Reaction time to the onset and offset of electrocutaneous stimuli as a function of rise and decay time¹

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Reaction times were obtained to the onset and offset of 70-cps electrocutaneous signals of five rise and decay times and five intensity levels. The results show that both onset and offset RTs increase linearly with increased rise and decay times. With fast rates of rise or decay, the onset produces faster RTs than the cessation of stimulation. The opposite effect is found when long rise and decay times are used. Interpretations of these results are given in terms of neural adaptation and accommodation.

Studies by Woodrow (1915) and Sticht and Foulke (1966) have shown that the reaction time (RT) to the onset of electrocutaneous ac stimulation is faster than the RT to its offset. Sticht and Foulke's Ss reported a tendency for sensations to "fade" with continued application of the stimulus. Thus, the subjective intensity was less at the offset than at the onset of stimulation and this was indexed by the longer offset RTs. It is likely that the "fading" of sensation with continued application of the stimulus was due to neural adaptation, as described by Adrian (1928). He showed that when a nerve is stimulated electrically, there is an initial high frequency "burst" of impulses. With sustained application of the stimulus, the frequency of nerve impulses decreases. Recently, Hensel and Boman (1960) have provided recordings of peripheral nerve impulses in single fibers in man which also show the adaptation phenomenon. If the intensity of a sensation depends upon the frequency of nerve impulses, as suggested by Adrian, then the decrease in the frequency of nerve impulses with continued application of an electrocutaneous stimulus should be accompanied by a "fading" of sensation.

On the basis of the foregoing, the following explanation for the observation that onset RTs are faster than offset RTs was suggested by Sticht and Foulke (1966). With the onset of stimulus current, there is an initial high frequency "burst" of nerve impulses which signals the stimulus onset. However, owing to adaptation, as stimulation continues, the impulse frequency decreases rapidly. Thus, the change in neural activity at the offset of the stimulus is less than the change produced by the onset of the stimulus. This difference is responsible for the increased offset RT. (To our knowledge, no "off" fibers, i.e., fibers producing impulses only at the offset of the stimulus, have been demonstrated in peripheral nerves, and therefore no new impulses are assumed following the cessation of stimulation.)

Further work by Adrian (1928, pp. 66-67) suggested a method for testing the above hypothesis. He showed that the initial high frequency burst of impulses could be avoided by the administration of a stimulus that approached full strength at a relatively slow rate. Taking advantage of his finding, we tested the hypothesis presented above by an experiment in which onset and offset RTs were determined for stimuli presented at five different rise and decay times. We expected to observe faster reactions to the onsets of stimuli with very fast rise and decay times than to their offsets. We further expected that as the rise and decay time was increased, this difference between onset and offset RTs would diminish and ultimately disappear. Our expectations were only partially fulfilled.

Subjects

Three male college students served as Ss in the experiment. Each S made 1000 practice reactions prior to the experiment.

Apparatus and Procedure

The stimulus was a 70-cps sinusoidal electric current produced by a Hewlett-Packard audio frequency oscillator, Model 201CR. The output of the oscillator was connected through a Grason-Stadler electronic switch, Model 829D, and a Daven attenuator, Type 7707, to the input of a 75 w McIntosh amplifier, Model MC72. Use of the electronic switch permitted transientless switching at controlled rise and decay times. The attenuator permitted adjustments of stimulus intensity in steps of 1 dB over a range of 20 dB. An approximate impedance match between the 600-ohm output of the amplifier and S's skin impedance was secured with a UTC transformer, Type LS12. A 200K-ohm resistance was connected in series with S in order to limit fluctuations in stimulus current due to changes in S's impedance. Stimulus current was determined by dividing by 100 the voltage drop, as measured by a Ballantine voltmeter, Model 200E, across a 100-ohm precision resistor connected in series with S. The stimulus was applied to the skin by means of a stainless steel active electrode, approximately 14 mm in diameter, centered on the volar surface of the distal phalanx of the left index finger. The passive electrode was a rectangular steel plate, 2-1/2 in. x 3-1/2 in. applied to the palm of the left hand.

Ramp times² of 0.5, 5, 26, 140, and 340 msec. were represented in the experiment. The ramp characteristics of the stimuli were displayed on a Tektronix storage oscilloscope, Model 549, and found to be slightly sigmoidal in shape.

Stimuli were presented at five intensities: 2, 4, 6, 8, and 10 dB above each S's offset threshold. The offset threshold was defined as that value of stimulus intensity at which S could detect the offset of the stimulus 50 percent of the time, following a foreperiod of from 2 to 4 sec. during which the stimulus was present. Offset thresholds were used because it was found that when stimulus intensities were adjusted in terms of onset thresholds, the stimuli of weakest intensity often adapted out during the foreperiod. Since each S's offset threshold was taken as 0 dB, absolute values for the five stimulus intensities used in the experiment varied from S to S. Over the course of ten experimental sessions, Ss showed occasional changes in sensitivity and it was necessary to increase the weakest stimulus intensity from time to time. However, in no instance was an adjustment of more than $20\mu\text{a}$ required. Because such adjustments were made, the intensity levels shown for each S in Fig. 1 (see Results section) are mean values.

With no special preparation of the skin, S was seated in an Industrial Acoustics Chamber, Model 400, with his left hand resting in position on the electrodes. To obtain a reaction from S, E set his controls and then signaled S that all was ready. Upon receipt of this

signal, S held down a telegraph key with his right hand. When S felt that he was ready to react, he depressed a footswitch which operated a Hunter-Timer Model 100B, connected in the external control circuit of the electronic switch. The relay closure occurring at the end of the time interval (the foreperiod in this experiment) for which the Hunter timer was adjusted, presented the stimulus by switching the electronic switch and also started a Hunter Klockounter. S's reaction, releasing the telegraph key, stopped the Klockounter, and his RT could then be read from its dials to the nearest msec.

The foreperiod was varied randomly from 2 to 4 sec. to prevent response synchronization by S. In the onset condition, electrical stimulation commenced at the end of the foreperiod and S reacted to its onset. In the offset condition, electrical stimulation was present during the foreperiod, and S reacted to its offset at the end of the foreperiod.

The program for an experimental session was as follows. Four offset RTs, then four onset RTs were obtained using a stimulus of a given composition. This procedure was followed for each of the 25 stimuli that result from a factorial combination of five intensities and five ramp times. Thus, 200 RTs were obtained during a single experimental session. There were 10 experimental sessions in all, and the order in which stimuli were presented was varied from session to session to control for the possibility of an effect due to order. In all, 40 onset and 40 offset RTs were obtained for each stimulus combination for each S.

Fig. 1. Mean reaction times for three subjects to onset and offset electrocutaneous stimuli of five rise and decay times (abscissa) and five levels of intensity (parameter).

Results

The means and standard deviations of each S's RTs were computed for all experimental conditions. Figure 1 presents the mean RTs of the three Ss for each stimulus combination. It is apparent that, with the exception of the offset RT to the stimulus of weakest intensity, there is a linear increase in RT as both rise time and decay time increase. The slope of the onset curves for the three Ss are quite similar (values found for the stimuli of weakest intensity were 1.6 for Ss L. M. and R. H., and 1.9 for E. P.) and their magnitudes decrease as intensity increases. The slopes of the offset curves do not change appreciably or consistently as intensity is increased. Curves for two of the Ss show an exponential increase in RT for the stimuli of weakest intensity as decay time is increased. An additional set of RTs, obtained from R. H. two weeks after the close of the experiment, also reveals this relationship as depicted by the crosses in Fig. 1. The exponential offset curves are similar to the accommodation curves obtained by Kugelberg (1944) using dc stimuli with exponential onsets and rheobase measures.

A finding of particular interest is the manner in which the difference between onset and offset RTs depends upon the ramp time of the stimulus. When ramp time is short, onset RTs are faster than offset RTs. However, as ramp time is increased, this difference diminishes until, at a certain ramp time, the value of which depends upon the intensity of the stimulus, onset and offset RTs are equal. This finding supports the adaptation hypothesis presented earlier. The fact that at longer ramp times, the offset RTs become faster than onset RTs, was not anticipated. This is discussed further later on.

Further inspection of Fig. 1 reveals a systematic change between stimulus intensity and the point of intersection of onset and offset curves. By dropping

Fig. 2. Rise and decay times which produce equal onset and offset RTs (on=off ramp time) for three subjects (dotted lines) and the mean for these three subjects (solid line) as a function of stimulus intensity.

a perpendicular from the point of intersection of a given S's onset and offset curves to the abscissa, the ramp time required for equal onset and offset RTs at a given intensity may be read. For the sake of brevity, this will be referred to henceforth as the on=off ramp time. Figure 2 shows on=off ramp time for each S (dotted lines) and mean on=off ramp time (solid line) as a negatively accelerated exponential function of stimulus intensity.

In order to explicate further the relationship among onset and offset RTs, intensity, and ramp time, Fig. 3 is presented. Onset and offset RTs are plotted against intensity with ramp time as the parameter. The figure indicates that both onset and offset RTs decrease as intensity is increased. This finding is consistent with earlier work (Sticht & Foulke, 1966). The figure also shows that, for each S, there is a critical intensity by ramp time combination below which onset RTs are faster and above which offset RTs are faster. It is also noteworthy that below the critical intensity by ramp time combination, the differences between onset and offset RTs decrease as intensity is increased. Above this critical combination, the relationship is not as simple. At a ramp time of 140 msec., the difference between onset and offset RTs increases as stimulus intensity is increased. At a ramp time of 340 msec., the difference between onset and offset RTs does not vary with intensity.³

Discussion

In earlier work (Sticht & Foulke, 1966), we found faster RTs to the onsets of ac stimuli than to their offsets. We suggested that the faster RTs might be due to a high frequency burst of neural impulses accompanying the rapid onset of cutaneous stimuli (cf., Adrian, 1928, with frog; Hensel & Boman, 1960, with man). It was suggested that the longer offset RTs were the result of a decrease in the frequency of impulses following a period of neural adaptation to sustained stimulation. On the basis of this hypothesis, we reasoned that if stimuli with gradual rather than abrupt onsets were used, the initial burst of impulses associated with abrupt onsets should be avoided, as demonstrated with frog nerves by Adrian in 1928, and with sensory and motor nerves of cats by Skogland in 1942, with the result that the differences between onset and offset RTs should disappear. This expectation was realized in the present study. As ramp time was increased, a point was found at which onset and offset RTs became equal. However, the finding that beyond this point offset RTs became faster than onset RTs was not expected. It may be that this finding can be explained by the accommodation of nerves. When an electrical stimulus with a relatively long rise time is applied to a nerve fiber, the threshold is higher than the threshold for a stimulus with a fast rise time. This elevation of threshold is called accommodation (Solandt, 1936; Skogland, 1942; Kugelberg, 1944).

Fig. 3. Mean RTs for three subjects to onset and offset electrocutaneous stimuli of five intensity levels (abscissa) and five rise and decay times (parameter).

Three factors may have combined to produce the increase in RTs to stimuli with gradual onsets, found in the present study.

A. Increasing stimulus rise time delays the threshold. For instance, Skogland (1942) found an 80 msec. delay in the appearance of the threshold spike in the motor nerve of the cat when the stimulus rise time was increased from 80 to 200 msec. He observed similar delays in sensory nerves of the cat.

B. With stimulus intensity held constant, increasing stimulus rise time results in a decrease in the number of fibers that produce impulses (see Skogland, 1942, pp. 42-48).

C. There is a decrease in the rate at which threshold intensity is exceeded for those fibers that remain responsive at longer rise times, as rise time is increased. As a consequence, not only the threshold impulse frequency but also the total impulse frequency per unit time is reduced (see Skogland, 1942, p. 60).

Thus, three factors, a delayed threshold, a decreased impulse frequency, and a reduction in the rate at which impulse frequency increases, operate to produce the

longer RTs for stimuli with gradual onsets. At the offset of the stimulus, on the other hand, only two of these factors are involved. There is a reduced number of fibers available to be "turned-off" at the termination of the stimulus with gradual onset. Increasing stimulus decay time has a retarding effect on the declining impulse rate at the offset of the stimulus. However, there is no factor comparable to the delay in onset thresholds due to accommodation. We are suggesting that the three onset factors exert a greater influence on RT than the two offset factors.

Examination of Fig. 3 reveals that offset RTs decrease at a faster rate than onset RTs as intensity is increased. This, coupled with the fact that the rate of increase in onset RTs is faster than that of offset RTs as ramp time is increased (see Fig. 1), results in the decrease in on-off ramp time with increased intensity (see Fig. 2). Presumably the finding that offset RTs were reduced faster than onset RTs as intensity was increased, was due to the fact that, at their offsets, the stimuli of weakest intensity were nearer threshold than at their onsets (see above). Thus, when the intensity of these

stimuli was increased, we found the rapid initial reduction in offset RTs that is characteristic of RTs in general when the intensity of stimuli near threshold is increased (cf., Woodworth & Schlosberg, 1954, pp. 19-20).

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Notes

1. This work was supported by NASA as Project No. NGR 18-002-007 at the University of Louisville.
2. The term "ramp time" refers to the time required for the rise or decay of the stimulus current to or from its peak value. It refers to both rise and decay times.
3. Subsequent to the study reported herein, mean data for sixteen untrained subjects for onset and offset stimuli of four rise and decay times and three levels of intensity has confirmed the present findings.

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