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Period from February 1, 1967 to October 15, 1967

I. Summary of Progress

The previous phase of this study afforded evidence for a model of the electrodermal response which implied that the recovery limb contained information of value. An approximate method for obtaining a characteristic measure of this limb, the recovery half-time, was adopted and used for initial explorations into possible applications of the new measure. Results were very encouraging and as a consequence a major effort has since been exerted toward the development of a more refined measure for characterizing the recovery limb and toward the evaluation of its behavioral indications. At the same time a parallel effort was maintained to continue experiments aimed at clarifying the nature of the peripheral mechanism of the response. The following summarizes progress made in these areas.

The subsequent section on Specific Findings (II), details the quantitative data of those items whose analysis has proceeded far enough for reporting.

A. Recovery Limb Measures

1. A superior manual method was developed for obtaining the time constant of the recovery limb. Its reliability between scorers and in repeated measures exceeds 0.90.

2. The basis for two automated systems for evaluating the time constant was established; one of these is an analog system, the other digital. Both are relatively simple.

3. The discriminating power of the new measure as an indicator of stimulus situation has been tested on several populations, using the manual method. It successfully distinguished between several paired categories of stimulus conditions with remarkable reliability.

4. The recovery limb time constant for a given individual during a standard stimulus situation was found to be characteristic and was correlated with his rate of habituation to a series of repeated stimuli. Individuals who had a short time constant also tended to have a slower habituation in their electrodermal response to a series of reaction time tests but not to a series of tones.

5. The variation in time constant was examined in a population of subjects in which each was exposed to a succession of eight conditions ranging from resting with eyes closed through a series of simple to complex tasks. A cold pressor test was also included. The time constant varied with the situation in a characteristic manner, being longest for the rest situation and becoming shorter as the task becomes more involving. This finding was a consistant one across subjects and was independent of amplitude. The cold pressor test, although producing high activation, was accompanied by a long time constant (about the same order as that of spontaneous responses during rest). These results strongly supported the interpretation of short time constants as accompaniments of goal directed behavior.

6. Shorter time constants were found, as predicted by the model, to be associated with positive skin potential responses and with reabsorption responses.

B. Studies of the Peripheral Mechanism

1. A major question regarding the nature of the absorbtion reflex (and presumably, therefore of the origin of the positive skin potential response believed to be related to it) is whether it depends upon absorption through the horny layer, mediated by the underlying epidermis, or upon sweat duct activity. An optical device for observing surface moisture has supported the hypothesis that reabsorption occurs via the sweat duct.

2. The local potential response (LPR) produced by stretching the skin was previously shown to contain a fast and a slow component which often respond differently to changes in surface conditions. A given variable may produce either potentiation or attenuation of the LPR in a manner which defies prediction at this stage, but the variation in amplitude of the experimental site is consistently greater than the control and an effect of the surface variable is consequently statistically significant. However, only three effects are consistant in direction of change:

a. Reducing surface temperature produces an increase in LPR amplitude.

b. Exsanguination produces an increase in LPR amplitude.

c. Background negative electrodermal potential activity produces an increase in LPR amplitude.

3. The striking effect of the aluminum ion in selectively potentiating the positive wave of the skin potential response was utilized as an aid in an attempt to identify which component of the biphasic potential response was primarily responsible

for the conductance change in the exosomatic response. Since individuals show a rather wide variation in their response to local application of $AlCl_3$, concordance between effects upon positive potential responses and effects upon conductance responses was examined. The results of this study on 20 subjects raised more questions than it answered. Although potentiation of the conductance response was correlated with the potentiation of the potential response across subjects, the specific relation to SPRs of negative as opposed to positive direction, and the relation of polarity of current flow to degree of potentiation presented a confused picture. Moreover, the associated measurements of capacitance and impedance revealed no significant effect of $AlCl_3$ on these for the group as a whole. These results are presently undergoing intensive examination and will not be reported here.

4. The report of a finding of sweat glands under the nail plate was clarified indicating that these were observed only at the distal tip near the margin with the naked skin. A new method for insuring that the nail plate site was confined to the center of the nail and for precluding spurious contributions by activity of the reference site demonstrated the following:

a. Positive or negative potential responses may be observed from the center of the nail plate.

b. These are not appreciably influenced (if at all) by the application of various surface electrolytes.

c. Local potential responses of high magnitude (all positive) are readily elicited from this same area.

d. Exosomatic nail responses showing the typical increase in conductance are not observed. Responses showing a decrease in resistance are not unusual, but entire records in which the nearby skin is active may show none of these. They are thought to represent the vasomotor effect upon conductance typically seen in the impedance plethysmogram. The lack of covariation between these conductance responses and the nail potential responses suggests that they represent different phenomena. At this stage it is believed that the nail potential responses because they correlate highly with skin potential responses (SPR), represent a component found in the SPR which is not of sweat gland origin.

C. Study of Bio-Psychological Adaptability

Initial exploration of the possibility of using the adaptability of autonomic behavior as an index of adaptability of psychological behavior has been started on a population of 60 subjects. These were run through a battery of psychological tests and then exposed to a behavioral situation which examined their rate of habituation to a series of repeated stimuli, their rate of activation from a rest state to a task state, and their rate of relaxation following the end of the task. Analyses completed to date have shown that individuals who demonstrate a capacity to maintain a high degree of appropriate inhibition during motor task performance also show rapid recovery of electrodermal levels after high activation. Moreover, post-activation recovery to original rest levels for pulse volume and for electrodermal activity proceed at different rates, and a large fraction of the test population shows a reciprocal relation between these two rates.

II. Specific Findings

A. Recovery Limb of the Skin Conductance Response

1. Manual measurement of the recovery limb time constant.

Gildemeister (1923) and Darrow (1937) had described the recovery limb as an exponential decay curve. All responses whose recovery limb has the same time constant should fall along this curve independent of amplitude as shown in figure 1. In actuality only the first portion of this limb falls upon an exponential slope, since the latter portion apparently represents a separate component as described in the previous report. Because this second component may come in at various levels, the half-time measure previously described is subject to considerable variation in the activity of the slow component (figure 2). In addition, if a second wave occurs during the recovery of the wave in question, measurement of the half-time is often precluded. For these reasons, a method for examining the time constant of the early portion of the recovery limb was developed. In this method a transparent template consisting of a family of exponential curves, each having a slightly longer time constant than the one to its left, is slid sideways over the response, its base-line at the level of response onset, until one of the calibrated slopes corresponds with the early portion of the recovery limb (figure 3). Interpolation is easily accomplished. A reading takes about 7 seconds, and reliability both for repeated measures and between scores is high (better than 0.9). If the baseline (during inactive periods) has an appreciable slope, a correction must be applied. This is accomplished by lowering the baseline of the template to a level half way between the level of wave onset and the

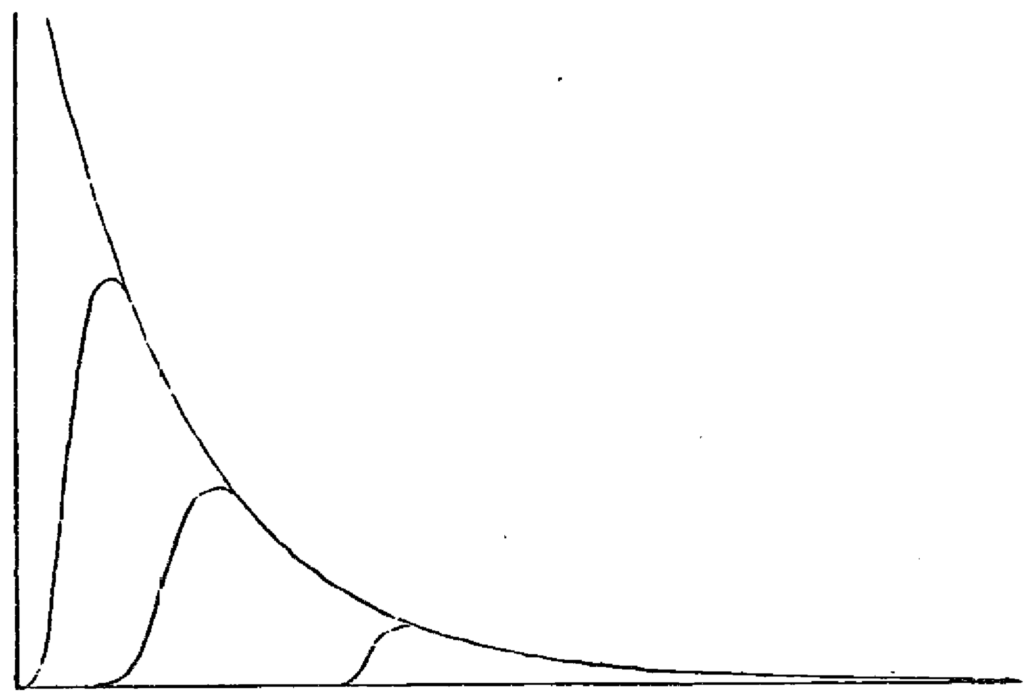

Figure 1. Illustration of variation in apparent shape of responses having same recovery time constant but different amplitudes.

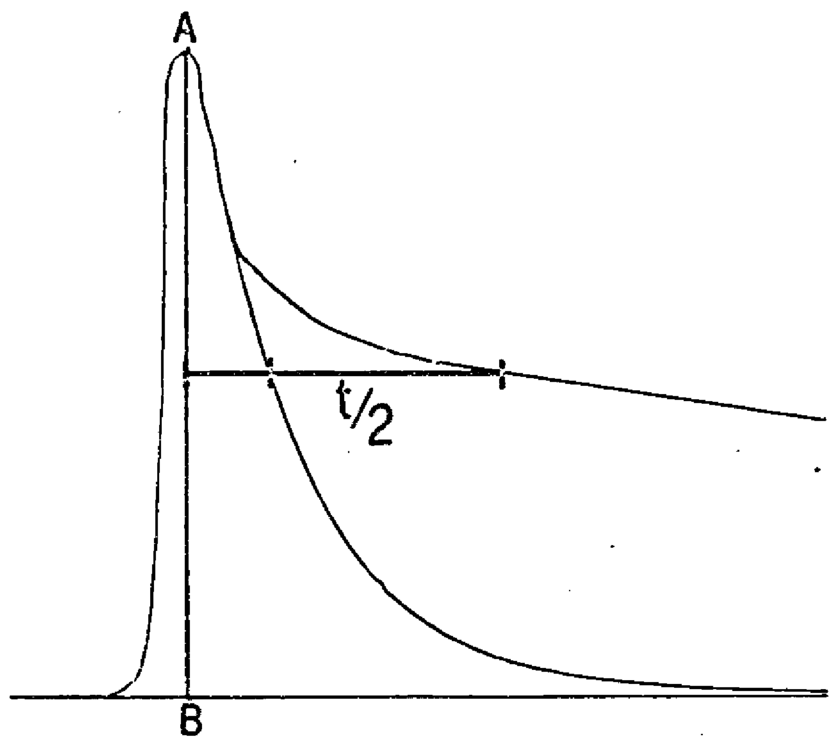

Figure 2. Variation in value of t/2 for same initial recovery limb but with varying activity of the slow compcnent.

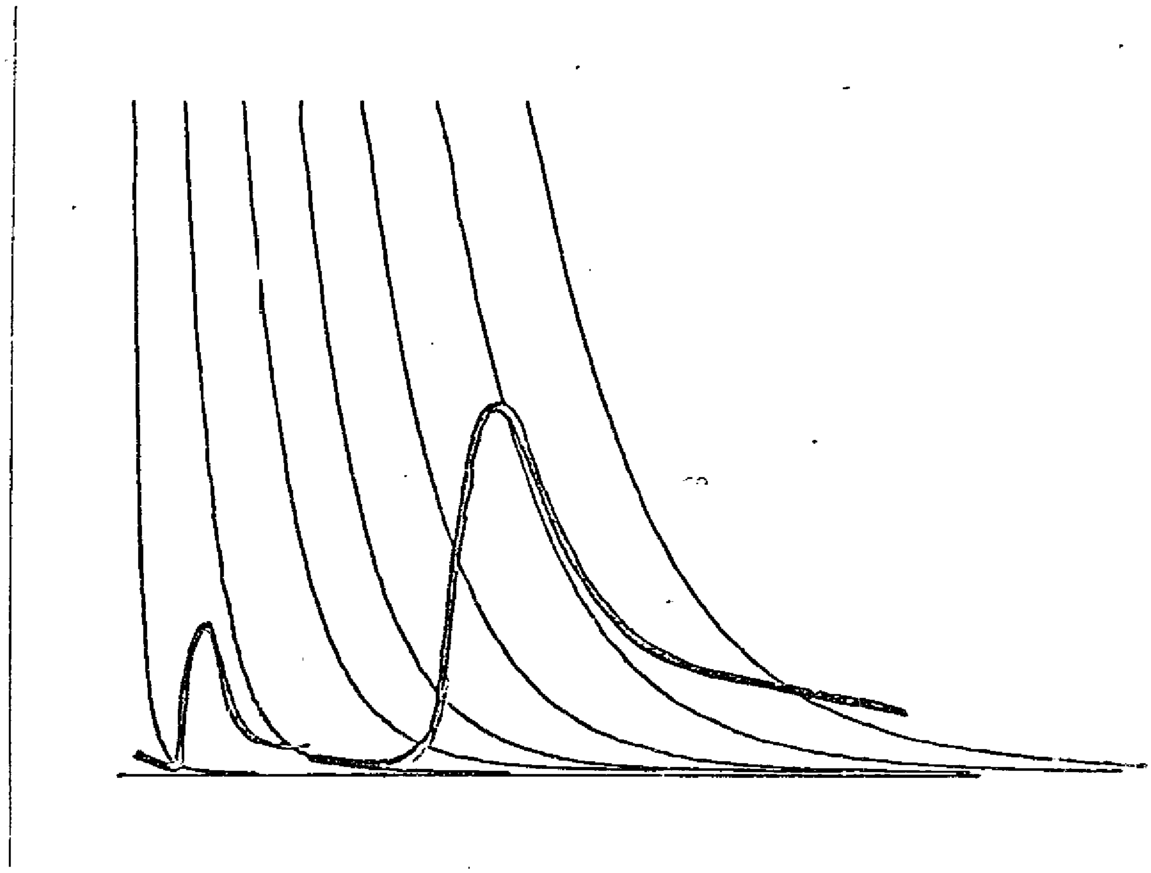

Figure 3. Method of determining recovery limb time constant by template method.

level at which it takes on the slope of the resting baseline. In practice this is a simple operation which is not commonly necessary. Needless to say D.C. recordings are mandatory whenever quantitative treatment of the time constant is attempted.

2. Automatic determination of the time constant.

a. Analog method:

(1) Since the equation for an exponential curve is

$$\frac{dE}{dt} = -kE$$

where E is the voltage, t is time and k is a rate constant which is the reciprocal of the time constant.

$$\frac{d^2E}{dt^2} = -k\frac{dE}{dt}$$

or

$$k = \frac{-Y''}{Y'}$$

where Y' and Y" are the first and second derivatives of the recovery limb with respect to time. These can be readily obtained by the use of operational amplifiers as shown in figure 4. Y' and Y" are fed into a simple division circuit which takes advantage of the logarithmic characteristics of a silicon diode (Glain, H. L. Review of Scientific Instruments 33, 235-238, 1962. The information of interest in the output will be the negative peaks of the rate constant which may be measured by a digital voltmeter.

(2) Another form of the exponential equation,

$$\log E = -kt + c$$

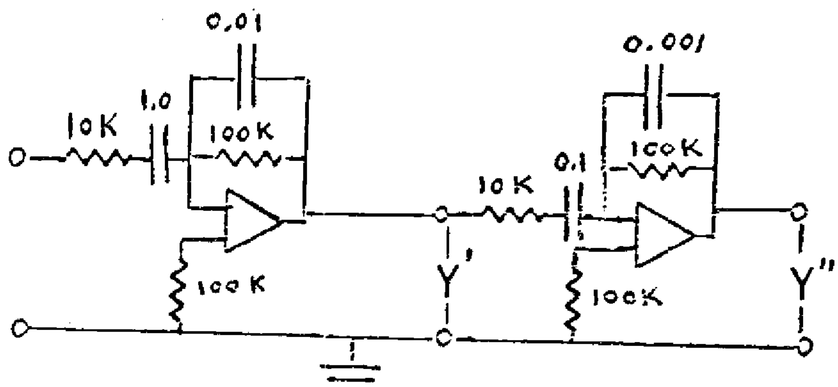

Figure 4. Circuit for obtaining the first and second derivatives (Y' and Y") of the recovery limb.

suggests that the rate constant can be obtained by the slope of log E against time or d(log E)/dt. Unfortunately this would be useful only if E represents voltage referred to final asymptotic level (i.e., to baseline), an arrangement which would be complicated, if indeed attainable.

b. Digital method:

An approximate solution for obtaining the rate constant lends itself readily to analysis by digital voltmeter and simple digital computation. It is based on the fact that exponential decay is essentially a percentage relation, i.e., in a small increment of time, the percent recovery is constant regardless of the amplitude chosen. From this it follows that the ratio of the absolute increments of recovery in two successive increments of time is related to the time constant. Thus if recovery is taking place at 5 percent per millisecond, the recovery rate may be obtained, for example at the 1 volt level, by taking

$$\Delta E_1 = .05 \times 1 \text{ volt} = .0500$$

$$\Delta E_2 = .05 \times 0.95 \text{ volt} = .0475$$

To calculate the rate constant, take

$$1 - \frac{\Delta 1}{\Delta 2} = 1 - \frac{.0500}{.0475} = .05$$

In practice, voltages are sampled by a digital voltmeter at 3 successive points on the recovery limb, e.g., at 0.2 second intervals, (figure 5) starting 0.5 seconds after peak and the

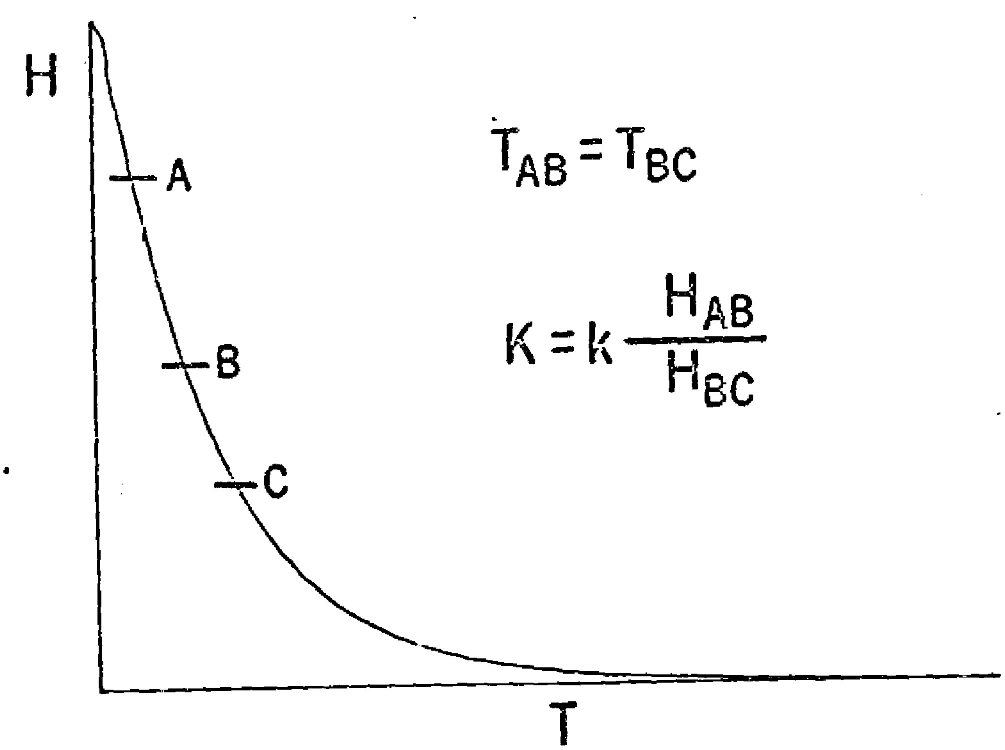

Figure 5. Method for determining time constant of recovery limb by digital measurements.

appropriate calculation made either manually or by computer.

3. Testing the discriminating power of the time constant measure.

The t/2 measure was previously shown to be capable of discriminating between rest and task performance and between the response to an alerting signal and the response to a task execution signal (for some subjects). The new time constant measure was tested on additional populations and under different conditions. One was a comparison on 35 subjects of the time constant associated with the orienting response to a series of tones as compared with that to a series of reaction time tests. Figure 6 shows the characteristic acceleration of the recovery limb attending the reaction time effort. Figure 7 shows the results for the entire population ($P < .001$). Only two subjects failed to show the acceleration.

In another evaluation (this one of the power of the t/2 measure) a population of 16 subjects was exposed to a series of moderate light flashes and their orienting responses obtained. They were then instructed that when the light flashed (same light) they were to observe the position of a moving pointer, but to withhold reporting until requested. Thus no motor activity was overtly involved in this perceptual task. Table 1 shows the result and also summarizes other tests for comparative purposes. All but 3 of the 16 subjects showed an acceleration of the recovery limb during the perceptual task.

Another example of the ability of the recovery limb to discriminate is seen in figure 8 which shows simultaneous recordings from the dorsal (hand) and palmar surfaces of two individuals. The letter A indicates an alerting signal for a forthcoming

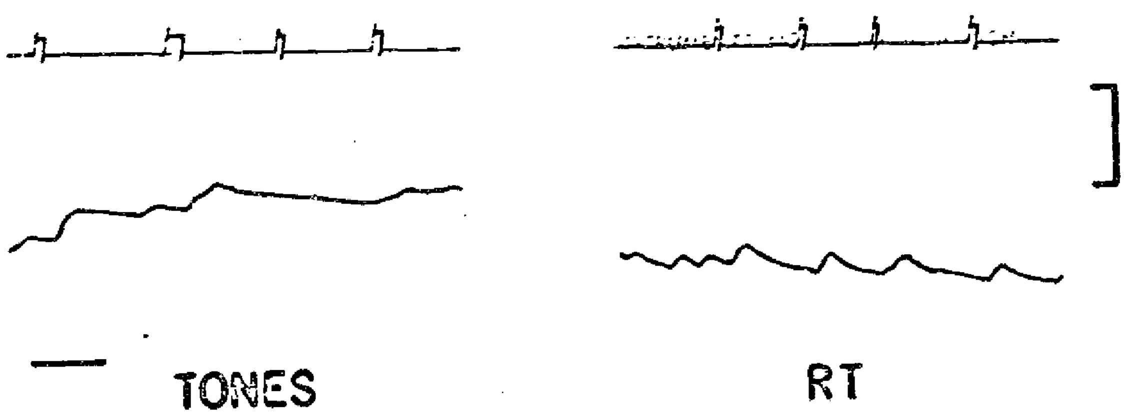

Figure 6. Recordings of responses to a series of tones and a series of reaction time signals, showing acceleration of recovery limb during reaction time series.

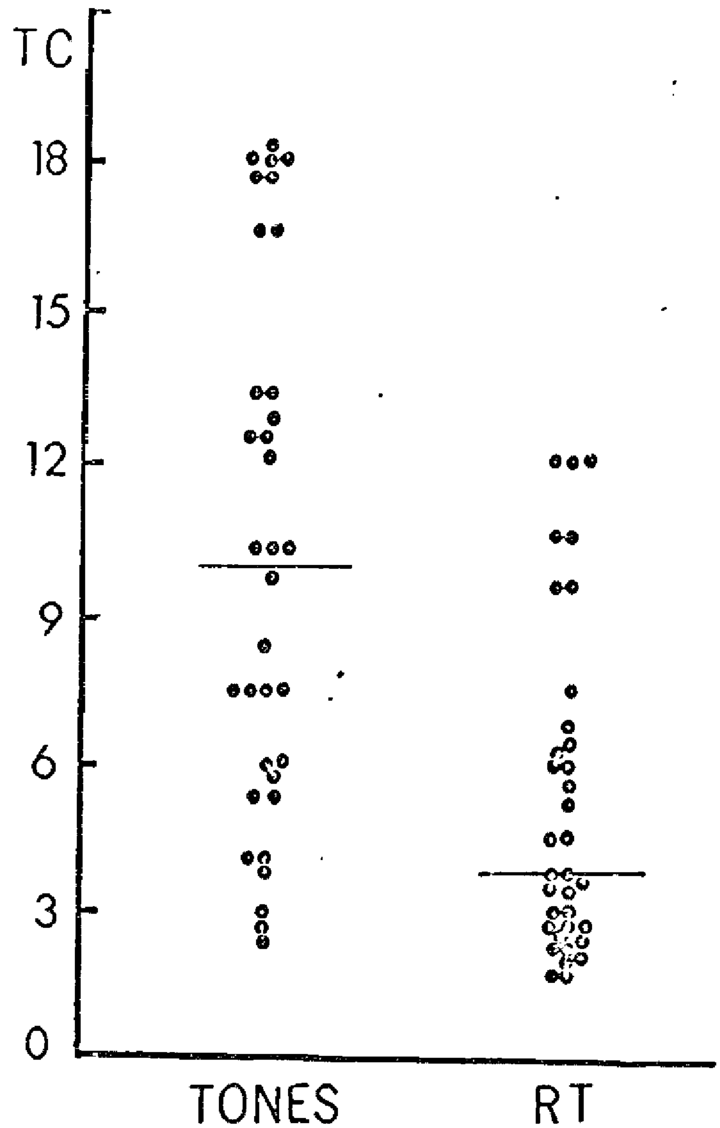

Figure 7. Scatter diagram of recovery limb time constants of responses to tones and reaction time signals for 35 subjects.

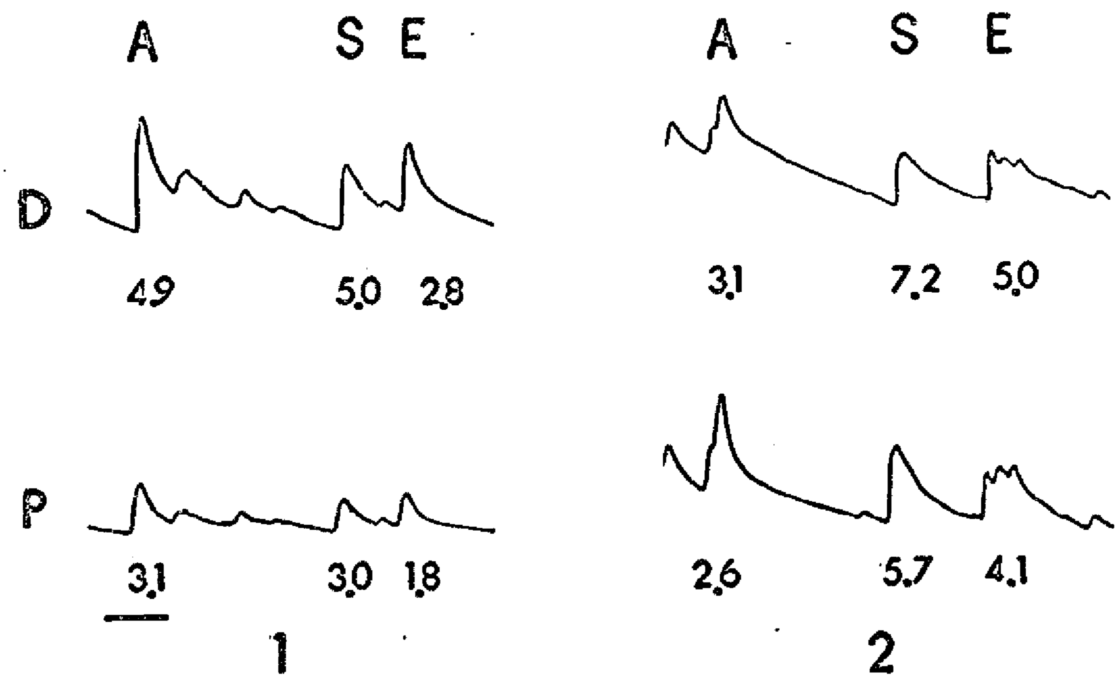

Figure 8. Simultaneous dorsal and palmar traces for two different subjects showing recovery limb time constants of responses to alerting signal (A), spontaneous activity (S), and reaction time execution signal (E).

N	MEASURE	CONDITION A	CONDITION B	MEAN CHANGE A to B	p
12 / 12	t / 2	Rest 5.6 sec	Aggressive Game 3.3 sec	-2.3 (-41 %)	<.001
16 / 13	t / 2	Light Flashes 7.9 sec	Perceptual Task 5.6 sec	-2.3 (-29 %)	<.05
35 / 32	t. c.	Tones 10.4 sec	Reaction Time 4.9 sec	-5.5 (-53 %)	<.001

Table 1. Effect of various stimulus conditions upon recovery limb time constant.

reaction time effort; E is the execution signal and S denotes a spontaneous wave occurring during the foreperiod. Below these responses are shown the time constants. In the dorsal trace of the first subject, the time constant of the spontaneous response is approximately equal to that of the alerting response while the execution response has a time constant of approximately half this length. Although the absolute levels for the palmar and dorsal traces are different, the same relationships hold. The second subject (right hand panel) shows a different sort of relation. This subject has a short time constant in the alerting response. That of the spontaneous response is almost twice as long. The execution response for this subject has a considerably slower recovery limb than does his alerting response. Here again the palmar responses though of different absolute value are in the same ratio as those from the dorsal surface. These autonomic pattern differences will be examined for possible use as an indicator of characteristic behavior patterns in an individual.

Figure 9 exemplifies the application of this measure in the identification of qualitatively different states, despite similarities in response amplitude. In the upper trace a subject is being presented with his first series of reaction time (RT) and word association (WA) stimuli. There was a forewarning signal for the reaction time and the subject in each case responded to this alerting signal as well as to the execution signal. In trace B which occurred 8 minutes later, the subject has apparently habituated to the situation and has ceased responding to the alerting signal. Notice the marked slowing of the recovery limbs, and especially that the response to the word association, though of similar amplitude to that in A, has a greatly differing time constant.

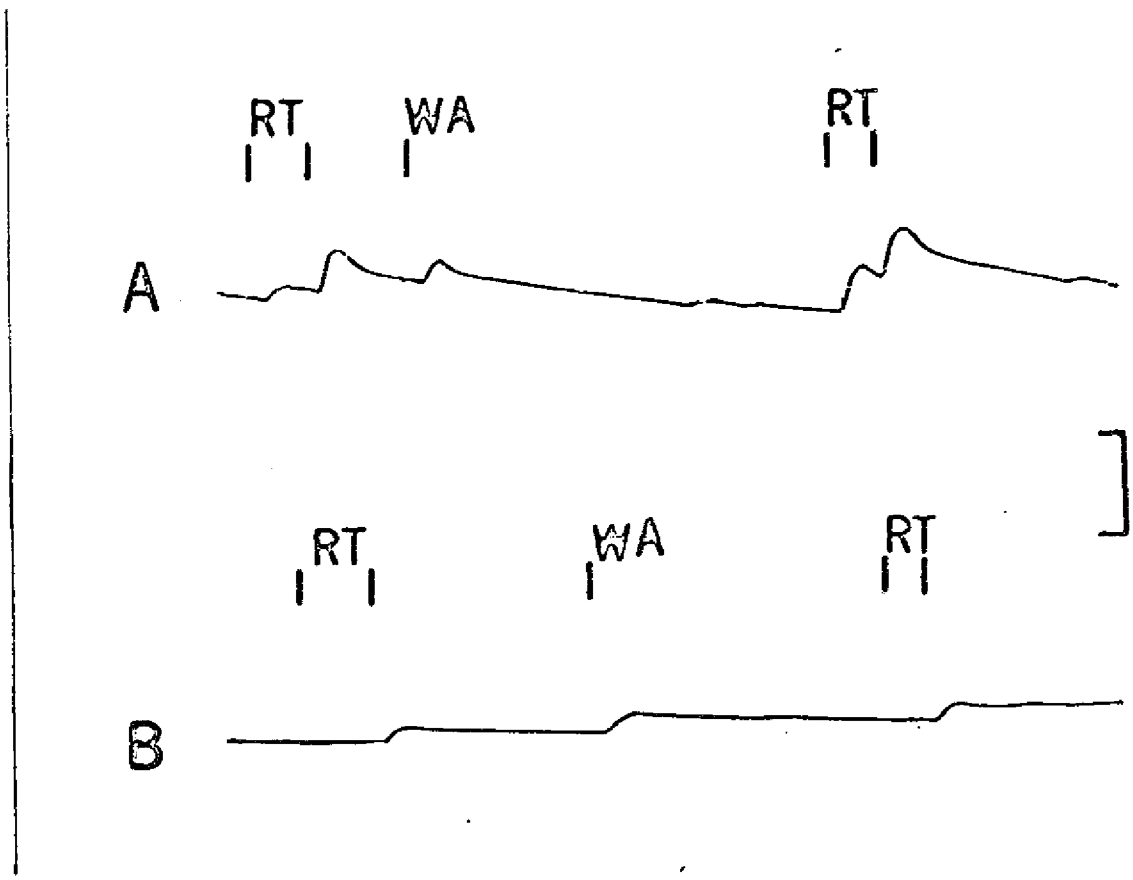

Figure 9. Conductance responses to reaction time signals (RT) and word association (WA). Traces A and B are taken on the same subject 8 minutes apart.

4. Correlation of an individual's time constant with his behavioral pattern.

One naturally wonders whether this measure which can differentiate between conditions within a subject independently of response amplitude can also differentiate between subjects having different behavior patterns in similar situations. To answer this question, the recovery time constants of responses to reaction time efforts were used to characterize the individual subjects. Also determined for each subject was a measure of the rate of habituation of their responses either to a series of tones or a series of reaction time efforts as seen in figure 6. The measure of habituation was the quotient of the amplitude of the second response of the series divided by that of the third response. The larger this ratio, the more rapid the habituation. Table 2 shows the results of comparisons across subjects. (Square root transformation was used in some cases to obtain a linear regression.) In all cases the time constant measure was that of the skin conductance response (SCR) obtained during the reaction time series. Various measures of habituation rate were compared with this. In the first case it was the skin conductance response during the reaction time series. This showed a 0.33 correlation with the recovery time constant, ($P < .05$) which is interpreted as indicating that a short time constant is associated with sustained activation (motivation?) in the RT task.

In another comparison, the habituation rate for SCR was obtained during the tone series and compared with the same time constants as above. There was no significant correlation.

Surprisingly the time constant obtained during the reaction time series did correlate significantly with the rate of habituation of the finger pulse volume response

N	HABITUATION MEASURE	r	p
53	SCR during Reaction Time	.33	<.05
32	SCR during Tones	.13	N. S.
51	FPV Change during Tones	.30	<.05

Table 2. Correlation of recovery limb time constants obtained during reaction time with various habituation measures taken across subjects.

obtained during the same tone series examined above ($r = 0.30$, $P < .05$). This relation of SCR recovery rate to an entirely different autonomic measure in a different stimulus situation is viewed as an indication of the basic significance of this measure.

5. Relation of time constant length to quality of stimulus situation.

To shed light upon the behavioral significance of changes in the time constant, its relation to a series of 8 graded stimulus situations was examined. Although data on 21 subjects are available, only 9 have been analyzed to date. The situations were:

Relaxing - Eyes open - 2 minutes

Relaxing - Eyes closed - 2 minutes

Counting aloud - 2 minutes

Reading aloud - 1.5 minutes

Counting backwards by 7's - 2 minutes

Deep breaths, 3 at 20 second intervals

Cold pressor test (ice bath) - 2 minutes

Mirror drawing - to completion

Average time constants were determined for each situation and the 8 categories rank-ordered for each individual, using a rank of 1 for the longest. These ranks were then averaged for each condition. Results were in the following order:

Situation	Average Rank
Rest, eyes open	2.2 ± 0.8 (Longest)
Cold pressor	3.1 ± 1.2
Rest, eyes closed	3.3 ± 1.2
Deep breaths	4.2 ± 1.5

Situation	Average Rank
Count, forward	4.4 ± 1.2
Count, backward	5.6 ± 1.9
Read aloud	6.1 ± 1.3
Mirror tracing	6.6 ± 1.3 (Shortest)

Two features of this ranking are most significant, first that time constant becomes shorter apparently as the goal direction of the behavior increases. The second is that the cold pressor test, though it produced high activation showed waves with time constants as long as those under resting conditions. This seems consistent with the above inference regarding the association of rapid recovery limbs with goal directed behavior. It is suggestive of a system in which mobilization for goal-directed activity, involves activation of a reflex mechanism which hastens electrodermal recovery.

Tests of statistical significance have not been made on this sample because of the additional analysis in progress. Nevertheless, inspection of the means and deviations makes it clear that the extreme categories are significantly different.

6. The biological basis for the variation in time constant was investigated on the basis of relations suggested in the last report. It had been hypothesized that the fast component of the recovery limb might represent an epidermal membrane process, associated with the reabsorption phenomenon and with the positive skin potential response (SPR). Records from 11 subjects were examined, and two "pure" negative SPRs and two with significant positive components were chosen from each. The time constants of the associated conductance responses were measured and for

all 11 subjects, were shorter when associated with positive SPRs (8.7 vs 14.9 seconds, $P < .001$). An example of a recording is seen in figure 10.

Since the reabsorption reflex had previously been shown to be associated with the positive wave, the association of short recovery times with reabsorption was to be expected. Figure 11 shows an example (panel B) of the faster recoveries associated with the activation of reabsorption (Hydration increases upward). Note the concomitant change in skin potential activity from negative to biphasic with a positive (downward) component appearing. The average time constant for the left hand panel was 7.4 seconds, for the right, 4.8. A comparison on 12 subjects showed that reabsorption waves were associated with steeper recovery limbs at the .01 level of significance.

B. Peripheral Mechanism

Because of the implicit involvement of the reabsorption reflex as a possible cause of the variation in recovery limb slope, efforts were made to clarify its mechanism. It had been previously postulated that this phenomenon represented a reflex increase in epidermal permeability. When this permeability increase occurred, the passive movement of water down its concentration gradient would appear as an inward movement if surface vapor tension were high enough. However, data on the low permeability of the corneum cast doubt that the route was through this layer (and then across the epidermis). It was considered more likely that the moisture was returning via the sweat duct. This possibility was investigated by a modification of the Netsky prism method described by Thomas and Korr (1957) which is sensitive to frank sweat (droplets). In this modification, a photocell was substituted for the

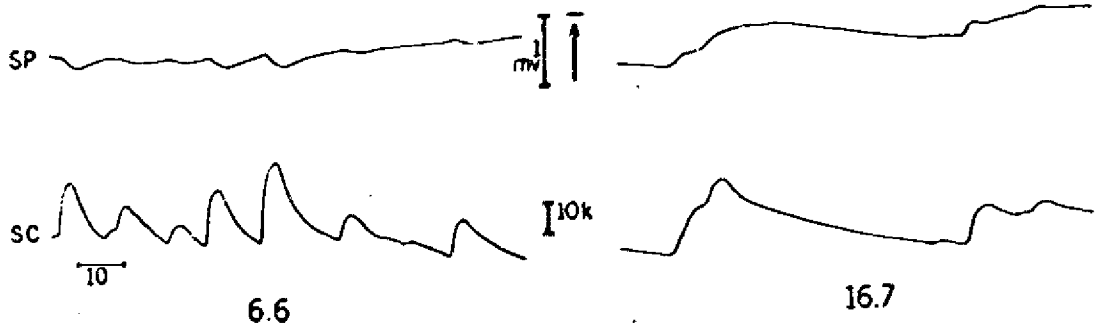

Figure 10. Relation of recovery limb time constant to presence and absence of positive skin potential responses.

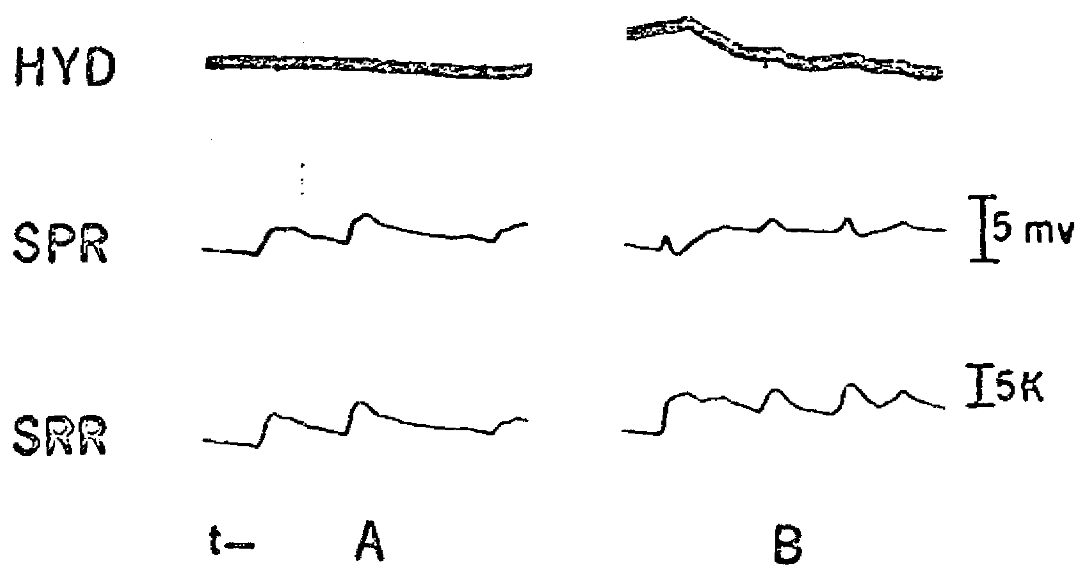

Figure 11. Relation of recovery limb time constant to presence or absence of absorption reflex (upper trace, absorption is downward). Note acceleration of recovery limb with appearance of reabsorption responses.

photographic equipment so that continuous recordings of sweat droplet concentration could be made. Unlike the photographic method it is very important in this method that the light be well collimated to prevent contamination of the records with vascular changes (figure 12). It is also necessary that there be no possibility of variation in skin contact at the edge of the masked area. Test of contamination by vasomotor activity were accomplished by inflation of venous and arterial cuffs on the arm to produce artificial vascular changes in the fingers. The system finally adopted was demonstrated to be free of such contamination. The recordings (figure 13) showed increases in sweat and also reabsorption. Although the device has been used thus far on only 5 subjects, all have manifested the phenomenon. It is now being used in conjunction with recordings of SPR, SCR, and hydration (electrical method). The implications of the findings with this device is that the droplets of sweat formed at the sweat pore rather suddenly disappear. This has been confirmed by microscopic observation of the finger tip. This would indicate that the cause of the reflex reduction of hydration previously observed is not due to drying of a uniformly moistened corneum but rather to draining of the sweat droplets back into the sweat duct. This may perhaps represent activity of the sweat duct wall at a relatively superficial level, e.g., at the germinating layer.

Local Potential Responses

The collection of data on the effects of variation in surface conditions upon LPR amplitude has been completed. As discussed in the summary, a relative range measure is a better indicant of effects than is an absolute comparison because of variation in direction of these effects. The data may be summarized as follows:

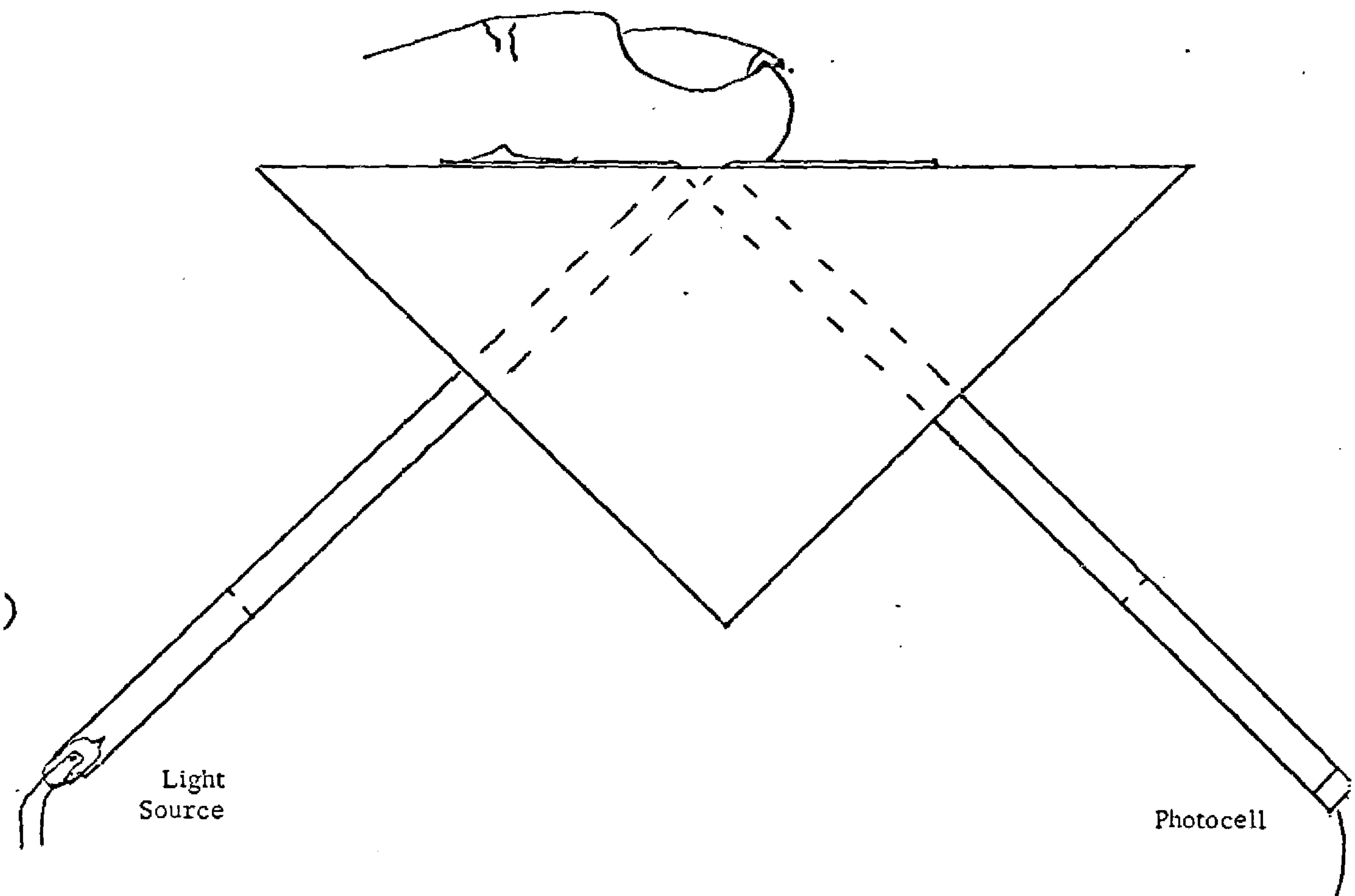

Figure 12. Arrangement of light source and photocell for observing changes in concentration of sweat droplets by the prism technique.

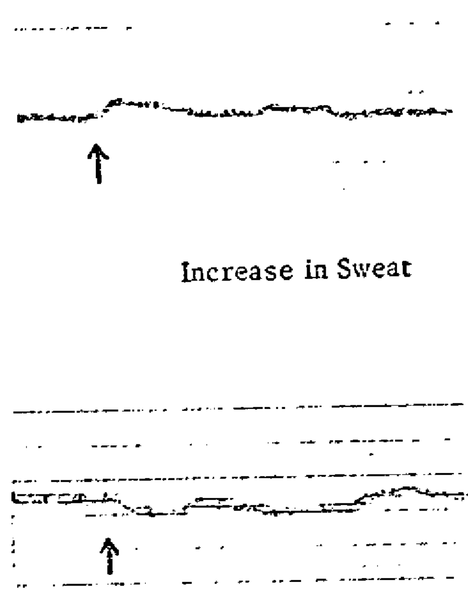

Figure 13. Records of sweat evolution and of reabsorption obtained by the photoelectric prism technique.

(The control sites were subjected to a blank procedure.)

Procedure	Component	Number of Subjects With Experimental Site Showing Widest Range After Procedure	Number of Subjects With Control Site Showing Widest Range After Procedure
0.5M Na2SO4	Fast	5	1
	Slow	6	0
5M NaCL	Fast	4 (1 equal)	1
	Slow	5	1
0.3M $AlCl_3$	Fast	3	6
Exsanguination	Fast	6	0
	Slow	3	3
Temperature	Fast	5	1
	Slow	4	2

In addition, of 7 subjects examined for effect of background negative activity upon LPR amplitude, all showed a substantial increase for both fast and slow components (average 430%, $P < .001$).

C. Bio-Psychological Adaptability

In the initial examination of adaptability or "gear-shifting" capacity, a population of 60 subjects was run through a battery consisting of the following:

a) Several paper and pencil psychological evaluations including personality trait inventories, and manifest anxiety ratings.

b) Performance tests: designed to examine rigidity-flexibility characteristics.

c) A knob-turning test designed to examine maintainance of appropriate motor inhibition over an extended period. The subject was instructed to turn a large knob as slowly as possible through 180 degrees. The time course of this effort was recorded and a comparison made of the angular velocity in the first third with that in the last third to detect breakdown of inhibition. This was expressed as a ratio K; a large ratio signifies a speeding up in the last third (i.e., loss of inhibition).

Following these tests the subject was fitted with electrodermal electrodes and a reflectance plethysmograph. He was exposed in sequence to:

a) 3 minutes of rest

b) a series of 5 tones, ca 80 db, 1000 cps

c) a series of 5 similar tones for reaction time test effort

d) 3 minutes of rest

e) a difficult discrimination task

f) 5 minutes of rest

Although analysis is not yet completed, it appears that the psychological and performance tests, except for the knob-turning task showed low correlation with the physiological data. The relation of SCR recovery limb time constant to habituation rate in these runs has already been described. A relation between performance and physiological behavior was also found. In these runs, as a measure of the "gear-shifting" ability of the subject, his time for 50% recovery from the difficult discrimination task to base level during the final rest period was determined for skin conductance, skin potential and finger pulse volume. The recovery half-time for the electrodermal level measures (not responses) was significantly related to K, the inhibitory index in the knob-turning task ($P < .05$). Longer recovery times were associated with a tendency to speed up toward the end of the task. Put another way, the capacity to maintain inhibitory motor control over an extended period was associated with an ability to shift autonomic gears rapidly.