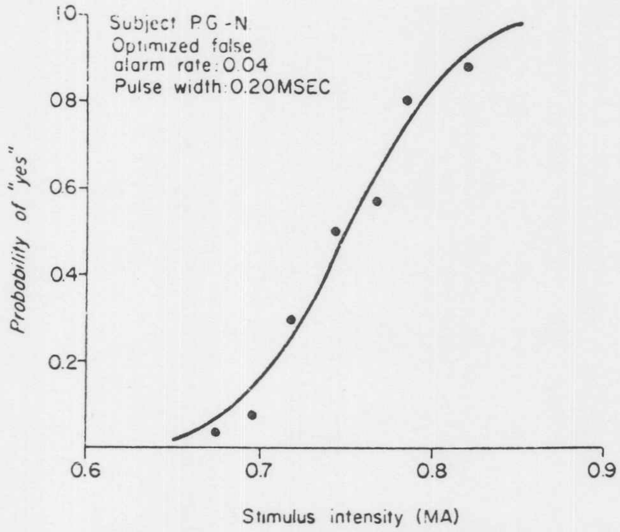


Fig. 1. Psychometric function for the detection of 0.2-msec electrical pulses. (From 51).

distribution, expressed as a percentage. For visual flashes, threshold intensity must be increased about 30% to 60% for the detection rate to go from 50% to 84% (one standard deviation higher), and for auditory bursts this value is greater yet. In marked contrast, the same change in detection is here accomplished for electrical stimulation of the skin with only an 8% rise in intensity. Thus, we see a remarkable sensitivity to slight alterations in the amplitude of an electrocutaneous pulse.

The 8% figure must be qualified by the results of more recent experiments in our laboratory. Figure 2 presents psychometric functions for pulses ranging from 0.08 to 100 msec. In terms of current, the functions for the long durations are steeper. The coefficient of variability is relatively unaffected by duration, however. It falls between 7% and 11% for all pulse widths between 0.08 and 10.0 msec, and rises to 19% for the longest pulse.

There are several possible explanations of the differences across sense modalities. One possibility is that the somatosensory system is appreciably more sensitive to small stimulus changes than are the visual or auditory systems. A second hypothesis, one which I favor, is that these results arise from fundamental differences in the transduction mechanisms involved. Visual, auditory, or mechanical stimuli (as well as gustatory or olfactory ones) act upon specialized receptor organs. These undergo a complex process resulting in generator potentials which initiate the nerve impulse. Electricity has a unique role in neurophysiological research, since it is capable of stimulating each of the sensory systems when directly applied to the afferent nerves. My own research (51, 53, 54), as well as that of several others (10, 11, 34, 40), suggests that an electrical stimulus applied to the skin surface also acts directly on the underlying peripheral nerves to initiate an action potential, bypassing the receptors which respond when adequate modes of stimulation are employed. Similar steep functions have been obtained when electrodes were placed directly on the nerve and the dependent variables were peripheral action potentials (9) or behavioral responses from cats (8).

If the steep psychometric functions are due to nerve stimulation rather than special sensitivity of the somatosensory system, then mechanical pulses should produce shallower functions. This is, in fact, what happens (54), as Fig. 3 illustrates. These curves are typical of those obtained when 3-msec mechanical taps are applied on the dorsal forearm or the middle fingertip. The differences in slope at the two loci may relate to receptor density, differences in receptor populations in hairy and glabrous skin, or small tremors of the body coupled with the exquisite sensitivity of the fingertips. Of present interest is the slope of these functions compared to those in Figs. 1 and 2. Here it takes about a 30% increase in amplitude to raise the

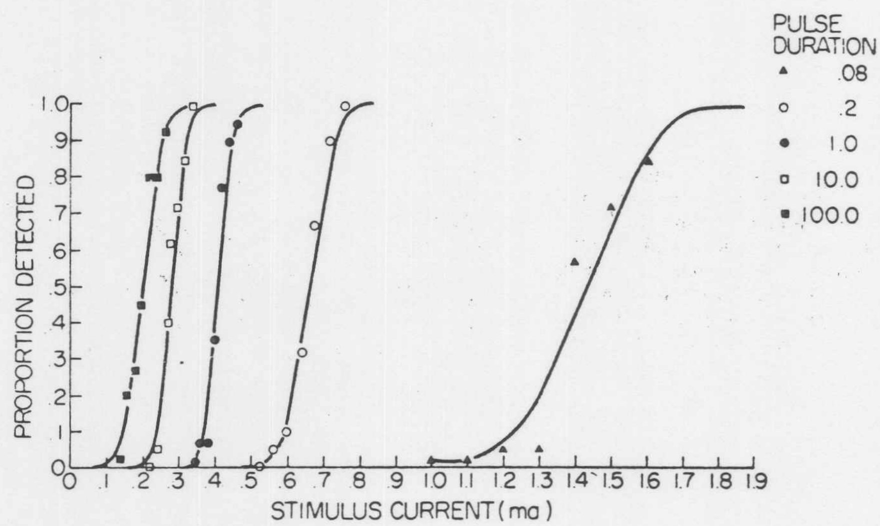


Fig. 2. Psychometric functions for the detection of electrical pulses of several durations. Times are in milliseconds.

detection probability one standard deviation above threshold for taps on the arm and a 60% increase on the fingertips; both are clearly greater than the values obtained for electrocutaneous pulses. If Fig. 1 were scaled to conform to this abscissa, it would extend from about 85 to 115 units.

A number of experiments were performed to examine the detection of weak electrical and mechanical pulses within the framework of signal detection theory (52). Two aspects of their results should be mentioned briefly. First, for both forms of stimulation, the results are inconsistent with a high threshold and support the predictions of either signal detection theory or a multistate model. Second, the slopes of the ROC curves on normal deviate coordinates for both kinds of pulse are the same—about 0.7. According to the signal detection theory interpretation, the standard deviation of the signal-plus-noise distribution is larger than that for noise alone, but whether the stimulus is transduced by the receptors or the nerve fiber does not seem to affect the signal-plus-noise variance.

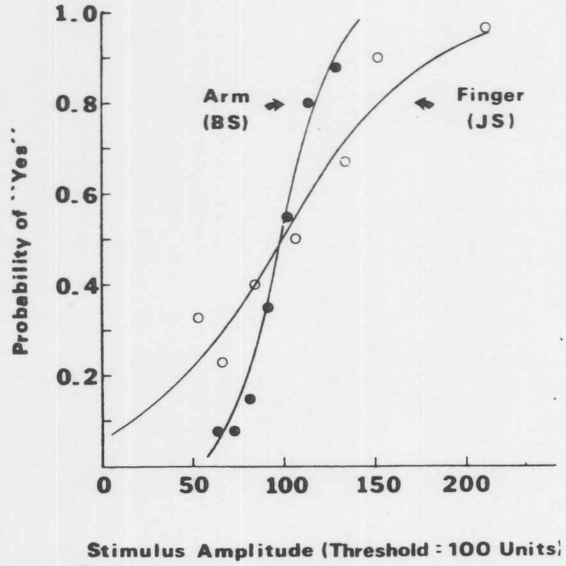


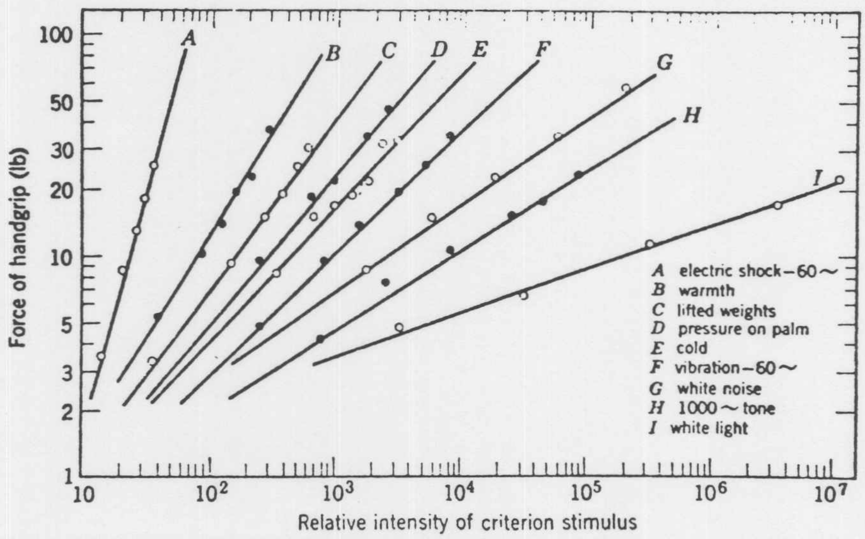
Fig. 3. Psychometric functions for the detection of 3.0-msec mechanical pulses at the fingertip and dorsal forearm. The threshold at the finger was 0.58 microns; at the forearm, it was 39.6 microns. (From 54).

Power Functions

The subjective effects of intensity above threshold can be examined in the context of S. S. Stevens's investigations regarding the power law. Stevens (65) summarized the results obtained up to 1961 for the scaling of a large number of prothetic continua, reporting that the exponent of the power function was about 3.5 for 60-Hz electric shock (66), more than twice the value for the next steepest function (warmth), and more than three times the slope of the functions for 60-Hz vibration or pressure on the palm. Figure 4 illustrates the size of this effect. The slopes of the functions are reduced considerably in this graph, however, since the ordinate represents the results of a cross-modality matching study, in which subjects squeezed a hand dynamometer to match the sensation magnitudes. While there has been some dispute in the recent literature concerning the exact exponents for both electrocutaneous shock and vibration, it is indisputably clear that the subjective magnitude of an electric pulse increases very rapidly with increases in physical amplitude.

Rosner and Goff (57) suggest that the results are more complex than Stevens's single function would indicate. Figure 5 presents some typical results from their study. Notice first that the points are fit by a double-limbed function, with a shallower slope for the higher intensities. While Stevens, Carton, and Shickman (66) obtained an exponent of 3.5, Rosner and Goff found median slopes for the lower and upper limbs to be 1.8 and 0.9, respectively. They suggest that the upper points

Fig. 4. Power functions for nine prothetic continua obtained by cross-modality matching with a hand dynamometer. The relative position of the functions along the abscissa is arbitrary. The exponent for handgrip obtained in magnitude estimation experiments is approximately 1.7. (From 65).



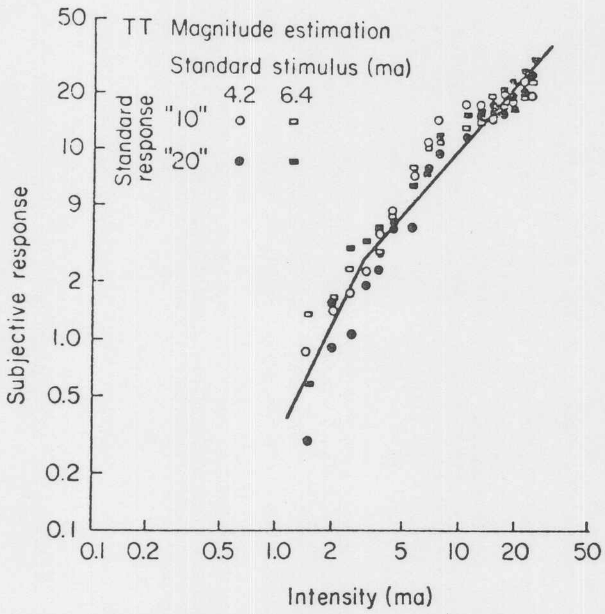


Fig. 5. Typical power functions from magnitude estimations of 0.5-msec electrical pulses. (From 57).

on the function Stevens et al presented would in fact be better fitted by a second function with a slope of 0.9. But a considerable difference in exponents for the steep limb still needs to be explained. Rosner and Goff point out that Stevens used a 60-Hz current delivered for 1 sec to two fingers dipped in a saline solution, whereas their results were obtained with a single 0.5-msec rectangular pulse at the wrist. When they changed to a 1-sec train of pulses at 60 Hz, subjective magnitude increased far more rapidly with intensity than for single shocks—a finding they attribute to the recruitment of small-diameter fibers and to a rhythmic, synchronous firing of the axons.

Beck and Rosner (5) carried the investigation one step further. Since a sophisticated statistical analysis revealed that a single-limbed function based on a correction for threshold fit the data as well as the double function which failed to apply such a correction, they proposed the former as the more parsimonious description of their data. The exponent, however, was only 0.7. Stevens, Carton, and Shickman's (66) value of 3.5 was determined for data uncorrected for threshold; Beck and Rosner indicate that application of this correction would reduce Stevens's exponent considerably.

The confusions which can results from such diverse methods of presentating data can be seen in Fig. 6, which illustrates power functions based on some magnitude production experiments in our laboratory. The stimulus presentation was either a single 0.1-msec pulse on the volar forearm or a train of 3 or 30 such pulses, with 16 msec between onsets. As the left side of the figure indicates, the slope of the function is indeed steeper for a repetitive train than for a single pulse. It is also the case that subtraction of the threshold current, using the equation noted on the right side of the graph over such corrected functions, leads to a considerable reduction of exponent. Moreover, in this instance, it had the effect of altering the relative order of the exponents, so that now the function for the single pulse is the steepest rather than the most shallow.

All this, of course, creates a problem. On the basis of the uncorrected data, one is tempted to conclude that for communication systems, repetitive stimulation is to be avoided in favor of single pulses, since the dynamic range is considerably larger for the latter. Examination of functions which have undergone the threshold correction would suggest quite the opposite.

My own view is that we should concentrate on the uncorrected power functions, since they more closely convey the subjective impressions of the observers. The difference in threshold between a train of 3 or 30 pulses is fairly small, but the sensation for 30 pulses in quick succession at a current twice threshold level is reported as being about three times as intense as the same current for the 3-pulse train.

Thus, as one goes from single pulses to long trains, one finds a reduction in the dynamic range—the span of amplitude between threshold and an upper limit which cannot reasonably be exceeded because of the pain reported by the subject (or, more precisely, the ratio of these high and low intensities). This upper limit is movable to some extent, as I will mention later. Teghtsoonian (70) has presented impressive evidence linking the variations in power function exponents to variations in dynamic ranges for several modalities. If several amplitudes of shock are to be employed in a cutaneous code, it seems that shallow power functions would be more desirable. The likelihood that a small error in setting the current value would prove painful is less for these parameters as well.

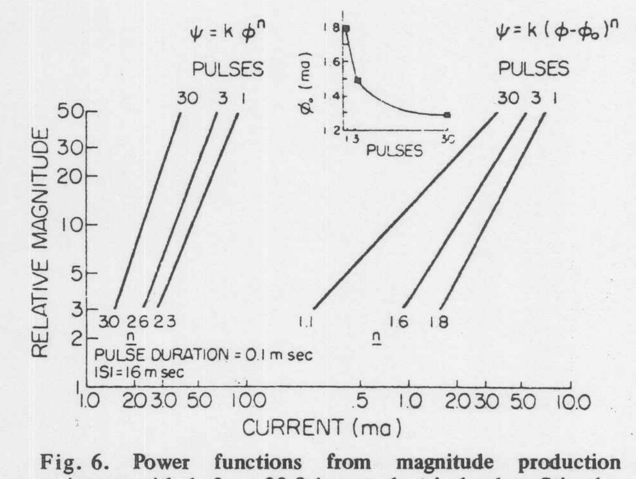


Fig. 6. Power functions from magnitude production experiments with 1, 3, or 30 0.1-msec electrical pulses. Stimulus onset asynchrony (interstimulus interval) = 16 msec. The functions on the left are for data uncorrected for threshold, while those on the right underwent such a correction. Slope value is shown at the foot of each function. Thresholds as a function of number of pulses are shown in the inset.

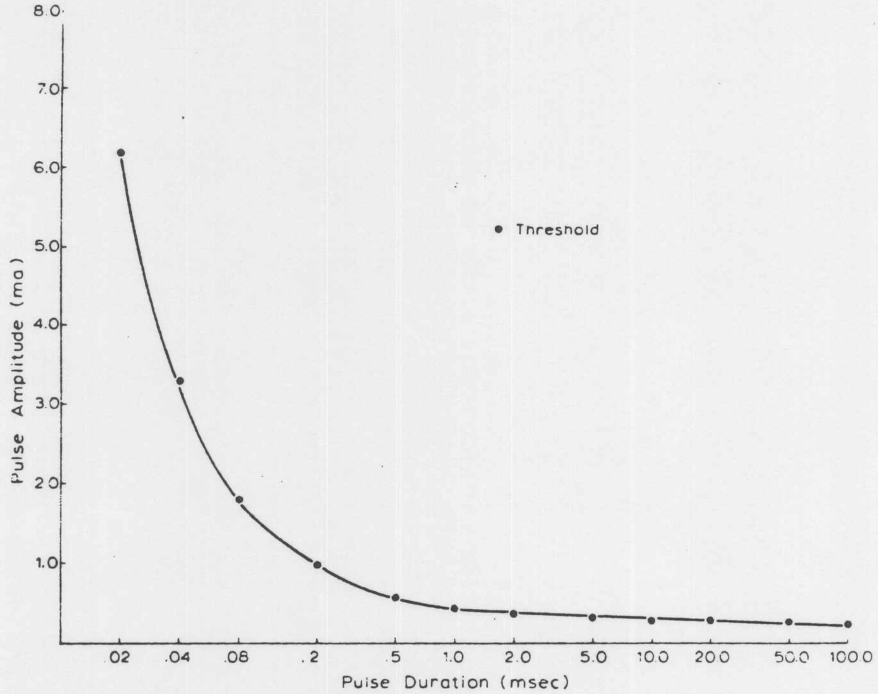


Fig. 7. Threshold current as a function of stimulus duration.

TEMPORAL FACTORS

Thus far, the paper has been principally concerned with intensity of stimulation as it affects thresholds, subjective magnitude, and the possibility of pain. This section will deal with temporal factors, emphasizing recent research in our laboratory which indicates the importance of time as a parameter influencing these same dependent variables. The studies will be reported in detail elsewhere.

Temporal Integration

Figure 7 presents the results of an experiment in which thresholds were obtained for single rectangular pulses ranging in duration from 0.02 to 100 msec.

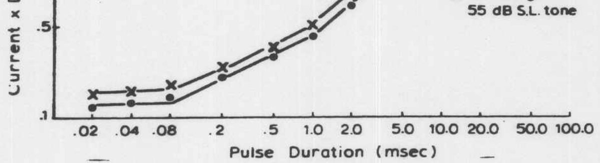


Fig. 8. The product of intensity and duration (charge) at threshold and suprathreshold levels as a function of stimulus duration.

A number of the features of this curve are of interest. First, note that threshold decreases as duration is increased. The drop is most rapid up to about 0.5 msec, and there is a real, but relatively small, decrease beyond that duration. The results further indicate that complete reciprocity between intensity and time exists over only a brief range, so that, for example, a doubling in pulse duration lowers the threshold to half its previous value. Such a relationship of temporal summation or integration is more easily seen in the lower function of Fig. 8, which plots the product of intensity and duration (the charge of the stimulating pulse) vs the duration. Such graphs are common in the vision literature, where the temporal summation effect is known as Bloch's law or the Bunsen-Roscoe law, and the upper limit on integration, where the curve departs from zero slope, is often given a value between 50 and 100 msec, though under some conditions (e.g., 4) values as small as 10 to 20 msec are obtained. The critical durations for auditory tone bursts often extend beyond 200 msec (30, 79), and a similar large upper limit has been determined by Verrillo (75, 76) for vibratory bursts on the skin.

In marked contrast, the limit for complete summation with electrical stimulation occurs at a duration less than 0.1 msec, a value 200 to 2,000 times smaller than those for the other modalities. Following this, the data are fitted by three additional limbs: one period of partial summation extending to about 1.0 msec, a second such period going to about 10.0 msec, and beyond that threshold is independent of pulse width.

Similar experiments are common in studies of nerve

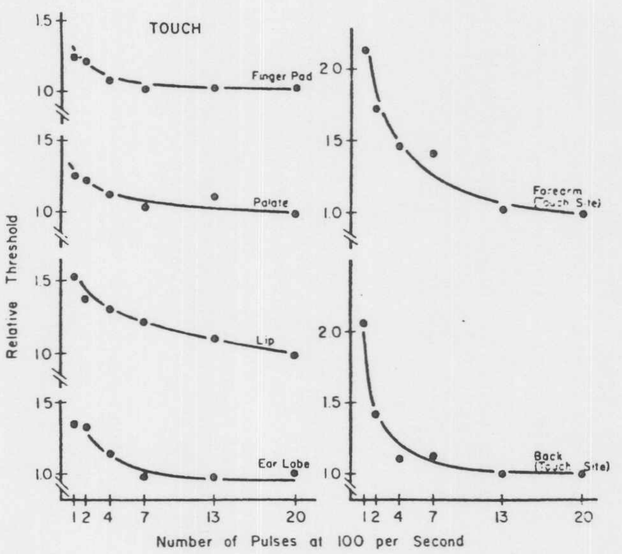


Fig. 9. Electrical thresholds on glabrous and hairy skin as a function of number of 0.5-msec pulses. Thresholds for 20-pulse trains have been assigned a relative value of 1.0. (From 32).

physiology, where curves such as that in Fig. 7 are known as strength-duration functions and their parameters, rheobase and chronaxie, are used to identify the nerve fibers under investigation. The characteristics of the physiological strength-duration curves for the large A-fibers which underlie the surface electrodes employed in this study are the same as those of the psychophysical curve in Fig. 7, supporting the earlier contention that percutaneous electrical pulses bypass the receptors and directly initiate action potentials in the afferent fibers. The stability of the psychophysical results and the ease with which they can be obtained suggests that behavioral techniques could supplant electrophysiological ones (e.g., 39) in clinical studies of peripheral nerve function and pathology.

Psychophysical strength-duration curves were also determined at suprathreshold intensities by requiring observers to adjust the intensity of pulses of varying duration until the subjective magnitude matched that of a constant 55-dB SL tone. As can be seen in the upper function of Fig. 8, the intensity of the pulse needed to be raised by a small amount, but the shape of the integration function and the critical duration were unaffected [in contrast to the results for visual flashes, where critical duration decreases with increasing intensity, but in agreement with the results of such studies in audition (64)].

The results suggest a form of spatial coding for electrocutaneous intensity. As current is increased, synchronous action potentials (63) are established in a larger number of A-fibers, differing in threshold but identical in temporal integrating capacities. Thus, the brief critical duration represents a peripheral limitation on summation imposed by the dynamic properties of the nerves, while longer integration times are found when "adequate" forms of stimulation are used to activate receptors which differ in integrating capacities and central neural consequences.

The contrasting results which occur when trains of brief electrical pulses are used instead of single long ones reinforce this view. Much of this literature is summarized by Gibson (32), but a few points should be emphasized. The inset of Fig. 6 shows that threshold decreased rapidly when the number of 0.1-msec pulses was increased from 1 to 3, with 16 msec separating the onsets. A further drop was obtained when the number of pulses was increased to 30. The total stimulation time for the three conditions was 0.1, 32.1, and 464.1 msec, respectively. Thus, threshold for intermittent stimulation continues to decrease long after integration for a single pulse has ceased. Figure 9, taken from Gibson's report, shows the same trend for pulse trains at a number of loci, with partial integration, particularly on hairy skin areas, extending beyond 100 msec. McCall (44) has obtained similar results for suprathreshold stimulation of the tongue.

These vast differences are important in understanding the neural mechanisms which underlie temporal summation. One interpretation is that the curves for single pulses represent the summating properties of the nerve fibers, whereas the integration of pulse trains is a higher-order phenomenon. Evidence from other modalities reinforces this point of view. Some work is under way in our laboratory to delineate the chracteristics of such central summation. We have found, for example, that while the threshold for brief pulses decreases as you increase their number, such is not the case for long pulses. The threshold for either 2 or 10 pulses of 20-msec duration and 25-msec stimulus onset asynchrony is no lower than that for a single pulse.

An experiment by Hahn (35) should be mentioned here, since he presented trains of stimuli but obtained results (Fig. 10) more like those I reported for single pulses. Hahn varied pulse duration and repeated the pulses continuously at rates between 60 and 1,000 Hz. The figure shows that threshold is dependent only upon the duration of each pulse and that the critical duration is less than 1.0 msec. In any 100-msec period, for example, the number of pulses presented ranges from 6 to 100, yet threshold is constant. Such is clearly not the case in the inset of Fig. 6 or in Fig. 9. Hahn's pulses were presented continuously, while our trains were switched on and off periodically. The differences in sensation are startling. A continuous train initially feels much more intense than a brief, gated train, but it also adapts rapidly and the sensation almost disappears. Little is known about adaptation properties, but such research is vital for both communication systems and an increased understanding of the neural mechanisms underlying this phenomenon and other possibly related ones (23).

Some years ago, Keidel, Keidel, and Wigand (41) published a paper entitled "Adaptation: Loss or gain of sensory information?" I find myself asking the same

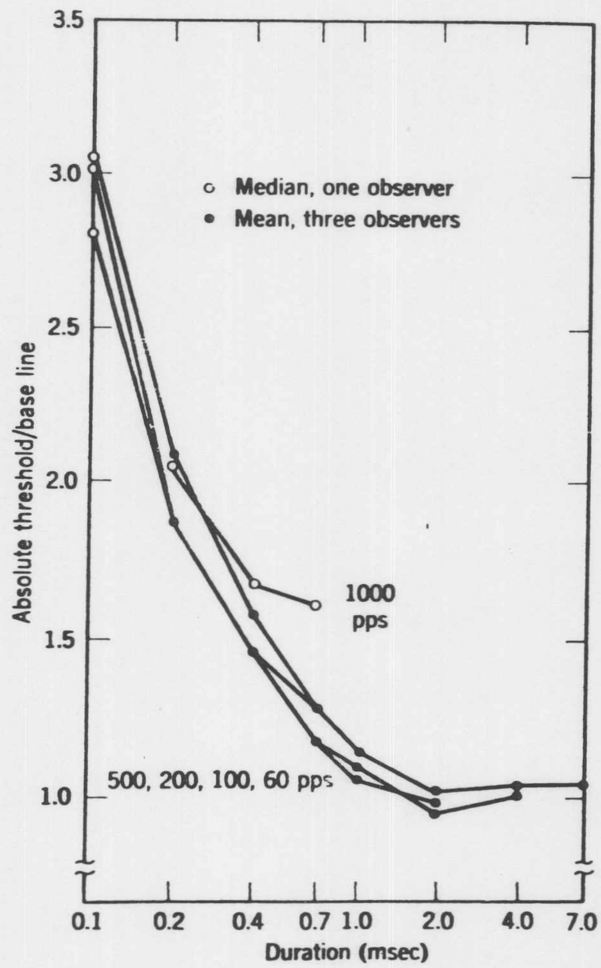


Fig. 10. Threshold current as a function of pulse duration for continuous trains of electrical stimuli presented at various pulse rates. The mean thresholds for pulses of 2.0 msec or greater have been assigned a relative value of 1.0. (From 35).

question about brief critical durations. Is it desirable, or important, to employ conditions which increase the integration time when designing a cutaneous communication system? Temporal summation over relatively long periods has some obvious advantages for sensory systems in contact with the "real world." But, in designing a system to be placed against the skin, the decreased threshold which results from long trains is not critically important, since current values can easily be adjusted so that they are optimal for the parameters being employed. Other considerations, particularly those dealing with the quality of the sensation and the likelihood of pain, should predominate.

Earlier in the paper, I indicated that trains of pulses show steeper power functions (uncorrected for threshold) than single pulses. Experiments by Beck and Rosner (5) indicate that the slope of the function is also directly related to the duration of a single pulse. So if steepness of power functions is a concern (because small fluctuations in output of the stimulator are more likely to cause painful reports for steep functions), one might conclude that single brief pulses are most appropriate.

Other evidence also suggests that if single pulses are used, brief ones are most comfortable. Figure 11 shows the results of an experiment in which stimulus duration was varied between 0.06 and 1.0 msec (for one fixed current) or between 0.5 and 100 msec (for a lower current). Observers used a magnitude estimation procedure to scale the resulting sensations in subjective magnitude. While I had expected that reported magnitude would not change when duration was extended beyond 5.0 or 10.0 msec, that is not what happened. The slope of the function is smaller on the upper limb than on the lower one, but magnitude increases all the way to 100 msec. I think this effect may be due to the change in quality which occurs at longer durations, since such pulses now tend to include a mild sting. It may be that the magnitude estimates at the

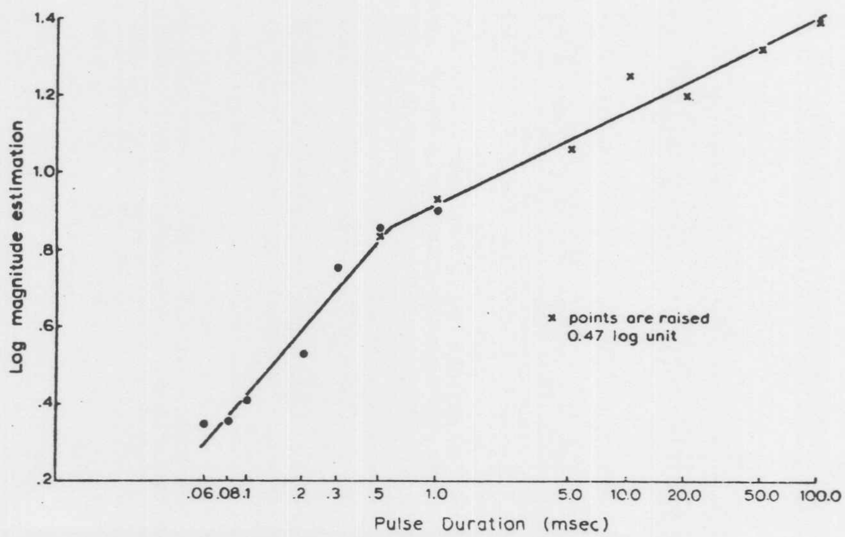


Fig. 11. Magnitude judgments as a function of stimulus duration.

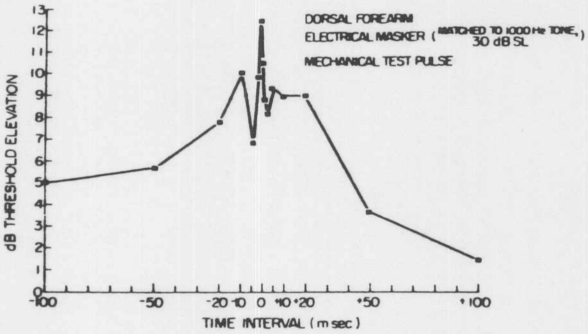


Fig. 12. Threshold elevation (forced-choice paradigm) for a mechanical test pulse as a function of the interval between its onset and that of an electrical masking pulse.

upper range represent two components–a tactile quality mediated by the large A-fibers plus a nociceptive component stemming from concurrent activation of the smaller C-fibers whose threshold is exceeded by the longer-lasting pulse (36). This interpretation is reinforced by the results of a loudness matching experiment where the level of the matching tone selected by the observer is relatively constant between 10 and 100 msec, perhaps because with this procedure observers are better able to concentrate on the tactile component of the sensation.

The problem which can arise from use of brief pulses is that the higher currents employed sometimes are sufficient to stimulate motor nerves, resulting in an uncomfortable muscle twitch. Judicious selection of stimulating sites is generally sufficient to avoid this.

Trains of pulses do have some advantages over single ones. First, they allow the addition of a secondary dimension of repetition rate, which can alter the sensation so that it feels like a stroke or vibratory flutter, thus rendering a signal more noticeable or immediate. Second, there is evidence that very brief pulses, when presented in a train, can produce a sensation which is fairly strong in magnitude and free of pain. Gibson (32), who has studied the ability of pulse trains to elicit reports of both touch and pain, suggests that a train of a few 0.5-msec pulses separated by 20 to 100 msec maximizes the ratio between threshold for pain and touch.

I would like to describe briefly the results from ongoing studies in our laboratory on other temporal properties of the somatosensory system. The impetus behind them is largely theoretical and physiological, but each has practical implications as well.

Masking

We have been engaged in a series of experiments on the interaction between mechanical and electrical pulses presented to adjacent sites on the arm. Instead of the yes-no paradigm normally used in such experiments, observers participated in a two-alternative forced-choice task, in which a strong masking stimulus was presented in two temporally defined intervals with a weak test stimulus presented as well in one of them. Observers were required to indicate which of the two intervals contained both signals, and the chance level of accuracy (75% correct in the two-alternative task) was determined with a modification (50) of the interactive P.E.S.T. procedure (69). When the masker was mechanical (a brief, single pulse), the test pulse was electrical, and vice versa. The masking signal was presented simultaneously with the test pulse or at various intervals before or after it. Figure 12 presents the results obtained with an electrical masking stimulus which was subjectively equal to a 30-dB SL tone of 1,000 Hz. I shall not dwell on all the features here. Masking is maximum at about simultaneous onset of the two pulses, raising the threshold of the tactile tap by nearly 13 dB. Backward masking (the test pulse preceding presentation of the masker) is greater than forward masking for the larger delays, and a substantial increase in the test stimulus threshold is seen for separations as long as 100 msec.

The outcome of a study in which mechanical pulses of two amplitudes masked electrocutaneous pulses is shown in Fig. 13. The left ordinate indicates the proportion by which threshold was raised, while the right expresses this elevation in decibels. The forward masking seems to be greater than the backward one, and little masking is seen at the longer interstimulus intervals.

It is striking, in comparing Figs. 12 and 13, to note the resistance of the nervous sytem to masking of electrocutaneous inputs. The subjective magnitudes of the electrical and 20-dB mechanical masker are roughly equivalent, yet mechanical thresholds over a large time range are elevated by 8 to 12 dB, while the maximum increase for electrical pulses is under 3 dB, and generally is closer to 1 dB. Davis, Osterhammel, Wier, and Gjerdingen (22) have presented related findings. Mechanical and electrical stimuli were equated for subjective intensity, and cortical evoked potentials were obtained for both single presentations and pairs with a 500-msec separation. The vibrotactile-evoked response following an electric shock was reduced considerably more than the response for shock after the tactile

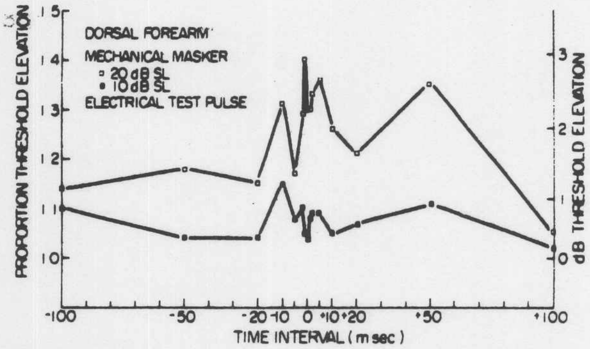


Fig. 13. Threshold elevation (forced-choice paradigm) for an electrical test pulse as a function of the interval between its onset and that of a 10- or 20-dB SL mechanical masking pulse.

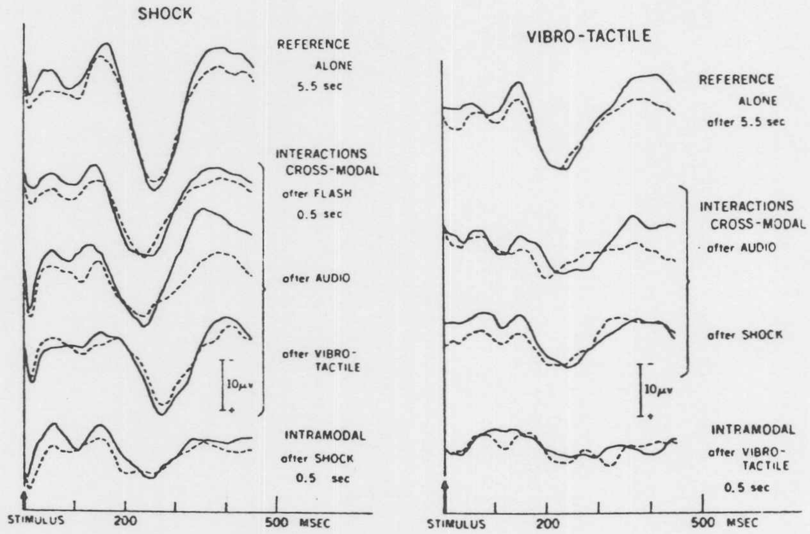


Fig. 14. Cortical evoked responses from one observer to electrical and vibrotactile stimuli presented at 5.5-sec intervals (reference) and after cross-modal and intramodal interactions at 0.5-sec intervals. The dotted functions were obtained from the second half of the session. (From 22).

presentation, as illustrated in Fig. 14.

Thus, it would appear that weak electrical stimuli are difficult to mask by mechanical ones. Higgins, Tursky, and Schwartz (40) noted that a pressure cuff constriction had no effect on electrical threshold, while Nathan, Noordenbos, and Wall (49) found that circulation blocks and peripheral warming caused only a slight threshold increase. Melzack, Wall, and Weisz (47) showed a more considerable increase in threshold following a powerful mechanical pulse, using a category scale rather than a forced-choice technique.

Greater masking of electrical pulses has been shown when the masker is also electrical, by Rosner (55, 56) and Schmid (58), among others. Figure 15 presents the results of one study (55) involving a test stimulus on one finger and a masker on an adjacent one. While the function does not indicate the unmasked threshold, it is

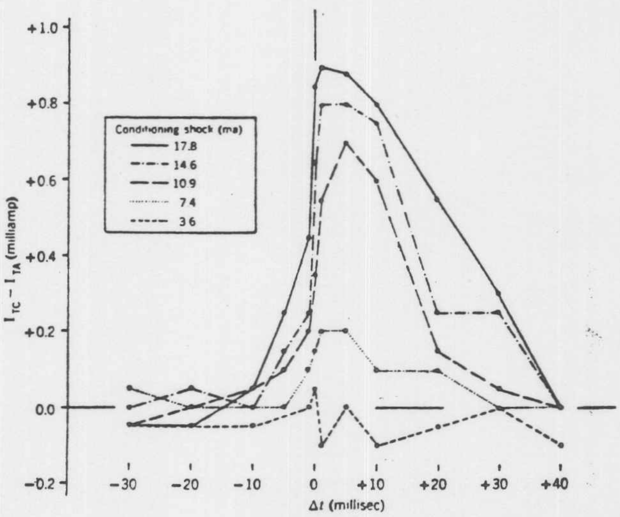


Fig. 15. Threshold elevation (yes-no paradigm) for an electrical test pulse as a function of the interval between its onset and that of an electrical masking pulse of several intensities. (From 55).

likely that the peak amount of masking approaches 6 dB. These thresholds were determined by a yes-no procedure in the method of constant stimuli. An attempt in my laboratory to replicate these conditions, but using a forced-choice procedure yielded very much smaller effects. Clearly, the task and the cues utilized in a forced-choice procedure are different from those employed when subjects must reply "yes" or "no" after each presentation. But, since the former technique minimizes the use of subjective criteria, it probably is more representative of the true amount of neural interaction. Gescheider, Herman, and Phillips (31) reported similar observations for the masking of mechanical taps, either by other taps or by auditory tones. For example, considerably larger shifts in threshold for the mechanical pulse were obtained when they used a Békésy tracking procedure than when a forced-choice paradigm was employed.

Reaction Time

To complete this section, I would like to present the results of a reaction time study. My model of the transduction sequence for electrocutaneous pulses suggests that the neural latency should be shorter, by a very small amount, for electrical as compared to tactile stimulation. The results of a number of recent studies of cortical evoked potentials support this notion, since the latency of several components is briefer for electrical stimuli than for mechanical ones (1, 22, 48).

These latency differences are small and not likely to be demonstrated in reaction time studies. But, since Bach-y-Rita (2) suggested that the rapid reaction time for electrical stimuli may involve an alternative, faster pathway than that responding to tactile stimulation, the following study was conducted. In each of five sessions with five well-practiced observers, threshold was first determined for a brief mechanical pulse. Then observers used a matching procedure to determine the current

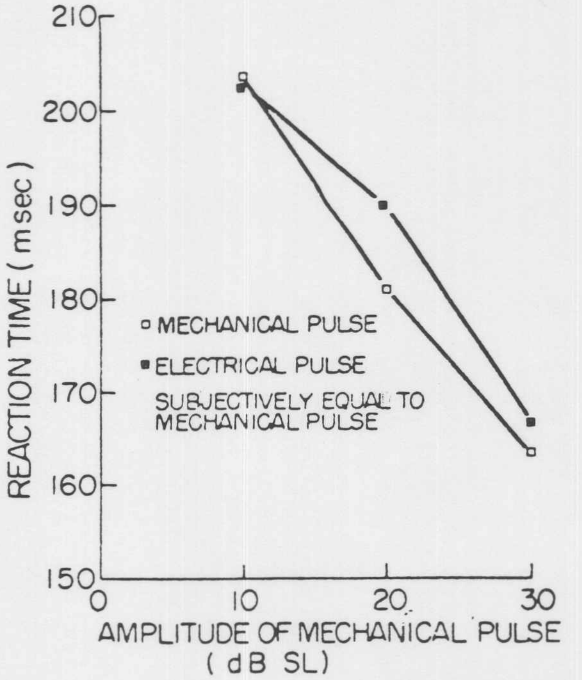


Fig. 16. Reaction times for subjectively equal electrical and mechanical pulses. The electrical stimuli were matched to mechanical pulses 10, 20, and 30 dB above threshold.

values of an electrical pulse which matched, in subjective magnitude, the sensations aroused by mechanical stimuli 10, 20, and 30 dB above threshold. Within a session, several random blocks of electrical or mechanical signals at the three intensities were presented and subjects released a telegraph key when the stimulus was detected. The results are presented in Fig. 16. Reaction time was inversely related to signal intensity, and the values are appreciably faster than those reported in studies with considerably more intense visual or auditory signals (42). However, no difference was noted between the response times for the two forms of somesthetic stimulation.

PAIN

The final section will deal with some of the literature relating to the painfulness of electrical pulses, since it is this aspect which seems to pose the greatest problem for the widespread acceptance of electrocutaneous communication devices. Clearly, intense pulses can feel painful, which is one reason for an increasing tendency to employ electrical stimulation in studies with analgesic drugs (e.g., 61). But, as many studies have demonstrated (see, e.g., 45 or 46), the pain reported by subjects is not simply a function of stimulus level or tissue damage, but is grossly influenced by motivational and individual factors.

The extent to which the "painfulness" of an electric shock is dependent on other variables is impressive. For example, Tursky and O'Connell (71) asked a group of male subjects to report when a 60-Hz current reached threshold and also levels which were uncomfortable, painful, and the maximum they would tolerate. While the range of threshold currents was reasonably small (.20 to .56 mA on the first day), some subjects rated 3.5 mA as painful, whereas others did not issue such reports until current had passed 12 mA. Likewise, the range for upper levels of tolerance extended from 5.7 to 14.1 mA. Clearly, what is no longer tolerable for one subject may be only mildly uncomfortable for another.

There is an interesting debate in the learning literature concerning the relative aversiveness of shocks which are presented a fixed interval following a warning stimulus (signaled shocks) and those which occur without any warning (unsignaled shocks). The literature is well summarized by Suboski, Brace, Jarrold, Teller, and Dieter (68), who cite and obtain evidence favoring the lesser aversiveness of either form, depending upon the task conditions. Figure 17 comes from one of their experiments. Subjects engaged in a time estimation task rated random unsignaled shocks (500 msec, 1.5 mA) higher than signaled shocks at the two interstimulus intervals which normally separated the warning and the pulse on the arm. But interstimulus interval played an important role when no such task was involved, for unsignaled shocks were rated higher at a small interval, but the reverse occurred for a longer pause. Suboski et al interpret their data within a classical conditioning framework, suggesting that under conditions which maximize conditioning (brief interstimulus interval or attention focused on the temporal characteristics of the experiment), subjects can make unspecified "preparatory conditioned responses" which attenuate the noxiousness of an electric shock. In support of such a conclusion, they note that the difference in ratings is affected by training, with the signaled shock receiving increasingly lower ratings at brief interstimulus intervals.

Lykken, Macindoe, and Tellegen (43) found that a warning tone delivered 5 sec prior to a shock resulted in both reduced skin conductance increases and reduced

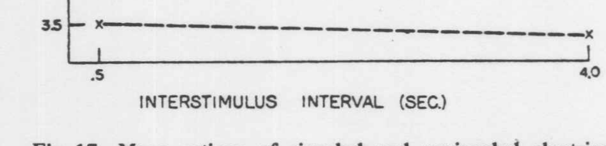


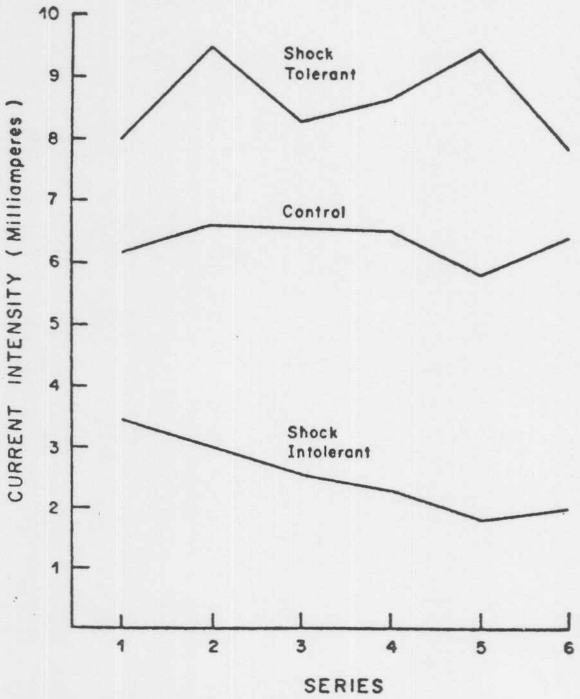
Fig. 17. Mean ratings of signaled and unsignaled electrical stimuli as a function of interstimulus interval for groups performing and not performing a time estimation task. Observers were assigned to one of the two ISI groups and signaled and unsignaled shocks were presented in random order. (From 68).

acceleration in heart rate following the shock compared to groups not so warned. However, the magnitude estimates given by the subjects were not influenced by a warning. They suggest that unsignaled shocks are more startling and disruptive than signaled ones, but the subjective magnitude of the pulse train is not altered. They also find that for 9 of 12 subjects the amplitude of the two major components of cortical evoked potentials recorded for electric shocks preceded by a constant warning interval were significantly reduced over the amplitude of shocks following a random foreperiod–a finding which unfortunately is not further discussed, but which relates to the debate between Clark, Butler, and Rosner (13, 14) and Donchin and Sutton (24), and to recent research on the slow dc potential shifts (16, 78) that are associated with anticipation (the contingent negative variation).

The Tursky and O'Connell (71) experiment demonstrated the wide range in individual criteria for pain, suggesting that electrocutaneous communication systems may be less suited for some observers than for others. Suboski et al (68) have shown that a warning signal, when subjects are clearly aware of time contingencies, causes the subsequent shock to be rated lower than a shock without warning. Unfortunately, it is not clear what this rating represents. At the start of the session, they presented subjects with three shocks and instructed them to rate these as 1, 4, or 7, but they then used the middle intensity level throughout the main portion of the experiment. One could interpret this to be an absolute judgment study, or could take the category ratings to represent intensity (as Suboski et al describe them in one portion of the paper) or unpleasantness (as they describe them elsewhere). Lykken et al (43), Rollman (53), Tursky and O'Connell (71), and others have noted that electric shocks have more than one subjective component, and questions regarding the influence of a warning on aversiveness still remain. Furthermore, if unsignaled shocks are rated higher because of their startling properties, little is yet known about the extinction or habituation of such responses.

It is becoming increasingly clear that instructions and expectations can influence pain reports. Studies using a signal detection paradigm have shown that analgesic agents can affect both d′ and criterion–the sensitivity to pain and the willingness to report it (12)–and that placebo effects are largely attributable to changes in response bias which accompany a raised criterion (15, 26).

These experiments were all performed with radiant heat stimulation, but recent experiments by Craig and Weiss (20, 21) have shown that pain thresholds for electric shock are easily manipulated. Naive subjects were paired with a confederate of the experimenter. Following each of a series of increasing electric shocks, both were required to rate the sensation along a 5-point scale ranging from "undetectable" to "painful." In the



Current intensities received on the last shock of each series.

Fig. 18. Mean threshold for "pain" on six blocks of trials for three treatment conditions: a confederate who rated shocks higher than the observer (shock intolerant), lower than the observer (shock tolerant), and typical of naive observers (control). (From 20).

"shock intolerant" condition, the confederate rated the stimuli as more intense than did the naive subject, while in the "shock tolerant" condition, he rated them less intense. A control group had the confederate give responses typical of naive subjects. Figure 18 shows the results of this study, plotting the current value for a "painful" report as a function of experimental condition over six blocks of trials. The behavior of the model had a profound effect on the reported painfulness of these 60-Hz, 500-msec pulses. The mean current intensities for the three groups ranged from a low of 2.5 mA to a high of 8.7 mA, a pain threshold more than three times greater. A replication of the "shock tolerant" condition with another confederate led to an even higher pain threshold, 12.4 mA, with some subjects going to 17.0 mA. Autonomic indices did not differ for subjects in the two experimental groups (19). Subjects receiving the low current shocks in the "intolerant" group showed the same increases in heart rate and skin conductance as subjects in the "tolerant" group receiving shocks more than three times as intense. Although the subjects denied that the models influenced their judgments, these studies, as well as the others I cited earlier, indicate that great care must be exercised both in the selection of subjects to wear electrocutaneous signaling systems and in the set which is established when they are instructed in its use.

SUMMARY

This paper has primarily concerned itself with the influence of intensity and time on the response of the somatosensory system to percutaneous electrical stimulation. Many other variables have received some attention, and their influence is described elsewhere. For example, Hawkes and Warm (38) and Hawkes (37) note some of the effects of ac stimulation, Gibson (32) discusses the electrical properties of tissue (as do Collins & Saunders, 18), and Gibson (32) and Bach-y-Rita (2) deal with some effects of electrode diameter and locus of shock application. Uttal and Krissof (74) present experiments on temporal acuity for missing pulses in a train. Electrical pulses at several loci, with appropriate temporal spacing, can give rise to apparent movement on the skin, as Gibson (32), Sherrick (60), and Geldard and Sherrick's (29) "rabbit" have shown, though Békésy (6) has demonstrated that with very brief intervals, subjects describe a single sensation localized between the stimulating sites. Finally, advances in the use of electrocutaneous displays for communication systems have been described by Bach-y-Rita (2), Collins (17), Collins and Saunders (18), and Strong and Troxel (67). It should also be noted that I have not attempted to deal with the central mechanisms which code and transmit information about electrocutaneous inputs. Some of the controversies regarding the pathways involved in spinal transmission are summarized by Somjen (62) and Wall (77). Physiological and behavioral consequences of sections of the dorsal columns and lateral lemniscus in monkeys on thresholds for electrical stimulation are described by Eidelberg and Woodbury (25) and Schwartz, Eidelberg, Marchok, and Azulay (59).

A number of psychophysical experiments have been described here. The somatosensory system appears to be exceedingly sensitive to small increments in the amplitude of electrical pulses, since both psychometric functions, and power functions, are steeper than those obtained with adequate stimulation. The Weber function also is extremely small (70). Likewise, the system responds differentially to the time domain, as demonstrated by studies of temporal integration for single pulses and trains, masking, and reaction time. Finally, the paper included a review of a number of recent studies on the painfulness of electric stimuli, emphasizing large intersubject differences in pain thresholds, the unresolved debate about the effects of prior warning signals, and the biasing effects which can manipulate both subjective reports and psychophysiological indices.

While the major impetus behind these experiments is an increased understanding of transduction and coding by the somatosensory system, the paper reviewed certain aspects of the data which have relevance for the design of communication systems. It is not yet possible to specify the precise parameters and operating conditions to be used in producing complex spatio-temporal patterns on the skin with electrocutaneous signals. Furthermore, some problems concerned with coupling a large number of independent electrodes to the skin surface of a freely moving observer are yet to be overcome. It seems clear, however, that such a system is a viable and probably preferable alternative to electromechanical ones, and that solutions for many of the remaining problems are relatively close at hand.

REFERENCES

1. Andersson, S. A., Norrsell, K., & Norrsell, U. Spinal pathways projecting to the cerebral first somatosensory area in the monkey. Journal of Physiology, 1972, 225, 589-597.
2. Bach-y-Rita, P. *Brain mechanisms in sensory substitution.* New York: Academic Press, 1972.
3. Bach-y-Rita, P., Collins, C. C., Saunders, F. A., White, B., & Scadden, L. Vision substitution by tactile image projection. Nature, 1969, 221, 963-964.
4. Battersby, W. S., & Schuckman, H. The time course of temporal summation. Vision Research, 1970, 10, 263-273.
5. Beck, C., & Rosner, B. S. Magnitude scales and somatic evoked potentials to percutaneous electrical stimulation. Physiology & Behavior, 1968, 3, 947-953.
6. Békésy, G. v. *Sensory inhibition.* Princeton: Princeton University Press, 1967.
7. Bliss, J. C., Katcher, M. H., Rogers, C. H., & Shepard, R. P. Optical-to-tactile image conversion for the blind. IEEE Transactions on Man-Machine Systems, 1970, MMS-11, 58-65.
8. Bourassa, C. M., & Swett, J. E. Sensory discrimination thresholds with cutaneous afferent nerve volleys in the cat. Journal of Neurophysiology, 1967, 30, 515-529.
9. Buchthal, F., & Rosenfalck, A. Evoked action potentials and conduction velocity in human sensory nerves. Brain Research, 1966, 3, 1-122.
10. Bujas, Z. Electrical taste. In L. M. Beidler (Ed.), *Taste. Handbook of sensory physiology.* Vol. IV/2. Berlin: Springer, 1971. Pp. 180-199.
11. Bujas, Z., & Pfaffmann, C. Potassium gymnemate and the sweet and bitter taste provoked electrically. Perception & Psychophysics, 1971, 10, 28-29.
12. Chapman, C. R., Murphy, T. M., & Butler, S. H. Analgesic strength of 33 percent nitrous oxide: A signal detection theory evaluation. Science, 1973, 179, 1246-1248.
13. Clark, D. L., Butler, R. A., & Rosner, B. S. Dissociation of sensation and evoked responses by a general anesthetic in man. Journal of Comparative & Physiological Psychology, 1969, 68, 315-319.
14. Clark, D. L., Butler, R. A., & Rosner, B. S. Are evoked responses necessary? A reply to Donchin and Sutton. Communications in Behavioral Biology, 1970, 5, 105-110.
15. Clark, W. C. Sensory-decision theory analysis of the placebo effect on the criterion for pain and thermal sensitivity (d'). Journal of Abnormal Psychology, 1969, 74, 363-371.
16. Cohen, J. Very slow brain potentials relating to expectancy: The CNV. In E. Donchin and D. B. Lindsley (Eds.), *Average evoked potentials.* Washington, D.C: National Aeronautics & Space Administration, 1969. Pp. 143-198.
17. Collins, C. C. Tactile television in mechanical and electrical image projection. IEEE Transactions on Man-Machine Systems, 1970, MMS-11, 65-71.
18. Collins, C. C., & Saunders, F. A. Pictorial display by direct electrical stimulation of the skin. Journal of Biomedical Systems, 1970, 1, 3-16.
19. Craig, K. D., & Neidermayer, H. Autonomic correlates of pain threshold influenced through social modelling. Journal of Personality & Social Psychology, 1973, in press.
20. Craig, K. D., & Weiss, S. M. Vicarious influences on

pain-threshold determinations. Journal of Personality & Social Psychology, 1971, 19, 53-59.
21. Craig, K. D., & Weiss, S. M. Verbal reports of pain without noxious stimulation. Perceptual & Motor Skills, 1972, 34, 943-948.
22. Davis, H., Osterhammel, P. A., Wier, C. C., & Gjerdingen, D. B. Slow vertex potentials: Interactions among auditory, tactile, electric and visual stimuli. Electroencephalography & Clinical Neurophysiology, 1972, 33, 537-545.
23. Dimitrijević, M. R., Faganel, J., Gregorić, M., Nathan, P. W., & Trontelj, J. K. Habituation: Effects of regular and stochastic stimulation. Journal of Neurology, Neurosurgery, & Psychiatry, 1972, 35, 234-247.
24. Donchin, E., & Sutton, S. The "psychological significance" of evoked responses: A comment on Clark, Butler, and Rosner. Communications in Behavioral Biology, 1970, 5, 111-114.
25. Eidelberg, E., & Woodbury, C. M. Apparent redundancy in the somatosensory system in monkeys. Experimental Neurology, 1972, 37, 573-581.
26. Feather, B. W., Chapman, C. R., & Fisher, S. B. The effect of a placebo on the perception of painful radiant heat stimuli. Psychosomatic Medicine, 1972, 34, 290-294.
27. Geldard, F. A. Cutaneous coding of optical signals: The optohapt. Perception & Psychophysics, 1966, 1, 377-381.
28. Geldard, F. A. Body English. Psychology Today, 1968, 2, 42-47.
29. Geldard, F. A., & Sherrick, C. E. The cutaneous "rabbit": A perceptual illusion. Science, 1972, 178, 178-179.
30. Gengel, R. W., & Watson, C. S. Temporal integration: I. Clinical implications of a laboratory study. II. Additional data from hearing impaired subjects. Journal of Speech & Hearing Disorders, 1971, 36, 213-224.
31. Gescheider, G. A., Herman, D. D., & Phillips, J. N. Criterion shifts in the measurement of tactile masking. Perception & Psychophysics, 1970, 9, 433-436.
32. Gibson, R. H. Electrical stimulation of pain and touch. In D. R. Kenshalo (Ed.), *The skin senses.* Springfield, Ill: Thomas, 1968. Pp. 223-260.
33. Green, D. M., & Swets, J. A. *Signal detection theory and psychophysics.* New York: Wiley, 1966.
34. Grundfest, H. The general electrophysiology of input membrane in electrogenic excitable cells. In W. R. Loewenstein (Ed.), *Principles of receptor physiology. Handbook of sensory physiology.* Vol. I. Berlin: Springer, 1971. Pp. 135-165.
35. Hahn, J. F. Cutaneous vibratory thresholds for square-wave electrical pulses. Science, 1958, 127, 879-880.
36. Hallin, R. G., & Torebjörk, H. E. Electrically induced A & C fibre responses in intact human skin nerves. Experimental Brain Research, 1973, 16, 309-320.
37. Hawkes, G. R. Cutaneous discrimination of electrical intensity. American Journal of Psychology, 1961, 74, 45-53.
38. Hawkes, G. R., & Warm, J. S. The sensory range of electrical stimulation of the skin. American Journal of Psychology, 1960, 73, 485-487.
39. Heckmann, J. R. Excitability curve: A new technique for assessing human peripheral nerve excitability in vivo. Neurology, 1972, 22, 224-230.
40. Higgins, J. D., Tursky, B., & Schwartz, G. E. Shock-elicited pain and its reduction by concurrent tactile stimulation. Science, 1971, 172, 866-867.
41. Keidel, W. D., Keidel, U. O., & Wigand, M. E. Adaptation: Loss or gain of sensory information? In W. A. Rosenblith (Ed.), *Sensory communication.* Cambridge: M.I.T. Press, 1961. Pp. 319-338.
42. Kohfeld, D. C. Simple reaction time as a function of stimulus intensity in decibels of light and sound. Journal of Experimental Psychology, 1971, 88, 251-257.
43. Lykken, D. T., Macindoe, I., & Tellegen, A. Preception: Autonomic response to shock as a function of predictability in time and locus. Psychophysiology, 1972, 9, 318-333.
44. McCall, G. N. Duration effects of supraliminal electrical stimuli to the tongue. Journal of Speech & Hearing Research, 1972, 15, 869-876.
45. Melzack, R. The perception of pain. Scientific American, 1961, 204, 41-49.
46. Melzack, R., & Casey, K. L. Sensory, motivational and central control determinants of pain: A new conceptual model. In D. R. Kenshalo (Ed.), *The skin senses.* Springfield, Ill: Thomas, 1968. Pp. 423-443.
47. Melzack, R., Wall, P. D., & Weisz, A. Z. Masking and metacontrast phenomena in the skin sensory system. Experimental Neurology, 1963, 8, 35-46.
48. Nakanishi, T., Takita, K., & Toyokura, Y. Somatosensory evoked responses to tactile tap in man. Electroencephalography & Clinical Neurophysiology, 1973, 34, 1-6.
49. Nathan, P. W., Noordenbos, W., & Wall, P. D. Ongoing activity in peripheral nerve: Interactions between electrical stimulation and ongoing activity. Experimental Neurology, 1973, 38, 90-99.
50. Pollack, I. Methodological determination of the PEST (Parametric Estimation by Sequential Testing) procedure. Perception & Psychophysics, 1968, 3, 285-289.
51. Rollman, G. B. Electrocutaneous stimulation: Psychometric functions and temporal integration. Perception & Psychophysics, 1969, 5, 289-293.
52. Rollman, G. B. Detection models: Experimental tests with electrocutaneous stimuli. Perception & Psychophysics, 1969, 5, 377-380.
53. Rollman, G. B. Temporal summation of threshold and suprathreshold electrocutaneous pulses. Paper presented at Eastern Psychological Association, Boston, Mass., April 1972.
54. Rollman, G. B. Tactile stimulation: Psychophysical studies of receptor function. Perception & Psychophysics, 1973, 13, 81-86.
55. Rosner, B. S. Neural factors limiting cutaneous spatiotemporal discriminations. In W. A. Rosenblith (Ed.), *Sensory communication.* Cambridge: M.I.T. Press, 1961. Pp. 725-737.
56. Rosner, B. S. Temporal interaction between electrocutaneous stimuli. Journal of Experimental Psychology, 1964, 67, 191-192.
57. Rosner, B. S., & Goff, W. R. Electrical responses of the nervous system and subjective scales of intensity. In W. D. Neff (Ed.), *Contributions to sensory physiology.* Vol. 2. New York: Academic Press, 1967. Pp. 169-221.
58. Schmid, E. Temporal aspects of cutaneous interaction with two-point electrical stimulation. Journal of Experimental Psychology, 1961, 61, 400-409.
59. Schwartz, A. S., Eidelberg, E., Marchok, P., & Azulay, A. Tactile discrimination in the monkey after section of the dorsal funiculus and lateral lemniscus. Experimental Neurology, 1972, 31, 582-596.
60. Sherrick, C. E. Studies of apparent tactual movement. In D. R. Kenshalo (Ed.), *The skin senses.* Springfield, Ill: Thomas, 1968. Pp. 331-344.
61. Smith, R. H., & Andrew, J. H. Gradable pain production. In N. L. Wulfsohn and A. Sances, Jr. (Eds.), *The nervous system and electric currents.* New York: Plenum, 1970. Pp. 89-91.
62. Somjen, G. *Sensory coding in the mammalian nervous system.* New York: Appleton-Century-Crofts, 1972.
63. Steriade, M., & Demetrescu, M. Simulation of peripheral sensory input by electrical pulse trains applied to specific afferent pathways. Experimental Neurology, 1967, 19, 265-277.
64. Stevens, J. C., & Hall, J. W. Brightness and loudness as functions of stimulus duration. Perception & Psychophysics, 1966, 1, 319-327.
65. Stevens, S. S. The psychophysics of sensory function. In W.

A. Rosenblith (Ed.), *Sensory communication.* Cambridge: M.I.T. Press, 1961. Pp. 1-33.

66. Stevens, S. S., Carton, A. S., & Shickman, G. M. A scale of apparent intensity of electric shock. Journal of Experimental Psychology, 1958, 56, 328-334.
67. Strong, R. M., & Troxel, D. E. An electrotactile display. IEEE Transactions on Man-Machine Systems, 1970, MMS-11, 72-79.
68. Suboski, M. D., Brace, T. G., Jarrold, L. A., Teller, K. J., & Dieter, R. Interstimulus interval and time estimation in ratings of signaled shock aversiveness. Journal of Experimental Psychology, 1972, 96, 407-415.
69. Taylor, M. M., & Creelman, C. D. PEST: Efficient estimates on probability functions. Journal of the Acoustical Society of America, 1967, 41, 782-787.
70. Teghtsoonian, R. On the exponents in Stevens' law and the constant in Ekman's law. Psychological Review, 1971, 78, 71-80.
71. Tursky, B., & O'Connell, D. Reliability and interjudgment predictability of subjective judgments of electrocutaneous stimulation. Psychophysiology, 1972, 9, 290-295.
72. Tursky, B., & Watson, P. D. Controlled physical and subjective intensities of electric shock. Psychophysiology, 1964, 1, 151-162.
73. Tursky, B., Watson, P. D., & O'Connell, D. N. A concentric shock electrode for pain stimulation. Psychophysiology, 1965, 1, 296-298.
74. Uttal, W. R., & Krissoff, M. Response of the somesthetic system to patterned trains of electrical stimuli. In D. R. Kenshalo (Ed.), *The skin senses.* Springfield, Ill: Thomas, 1968. Pp. 262-303.
75. Verrillo, R. T. Temporal summation and vibrotactile sensitivity. Journal of the Acoustical Society of America, 1965, 37, 843-846.
76. Verrillo, R. T. A duplex mechanism of mechanoreception. In D. R. Kenshalo (Ed.), *The skin senses.* Springfield, Ill: Thomas, 1968. Pp. 139-159.
77. Wall, P. D. The sensory and motor role of impulses travelling in the dorsal columns towards cerebral cortex. Brain, 1970, 93, 505-524.
78. Walter, W. G. The contingent negative variation. An electrical sign of significant association in the human brain. Science, 1964, 146, 434.
79. Zwislocki, J. Theory of temporal auditory summation. Journal of the Acoustical Society of America, 1960, 32, 1046-1060.