PSYCHOPHYSIOLOGY
Vol. 8, No. 5

DIRECT MEASUREMENT OF SKIN CONDUCTANCE: A PROPOSAL FOR STANDARDIZATION

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ABSTRACT

A provisional standard method of measuring tonic skin conductance (SCL) and GSR (SCR) is advocated, using a *constant-voltage method* for which circuits are provided useable with Beckman, Grass, and other common polygraphs. A standard *electrode* methodology is also presented. The problem of *units of measurement* is considered in detail with an analysis of the so-called *Law of Initial Values*. Methods are given for correcting both tonic SC and SCRs for individual differences in their respective ranges of variation and the purpose and relative advantages of these *range-correction* methods are discussed.

DESCRIPTORS: SCL, SCR, GSR, electrodes, Units of measurement, Range correction. (D. T. Lykken)

Of all psychophysiological variables, the GSR can lay reasonable claim to being the most popular in current use. In spite of years of searching study, we are still surprisingly uncertain about the function, not to say the mechanism of this phenomenon (Edelberg, 1967, 1970; Lykken, 1968; Venables & Martin, 1967). Nevertheless the GSR seems to be a robust sort of variable since, in hundreds of experiments, it continues stoutly to provide useful data in spite of being frequently abused by measurement techniques which range from the arbitrary to the positively weird.

Even the relatively sophisticated studies reported in this Journal display a disconcerting diversity of electrodermal measurement technique which, at best, makes it difficult to compare one set of results with another and sometimes even casts real doubt on the interpretation of the findings. Our purpose in this paper is to describe in detail a method of measuring skin conductance which we would advocate for general use and to defend our claim that this method represents the current state of the art. It would obviously be as fatuous for us to try to legislate usage as it would be ill advised for the field to fixate immoveably upon any particular method of measurement at this time when we must admit igno-

Supported in part by Grant MH 15461-01 from the National Institute of Mental Health and by an NIMH Senior Fellowship which permitted the first author to spend 1968–69 at Birkbeck College.

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rance about many aspects of the phenomenon being measured. But it is feasible and, we think, expedient to promote a provisional standardization by describing a method which could easily be followed by any investigator and which is so well based in current knowledge of electrodermal processes that someone choosing to depart from this method might feel some onus to justify that deviation.

Terminology

The electrical conductance of the volar skin displays slow, tide-like changes due to diurnal variation, the general press or excitatory value of the immediate stimulus situation, and other factors. Superimposed upon these tidal drifts are transient, wave-like changes which may be elicited by external stimuli or may be "spontaneous," i.e., elicited by internal events. The average prestimulus level is commonly called the "basal" conductance while the phasic increase in conductance is most often referred to as a "galvanic skin response" or "GSR." But the term "basal" as used in metabolic studies has the connotation of a standard, reproducible reference level obtained in a stress-free, resting situation and it is therefore typically inappropriate in the electrodermal context. We recommend that the term "basal" should be dropped from this vocabulary and that we henceforth refer to the average level of skin conductance, resistance, or potential in a given situation as the *tonic level* of that variable in that situation. Specifically, the tonic level of skin conductance during an interval of length t will be the mean value of conductance during that interval exclusive of phasic changes. Where there are phasic changes or GSRs in the record, the tonic level can often be estimated by connecting with straight lines the conductance level at the start of each wave with the asymptotic level reached at the end of the recovery limb of that wave. Tonic levels of conductance or resistance will be referred to as SCL or SRL, respectively, with the understanding that the experimental conditions and the length of the interval in question will always be specified.

Since the term "GSR" is traditionally applied to phasic changes generally, it is convenient to employ a more specific terminology. We shall refer to the phasic, usually elicited, increase in SC as the "skin conductance response" or SCR. Similarly, we shall refer to the "skin resistance response" or SRR.

Conductance or Resistance?

Skin resistance can be measured by the basic circuit shown in Fig. 1-A in which a constant current is passed through the skin producing a voltage drop across the skin which can be amplified and recorded. Constant current is obtained by including a resistance R_s, in series with the subject, which is very large (i.e., 10× to 50×) compared to SRL, so that changes in SR produce relatively little change in current level. By Ohm's Law, SR = E/I so that, I being constant, SR is linearly related to the voltage, E, across the subject, the quantity actually measured.

The basic circuit for conductance measurement is given in Fig. 1-B. A voltage source is placed in series with the subject and a small 'signal' resistor, R_x. Since both R_x and the source impedance of the battery (R_e) are very small in comparison to SRL, the voltage across the subject electrodes remains essentially constant in spite of changes in current (as SC changes). The voltage developed across R_x is linearly proportional to the amount of current flowing which in turn is a linear function of SC (since conductance is the reciprocal of resistance, SC = I/E and E here is constant).

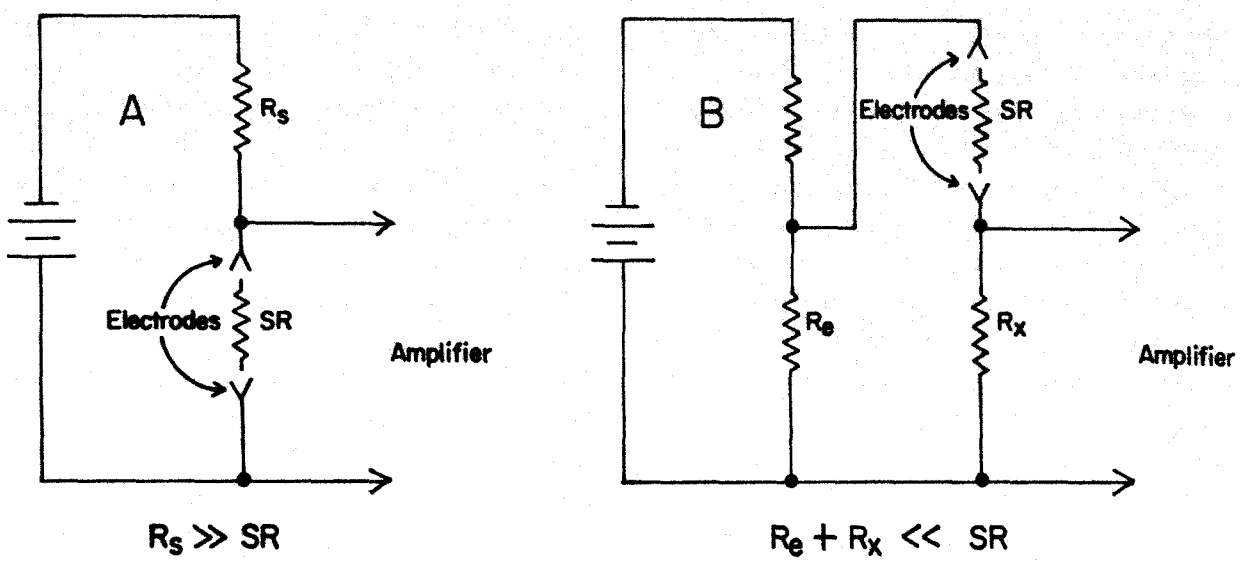

FIG. 1. A. Basic circuit for measuring skin resistance (SR). Because the series resistor, R_s, is many times larger than SR, current flow remains essentially constant in spite of SR variations. Therefore, the voltage across the subject, E = i(SR), will be linearly proportional to SR.

B. Basic circuit for measuring skin conductance (SC). Because both the battery resistance, R_e, and the signal resistor, R_x, are very small compared to SR, the voltage applied across the skin electrodes will be approximately equal to the voltage across R_e and will remain constant in spite of changes in SR. The output voltage across R_x varies directly with current, i, and the current in this circuit, i = E(SC), will vary directly with SC since the voltage, E, is constant.

This voltage is then amplified and recorded as a measure of SC.

Darrow (1934, 1964) has shown that SCL is linearly related to the rate of secretion of sweat. Since sudomotor activity is the primary source of changes in SC, this linear relationship recommends the choice of SC, rather than SR, as the simplest unit for psychophysiological use. From another point of view, since the sweat glands provide relatively low-resistance current pathways through the epidermis, and since the typical pattern of sudomotor activity is for an increasing proportion of the glands in a given area to become active in response to arousing stimulation or the sorts of stimuli which produce phasic electrodermal activity, one can say that the skin consists of multiple parallel resistances which can individually change in value (Tregear, 1966). Now the overall resistance of a parallel circuit is a complex function of the individual resistances and the change produced by a change in one branch depends upon the resistances of all the other branches. In contrast, the *conductance* of a parallel circuit is a simple sum of the conductances-in-parallel and a change in one of these produces simply an equivalent change in the total, independently of the values of the others. Corroborating this view, Thomas and Korr (1957) obtained an essentially linear relationship between the number of active sweat glands per unit area and intercurrent measures of SC. Thus, again, the structure of the skin as an electrical conductor motivates the use of SC rather than SR.

Quite recently, Lader (1970) reported an experiment in which atropine, a cholinergic blocking agent which inhibits sweat gland activity, was introduced into a palmar site by iontophoresis. Over a period of time following the application of this drug, SCL drops to a low level and GSR

activity gradually subsides to zero. During the time while the drug effect was accumulating, Lader produced a series of GSRs which were recorded both from the treated site and an untreated control site. When expressed as changes in conductance (i.e., as SCRs) and then as proportions of the simultaneous SCRs recorded from the control site, this series of SCRs showed a regular, monotonic decrease to zero over the half-hour required for the drug to take its full effect. In contrast, when these GSRs were expressed as changes in resistance (SRRs) and then as proportions of the simultaneous control SRRs, the measure of phasic response varied widely and erratically with time.

Thus, there can be little doubt that skin conductance bears a simpler and more linear relationship to the underlying processes of psychological interest than does its reciprocal, SR. Although implied in the above discussion, it may be worth emphasizing explicitly that the use of SC rather than SR also simplifies the nagging problem of the dependence of phasic response upon tonic level. If a set of conductances-in-parallel is an appropriate model for current pathways through the skin, and if a transient increase in some of these conductances suitably represents the mechanism of the phasic change, then it can be seen that, while the SCR is potentially independent of SC because conductances in parallel are additive, the SRR must necessarily be highly correlated with tonic SRL since a change in one parallel resistance has an effect on the total R which is dependent upon the (constant) values of the Rs of the other branches. In support of this analysis, it is generally true that correlations of SRR with SRL tend to be high in comparison with the correlations of SCR with SCL. It is *not* generally appropriate to strive to eliminate all correlation between phasic change and tonic level since, as in most other areas of psychology or physiology, one expects the immediate response to stimulation to have some relationship to the state of the organism or organ system at the time of stimulation. But a correlation which results directly from the mathematical properties of the measuring units employed is obviously to be avoided.

This argument in favor of the use of SCL and SCR in place of SRL and SRR would appear to conform with current practice since the vast majority of contemporary electrodermal research is reported in these terms (although frequently the basic SC measure is further modified by means of a logarithmic or square root transformation; we shall not go into the merits of this tradition at this time). Curiously, however, most investigators still *measure* SRL and SRR, using the constant-current circuit, and then transform these measures into SCL and SCR by subsequent computation. This extra step involves considerable labor as well as the attendant likelihood of computational errors. Both of these difficulties can be easily avoided by measuring SC directly in the first place with a constant-voltage circuit.

Another advantage of the constant-voltage method is the relative convenience of the recording process itself. In both methods, one normally employs a calibrated zero-suppression control by means of which one can subtract a portion of the input signal corresponding to a known amount of SRL or SCL. Thus, if the subject's tonic SCL is 10 μmhos and his largest SCR is on the order of 1 μmho, one might set the zero-suppression to subtract the equivalent of 10 μmhos from the input. Then one could increase the gain of the measuring circuit to give full-scale deflection for, say, 2 μmhos so that the phasic changes or SCRs will be written out large enough for con-

venience of measurement. If the tonic level drifts to, say, 8 μmhos, then the suppression must be reset and the new value recorded on the chart. Suppose now that a subject's SCL changes slowly from 10 to 5 μmhos as he relaxes over a one-hour session and suppose also that one desires a recording sensitivity of 1 μmho full-scale in order to get adequate recordings of his SCRs during this time. This will require between 5 and 10 resettings of the suppression control during the hour while the gain or input attenuator setting will remain constant. If the same subject were being measured by the constant-current method, his SRL would increase from 100 to 200K ohms during the hour while at the same time the SRR corresponding to, say, a 1 μmho SCR would increase from 9 to 33K ohms. If one chooses to maintain a 9K ohm full-scale sensitivity throughout, then from 10 to 20 resettings of the suppression will be called for. Alternatively, one might periodically decrease sensitivity and thus reduce the frequency of suppression resettings. In either case, the constant-voltage method of direct measurement of SCL will require fewer range-changes or resettings and produce correspondingly fewer errors at a lower cost of operator time and attention.

In his thorough and remarkedly impartial review of the relative merits of the constant-voltage and constant-current methods, Edelberg (1967, pp. 26–27) lists several apparent advantages of each. We would argue that the "advantages" he mentions for the constant-current system are more apparent than real and are easily outweighted by the substantial advantages of measuring SC directly. Edelberg points out, for example, that the latter requires more amplifier sensitivity since, e.g., a 10 μmho subject with a measuring current of 5 μa yields an output signal of 500 mv in a constant-current system, compared to only 0.5 mv in a typical constant-voltage system with a signal resistor, R_x, of 100 ohms. But the DC preamplifiers of any modern polygraph can easily deliver a sensitivity of 0.01 mv/cm with good stability. Moreover, with a constant-voltage circuit, the amplifier looks into a constant source impedance which is typically only a few percent of the (variable) source impedance in a constant-current system. This means that amplifiers with low input impedance, such as 'chopper'-stabilized amplifiers with their higher sensitivity and stability, can be employed when SC is measured directly.

Secondly, Edelberg points out that, with a constant-current system, one can hold current flow to a low level which minimizes electrode polarization and, more importantly, ensures that one is operating in the region in which the skin is obedient to Ohm's Law, i.e., a level of current which does not itself affect the resistance one is trying to measure. However, this same important desideratum can be achieved with the constant-voltage circuit, as will be explained below.

Effect of Measuring Current on Apparent SC

At very low levels of DC measuring current, the skin behaves as a passive conductor with a constant apparent resistance. As measuring current increases, a point is reached beyond which apparent resistance decreases with increasing current, i.e., the voltage-current curves become nonlinear. There are two components to this nonlinear effect; an immediate or time-invariant component which can be seen with very brief current pulses, and a time-variant or "hysteresis" effect (Kryspin, 1965), involving a gradual decrease in apparent SR while current is maintained constant for

periods of seconds or even minutes. Both phenomena implicate impedance (e.g., capacitative) properties of skin not discussed in this paper; see Edelberg (1967), Lykken (1968) or Venables and Martin (1967). Edelberg (1967, p. 19) concluded from his own studies that time-invariant nonlinearity is determined by the voltage applied to the skin rather than the amount of the measuring current. Subjects with very low SRLs could tolerate much higher currents without nonlinearity than could those with high SRLs but individual differences in voltage tolerance were much smaller. When SR is high only a few sweat glands may be active. With a constant-current circuit, these few pathways must still carry the load so that current densities in each may become very high. With a constant-voltage circuit, current flow in one pathway is independent of the number of pathways active at the time. Supporting evidence based on current waveforms produced by very short voltage pulses is presented by Lykken (1970).

The time-variant or hysteresis effect has been less systematically studied but it seems probable that it too is a voltage-dependent phenomenon. Although Kryspin (1965) concluded that hysteresis requires higher voltages than the time-invariant component, his observations apparently involved only short voltage pulses; our own experience indicates that voltages too low to yield an immediate decrease in apparent resistance may still produce a slow drop in SR over a period of minutes. Reports by Edelberg, Greiner, and Burch (1960) and by Wenger and Gustafson (1962) support this view. Nevertheless, we would agree with Edelberg that a constant-voltage system set at 0.5 volts would very probably avoid the region of nonlinearity in most cases. Thus, with the constant-voltage method one can quite easily keep both voltages and current densities within tolerable limits, meeting the last of Edelberg's requirements.

Summary

(1) There is little doubt that conductance is more simply related to the underlying variable of interest than is skin resistance. (2) SC can be directly measured by means of a constant-voltage circuit far more easily and accurately than by measuring SR and then converting to conductance arithmetically. (3) The constant-voltage method requires less range or gain changing and therefore takes less operator attention and results in less frequent loss of data. (4) Where SC is measured directly, the shape characteristics of the waveform are more meaningful than in the case of SR measurement. (5) High voltages are avoided in direct measurement of SC and therefore injurious currents are avoided; current density is independent of electrode area. (6) Present instrumentation is easily adapted to direct measurement of SC as will be demonstrated below.

Instrumentation for Direct Measurement of SCL and SCR

Circuits for two practical and efficient signal conditioners for direct measurement of SC are given in Figs. 2 and 3. The circuit of Fig. 2 is designed for use with the popular Beckman-Offner Type R Dynograph and, can be built into a standard Type 9801 blank coupler chassis. All switches are the miniature variety with gold-plated contacts. For the zero suppression control (R_9) we used a Bourns 'Knobpot' Type 3640S. A relay powered by the Dynograph opens both battery circuits automatically when the polygraph is switched off. The input can be switched between the subject and a 'dummy subject' of 10 μmhos conductance for calibration purposes (SW_1)

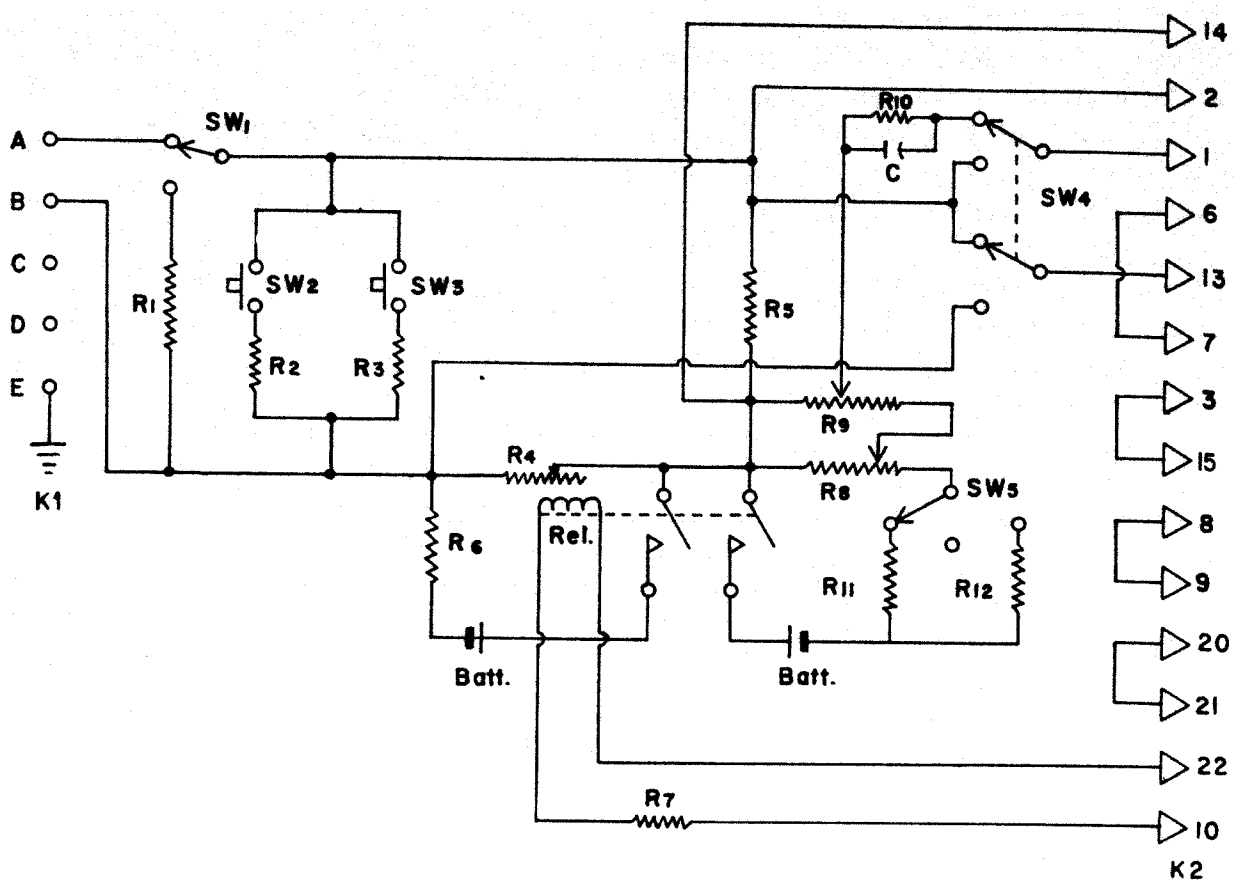

FIG. 2. SC Signal Conditioner. Designed for blank plug-in chassis for Type R Dynograph (Beckman). With SW_4 in down position, adjust R_4 for 0.5 volts to subject. With dummy subject of 10 μmhos (i.e., SW_1 in up position), adjust R_8 for zero output when zero suppression (R_9) is full on and suppression range switch (SW_5) is set at '10' (i.e., on R_{11}). The output to the preamplifier will be 100 μv/μmho. With the power amplifier attenuator set at '×.1,' the preamplifier attenuator will then read directly in μmhos/cm. Total signal (i.e., without suppression) is connected via pins 2 and 14 to outputs at the rear of the Dynograph. This can be routed through another preamp channel to an on-line computer if desirable.

R_1 - 100K ohms, 1%
R_2 - 2 Megohms, 1%
R_3 - 200K ohms, 1%
R_4 - 200 ohm Trimpot
R_5 - 200 ohms, 1%
R_6 - 200 ohms
R_7 - 200 ohms, ½ watt
R_8 - 200 ohm Trimpot
R_9 - 500 ohms, 10-turn
R_{10} - 10 ohms, 1%
R_{11} - 10K ohms, 1%
R_{12} - 100K ohms, 1%
Batt. - 1.35 volt merc.
C_1 - 500 mfd, 3 volt
Rel. - DPST Reed Relay (Hathaway J-2A)
K_1 - Input connector on Plug-in
K_2 - 'Ribbon' connector at rear of plug-in
SW_1 - SPDT miniature toggle Input Switch
SW_2 'Subj. - 10 μmhos'
SW_2 - Miniature push-button, '0.5 μmho'
SW_3 - Miniature push-button, '5 μmhos'
SW_4 - DPDT Miniature toggle, 'Cal. - Operate'
SW_5 - SPDT center off, min. toggle. Suppression Range Switch, '10–100 μmhos'

and two miniature pushbuttons (SW_2 and SW_3) make it possible to add 0.5 or 5 μmhos to the input as another aid to calibration. The first step in calibration is to set the output switch (SW_4) so as to connect the voltage across R_4 (i.e., the subject voltage) to the preamp input and adjust R_4 for 0.5 volts. SW_4 is then switched to the 'operate' position, SW_1 to '10 μmhos,' and the zero suppression range switch, SW_5, is set to '10 μmhos.' Now the zero suppression control (R_9) should just cancel out the 10 μmho input when turned full on (i.e., to read '10.00'). The 'suppression calibration control' (R_8) is used for this adjustment. If the Dynograph has been properly cali-

brated itself and if the power amplifier attenuator is set at '×.1,' the Dynograph preamp attenuator switch will now read directly in μmhos/cm; that is, when this switch is set at '×.5,' the system will have a sensitivity of 0.5 μmhos/cm, etc. The maximum sensitivity, with the power amplifier set at '×.02,' will be 0.1 μmho/cm. (The filter circuit composed of R_{10} and C_1 may be necessary to counteract any slight noisiness in the suppression control, R_9.)

The circuit shown in Fig. 3 is designed to be housed in a separate small box and used with other popular polygraphs such as the Grass Models 5 or 7, having an input sensitivity of at least 10 μv/cm. Two pushbutton switches allow one to add 1 or 5 μmhos to the input conductance and four 'dummy subject' conductances of 2, 5, 10, and 20 μmhos are provided for use in calibration. The subject voltage is adjusted using R_8 with a voltmeter at the input terminals. Calibration is accomplished in the same way as in the previous circuit. With the Grass, which has a maximum sensitivity of 10 μv/cm, this system will provide a sensitivity of 0.1 μmhos/cm. If the range of conductances being measured is fairly low, e.g., below about 10 μmhos, as when using two small finger electrodes, the signal resistor, R_9, can be made larger without losing the constant-voltage property; if the values shown in parentheses for R_9, R_{12}, and R_{13} are employed, system sensitivity will be increased by a factor of 10.

With either circuit, after calibration, the preamp attenuator is set for re-

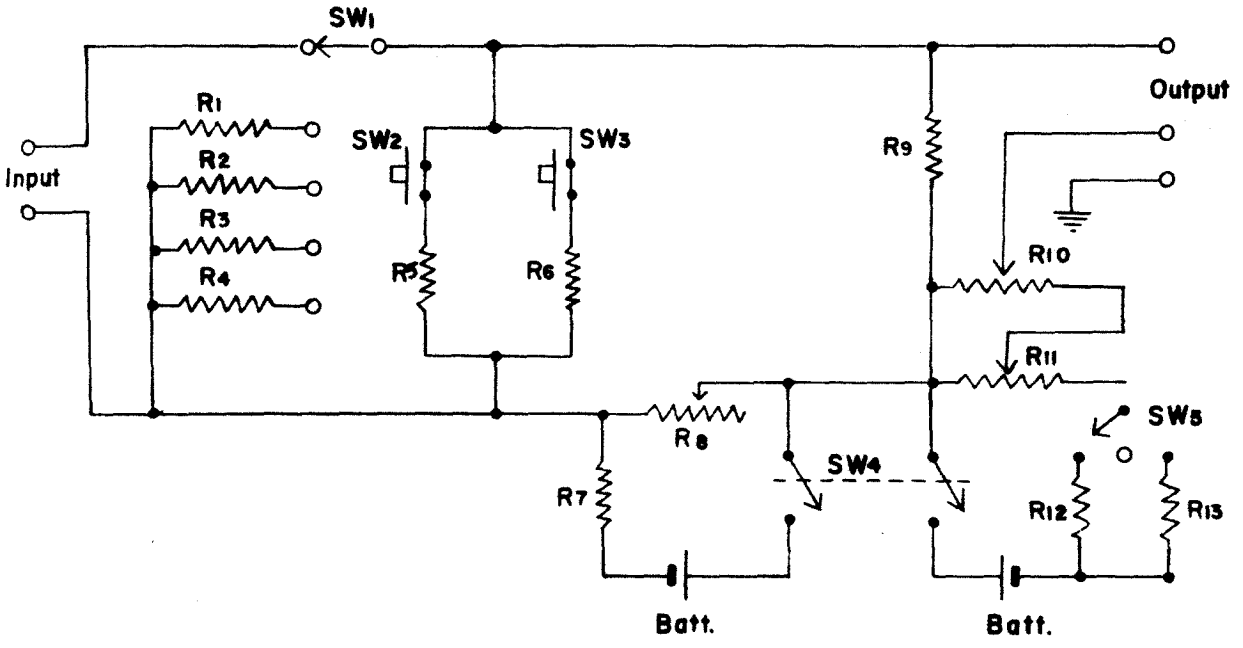

FIG. 3. SC Signal Conditioner for use with Grass low-level DC preamp or equivalent. Output is 100 μv/μmho (a sensitivity of 0.1 μmhos/cm with the Grass set at .01 mv/cm). Using values in parentheses for R_9, R_{12}, and R_{13} will increase output to 1 mv/μmho. R_8 is adjusted for 0.5 volts across the input terminals.

R_1 - 500K ohms, 1%
R_2 - 200K ohms, 1%
R_3 - 100K ohms, 1%
R_4 - 50K ohms, 1%
R_5 - 1 Megohm, 1%
R_6 - 200K ohms, 1%
R_7 - 150 ohms
R_8 - 100 ohm Trimpot
R_9 - 200 ohms, 1% (2000 ohms)
R_{10} - 500 ohms, 10-turn
R_{11} - 200 ohm Trimpot
R_{12} - 10K ohms, 1% (1K ohm)
R_{13} - 100K ohms, 1% (10K ohms)
Batt. - 1.35 volt merc.
SW_1 - 5-position rotary 'Input Switch'
SW_2 - Pushbutton, '1 μmho'
SW_3 - Pushbutton, '5 μmhos'
SW_4 - DPST toggle, 'on - off'
SW_5 - SPDT center off, toggle 'Suppression Range,' '10 - off - 100 μmhos'

duced sensitivity, the subject is switched in and the attenuator is set back again until a reasonable pen deflection is observed. The suppression control is then advanced to cancel out this deflection. The attenuator is further advanced until the desired level of sensitivity is reached, i.e., until the subject's SCRs produce adequate pen excursions. The reading of the suppression control and the attenuator setting are both marked on the chart. Should the pen drift off the chart it can easily be re-centered with the suppression control and the new reading is then recorded. An example of how one can determine the exact value of SCL represented by any pen position on the chart may be useful. Suppose that the pen is 1.4 cm above the base or zero line, the suppression reading is '08.20' (suppression range set at 10 μmhos), and the attenuator is set at '× 1' (Beckman) or '×.1' (Grass). We know that the subject's SCL would be exactly 8.20 μmhos if the pen were exactly on the zero line and we know that the present sensitivity setting is 1 μmho/cm. Since the pen is in fact 1.4 cm above the zero line, the present SCL must be 8.20 + 1.40 = 9.60 μmhos. Suppose the suppression range was set at 100 μmhos and the suppression reading is '03.27.' The attenuator is at '× 5' (Beckman) and the pen again is 1.4 cm above the zero line. SCL at the zero line would be 32.7 μmhos; present sensitivity is 5 μmhos/cm. Hence, the subject's SC must be 32.7 + 5(1.4) = 39.7 μmhos.

Electrodes and Electrolytes

The silver silver-chloride electrode is undoubtedly the most expedient choice for electrodermal measurement. Excellent electrodes of this type can be made easily and cheaply following Venables and Sayer (1963) or Miller (1968) and they are also available commercially from several manufacturers.[1] When applying the electrodes to the body it should be remembered that the amplitude of both SC and SCR will depend upon (1) the density of sweat glands in the skin area chosen, (2) the degree of 'psycho-activity' of the sweat glands in that region, and (3) the size of the skin area in contact with the electrolyte. Both sweat gland density and 'psycho-activity' are greatest on the palms and soles, greatest of all on the volar surface of the finger tips. Edelberg (1967) recommends using the second phalanx as an electrode site since this area is less likely to show small cuts or other damage; alternatively, one can examine the distal phalanx under a lens to rule out possible abrasions and then take advantage of the fact that this finger tip area is usually most reactive of all and that electrodes applied here are less vulnerable to movement artifacts.

If the distribution of sweat glands is reasonably homogeneous, SCL will vary linearly with the area of skin in contact with the electrode paste (Lykken, 1970); the size of the electrode itself is unimportant. Therefore this area must be controlled in some manner. One way is to use a commercial electrode collar—a disc of tape, sticky on both sides, with a hole in the center—which can be stuck to the dry skin, the exposed skin area covered with electrolyte, and then the electrode applied on top. Another way is to apply a felt corn pad, sticky side to the skin, fill the center hole with elec-

[1] Silver silver-chloride skin electrodes are available from: Beckman Instruments, Inc., 3900 River Road, Schiller Park, Illinois 60176; IMI Division of Becton, Dickinson Co., 4321 Birch Street, Newport Beach, California 92660; In Vivo Metric Systems Co., 10709 Venice Blvd., Los Angeles, California 90034; and Mennen-Greatbatch Electronics, Inc., 10440 Main Street, Clarence, New York 14031.

trolyte and then attach the electrode over the top with a length of tape around the finger. The latter system is especially secure and the felt pad seems to minimize movement and pressure artifacts. A third approach is to use a cup-shaped electrode in which the rim seals and delimits the electrode area. One of us (PHV), using an agar electrolyte (see below), has observed seepage under the adhesive discs or pads and prefers the rim sealed electrode. The other author (DTL) has had good results with the felt pad, using a viscous and hygroscopic ointment cream as the electrolyte medium.

Since conductance varies directly with effective electrode area, all measurements should be reported as *specific conductances*, i.e., in μmhos per square centimeter. Suppose, for example, that two 1 cm^2 electrodes yield an SC of 10 μmhos. Assuming that the two skin areas are similar, the specific conductance of each 1 cm^2 area must be about 20 μmhos. This is best understood by converting to resistance terms; $R_1 + R_2 = R_t = 10^6/20 =$ 100K ohms; $R_1 = R_2 =$ 50K ohms $=$ $1/C$; $C_1 = C_2 = 1/(50 \times 10^3) = 20$ μmhos. In general, if both electrodes are applied to intact skin areas of equal size, the *specific conductance* will be equal to the measured SC divided by one-half the area of one electrode. If a drilled reference site is employed, having a conductance of hundreds of micromhos, then the specific conductance is well enough approximated by dividing the measured SC by the area of the single active electrode.

Experimental circumstances will dictate electrode location; where possible, the best arrangement is probably to center the two electrodes on the volar surfaces of the distal phalanx of the first and second fingers of the right hand (or the non-dominant hand if the subject will be required to use one hand). Electrode location and electrode area should always be controlled and always specified in the experimental report.

Some sort of non-drying electrode paste must be used to make contact between the electrode and the skin. Both the nature and the concentration of the salts in this electrolyte can make enormous differences in the values of SCL and SCR observed and may cause marked changes over time (Edelberg, 1967). On theoretical grounds, one might suppose that a solution of KCl and NaCl in concentrations approximating those of sweat would provide the best electrode paste in the sense of being least likely to affect the tissue and, hence, the phenomena being measured. This matter does not seem to have been studied, however, and the medium most commonly used contains 0.5 percent KCl alone. It is especially important to realize that commercial pastes or jellies intended for EEG or EKG recording are *not* appropriate for electrodermal measurement; these electrolytes are made of strongly hypertonic solutions specifically designed to depolarize the skin and to reduce skin resistance.

The most common electrolyte medium is an agar paste made by heating two grams of agar in 100 ml of 0.5 percent KCl almost to boiling and then stirring until cool. Agar paste deteriorates after a week or two, however, and its consistency is not always ideal. Another method is to use a commercial neutral ointment base thinned slightly with salt solution. The following recipe has been used for years with apparent success although it must be admitted that its electrochemical properties have not been studied; to one pound Unibase (Parke-Davis) add ½ part by volume physiological saline, beat until creamy. This

mixture has the consistency of thin coldcream, is slow to dry, and appears to last indefinitely. It might be mentioned here that the little water-jet device made as a toothbrush substitute is a handy tool for cleaning electrodes after use.

Units of Measurement

Normality of Distribution

Given that we have obtained our measure of tonic level and of phasic change both in conductance units (i.e., SCL values in μmhos and SCRs in μmhos-change), shall we proceed with our statistical analyses at once or should we first undertake some transformation or change of units before we compute means or correlations or analyses of variance? There are three considerations which have motivated the considerable literature which has evolved around this topic. First is the problem of normality of distribution. Many statistical procedures assume normality and scalar transformations to reduce skewness, etc., are a common and legitimate technique. In the case of electrodermal measures, however, one gets the impression that the search for normality became for a time a sort of end in itself, dictated by the dubious assumption, which goes back to Quetelet, that all *true* measures of biological variables are in fact Gaussian and that, therefore, if a log or square-root transformation tends to normalize a distribution of GSRs, then it is more probable that the transformed index will prove to be a simple, linear measure of the underlying variable of interest. This doctrine is as unreasonable as it is old-fashioned (cf. Hogben, 1957). If, after any other rational transformations have been made, one's data are so skewed as to jeopardize the validity of the tests one wishes to make, then an *ad hoc* scalar transformation may be appropriate but one should beware of attaching any magical significance to the result.

Correction for Individual Differences in Range

A second consideration motivating concern about units of measurement has been the general awareness that the wide range of individual differences in levels of SC and amplitudes of SCRs probably cannot be explained in terms of psychological variability alone. Lykken, Miller, and Strahan (1968), for example, report a study of 19 normal males in which the *minimum* SC shown by one *S* after 30 min relaxation was nearly twice as high as the *maximum* shown by another *S* while blowing up a balloon to bursting; surely the first *S* was not more psychologically aroused while relaxed than the second was while the balloon was exploding in his face! Anyone who has worked with the GSR knows that some *S*s habitually give much larger responses to mild stimuli than other *S*s give to loud, startling noises or strong shocks. This same inter-subjective variability persists even when one measures SC directly, being careful to control electrode area and location and to use isotonic electrolytes, etc. The conclusion is inescapable that a substantial proportion of the variance in any distribution across *S*s of SCL or SCR values must be attributable to physiological differences which are essentially unrelated to the psychological processes in which we are primarily interested. That is, both the maximum and minimum SCL of which a given *S* is capable must be determined by structural, physiological, and biochemical factors which themselves differ widely from one individual to another; it is the variation *within* these limits which is normally of psychological interest. Therefore, if one could obtain for each *S* a good estimate of his absolute maximum and

minimum SCL limits, then one could in effect partial out these extraneous sources of variation and produce a variable determined mainly by psychological factors by the simple expedient of expressing each *S*'s tonic SCL (at any given time) as a proportion of his individual range of variation. That is, if SCL_{ix} is the tonic SCL of the *i*th *S* under the experimental conditions *x*, then the transformed value would be

$$1. \quad \phi_{ix} = \frac{SCL_{ix} - SCL_{min}}{SCL_{max} - SCL_{min}}.$$

This is Rose's range correction as described in Lykken, Rose, Luther, and Maley (1966), who provide evidence that, indeed, the use of the range correction can succeed in reducing error variance and thus increase the magnitude of correlations and treatment effects. More corroborating data will be published shortly.

A cautionary note should be added, however. The rationale of this range correction depends on the assumption that one has reasonable estimates of individual maximum and minimum SCs and, therefore, that these estimates will not themselves be correlated with the individual's *psychological* arousal or reactivity levels. In practice, such estimates may be difficult to obtain. The balloon-bursting procedure has worked reasonably well in producing maxima but in at least one study (Lykken & Maley, 1968) this stressor produced SCLs in schizophrenic *S*s which averaged twice as high as those from the normal controls. This suggests that the patients, who had been removed from medication and were quite excitable, reacted *psychologically* more strongly to the stressor than did the normals so that the SC values obtained were poorer estimates of the true maximum values for the normals than for the schizophrenics. Similarly, it is notorious among psychophysiologists that there are wide individual differences in the ability to relax in an experimental chamber, that after 20 min of silence some *S*s will be sound asleep while others are still nervously reviewing their sins or awaiting Armageddon. Therefore, adequate estimates of minimum SC not only require a reasonable rest period but also should include EEG evidence of light sleep. While the range correction procedure does involve problems of this sort and always requires additional experimental effort, we feel that experimenters using electrodermal measures should give serious consideration to its use.

Range-Correction of SCRs

Lykken and Maley (1968) propose that the phasic SCR, which is the difference between a prestimulus and the peak poststimulus SC, can be range-corrected by using range-corrected values for these pre- and poststimulus conductances; this is algebraically equivalent to simply dividing the SCR by the same denominator used in Formula 1 (i.e., by that *S*'s range of SC variation). But this approach assumes that the underlying mechanisms responsible for phasic changes are identical to those which determine the tonic level of SCL and this assumption now appears to be questionable. For example, if an *S*'s SC_{max} is 20 μmhos/cm^2 and his present SCL is 10 μmhos, it is probably *not* safe to assume that he is now capable of a maximum SCR of 20 − 10 = 10 μmhos; that is, for his conductance to reach the level of his SC_{max} would probably require something more than the maximum increment in sudomotor activity that can be elicited phasically. In some recent unpublished research, one of us elicited SCRs in 48 *S*s with a series of 48 painful shocks over a period of 90 min. Each *S*'s largest SCR was compared to this hypothetical 'largest possible SCR,' obtained by subtracting his pre-shock SC from his SC_{max}; the

ratio of the former to the latter ranged over the 48 *S*s from .24 to 1.00 with a mean of .66. For about 25 percent of these *S*s the SC_{max} was indeed obtained at the peak of their largest SCR but, for another 40 percent, the largest SCR elicited by shock drove their SC less than half of the distance toward the SC_{max} value shown by that *S* at some other time during the session.

These considerations indicate that SCRs should be corrected for individual differences in *range of SCR* specifically, rather than for differences in range of tonic SC. Since the minimum possible SCR is always zero, this will require only that one obtain an estimate of each *S*'s SCR_{max}, by presenting at least one strong shock or noise or other startle stimulus during the session. Each SCR can then be corrected for individual differences in range of SCR by the simple formula:

$$2. \qquad \Delta\phi_{ix} = \frac{SCR_{ix}}{SCR_{i(max)}} .$$

Thus, whenever one is comparing SCRs across individuals, as in habituation studies or experiments relating SCR amplitudes to types or intensities of stimuli, one can obtain the range-correction effect and scale one's data in a form suitable for inter-individual comparison simply by dividing each SCR by the largest SCR elicited from that individual in the session. (This unit is similar to that proposed by Paintal, 1951.)

In the experiment mentioned above, the correlation (over 48 *S*s) of SCRs corrected for range of SCR with the same SCRs corrected for SC range was about .60, showing that the two methods yield quite different results. When used as dependent variables in analyses of certain treatment effects (analyses concerned with the effect of predictability on the SCR to shock), *F*-ratios which were significant for SCR/SC_{range} were consistently and substantially increased (and thus more significant) using SCR/SCR_{max}. Thus, experimental findings support the logical considerations which suggest that Formula 2 above is the appropriate unit in which to express the SCR for comparing individuals.

The Law of Initial Values

The third and final consideration which has prompted discussion of electrodermal units of measurement is expressed in the so-called 'Law of Initial Values' (LIV) which asserts that the size of the response to an experimental stimulus is related to the prestimulus level of the variable under observation (Wilder, 1962). From one point of view, this 'Law' is a platitude, asserting merely that the response to a stimulus is a function, not only of the stimulus itself, but also of the state of the organism at the time; surely this is common knowledge to psychologists and physiologists alike. As will be outlined below, the observed covariation of response magnitudes with tonic levels may result from a combination of at least four different factors, not just one as this alleged 'Law' may seem to suggest; whether one will wish to "undo" this dependency by statistical maneuvers (Benjamin, 1967) will depend upon the particular experimental situation and the questions one is asking of the data.

We venture here upon much more controversial ground. The recommendations made earlier in this paper, we believe, would upon reflection be acceptable to most experienced and sophisticated workers in this area. The problem which we now address is both complex and still *sub judice* and it might be argued that such an issue should not be raised in a deliberately 'cookbook' article. Unfortunately, however, it is obvious that many investigators are using, e.g., covariance procedures in a "ritualistic" (Lubin,

1965), cookbook fashion already and often inappropriately. We are reluctant to make recommendations for the standardization of SCL and SCR measurement knowing that their potential benefits will at once be lost in some hands through ill-advised statistical manipulations. Our analysis, below, of the tonic-phasic dependency problem is not intended to be exhaustive or definitive; we believe, however, that it is correct as far as it goes and that it may help to save some neophytes from straying to the paths of error.

Causes of Tonic-Phasic Dependency

(1) The first way in which a phasic response can be made to correlate with tonic level is by making an improper choice of basic units in the first place. If we are correct in believing that the local effect of GSR innervation is primarily an increase in number of active sweat glands, i.e., an increase in conductive pathways through the epidermis, then SRR will inevitably be strongly correlated with SRL even though SCR and SCL, the proper units for this measurement, may be completely independent. Suppose, for example, that repetitions of the same stimulus elicits a 1 μmho SCR from an individual *S* when his tonic SC is at 10, 11, 12, 13, 14, 15, and 16 μmhos; the correlation between SCR and SC here is obviously zero. In resistance terms, the same series of tonic levels would be 100, 91, 83, 77, 71, 67, and 62 K ohms; the associated SRRs would be 9.09, 7.57, 6.41, 5.49, 4.76, 4.17, and 3.68 K ohms. The correlation between phasic change and tonic level in this case would be .998 i.e., complete dependency arising as an artifact of the laws of arithmetic even though the phenomena being studied, the central states giving rise to the sudomotor innervation pre- and poststimulus, are completely uncorrelated in this hypothetical example. The way to avoid this type of phasic-tonic dependency—and it is clearly to be avoided—is to use the proper basic units in the first place.

(2) A second determiner of phasic-tonic correlation may be the presence in both SCL and SCR of a common factor which is extraneous to the central activity one is interested in measuring. From the wide individual differences in range of variation of SCL, already noted, it is apparent that the same level of central activity can produce very different tonic SCL levels in different individuals. That is, individuals differ in the responsivity of their electrodermal apparatus. Therefore, the SCL levels actually measured will be some function of the *product* of the level of central excitation (ψ) and some measure of end-organ reactivity (ρ); that is $SC_{io} = f(\rho_i \times \psi_{io})$, where *i* indicates the *i*th individual and *o* denotes the prestimulus state of affairs. To simplify exposition, let us assume a linear relationship between SCL and central excitation, $SCL_{io} = \mu_i + \rho_i\psi_{io}$, where μ_i represents the minimum conductance of the inactive tissue, e.g., at "zero arousal." Then, if SC_{ip} is the peak poststimulus SC for this individual, we can write $SCR_{io} = SC_{ip} - SC_{io}$ or $SCR_{io} = \rho_i(\psi_{ip} - \psi_{io})$. That is, SCL and SCR are functions of elecdermal reactivity, ρ, which we assume to be unrelated to the central changes we are interested in measuring. Note that this will not lead to a correlation between SCR and SC *within individuals*, as long as the reactivity factor, ρ_i, remains constant. But, since we know that reactivity differs widely *across* individuals, *between-subject* correlations will be substantially inflated by the presence of this extraneous factor. (It is for similar reasons that the number of churches in a town is almost perfectly correlated with the number of taverns; both measures are

themselves functions of the same extraneous variable, the size of the town.)

This sort of phasic-tonic covariation is also always undesirable and it seems probable that this is the problem which most advocates of covariance analysis have had in mind. It will be noted, however, that it is to deal with precisely this problem that the range-correction, outlined above, was invented. One can show algebraically that covariance analysis and range-correction accomplish the same result *providing* that the presence of this extraneous common factor is the only source of phasic-tonic correlation present *and* providing also that the linearity assumptions of covariance analysis are also met. However, as we will show below, there are other probable sources of covariation between SCL and SCR, i.e., sources which may produce correlations even between the range-corrected values, ϕ_{sc} and $\Delta\phi$, and the covariance procedures indiscriminantly attempt to eliminate these as well. Moreover, as we shall see, it is most unlikely that the relationship between ϕ_{sc} and $\Delta\phi$, or between the raw values, SCL and SCR, for that matter, will prove to be linear as assumed by the covariance procedure. Therefore, we would advocate the use of the range-correction procedure in order to eliminate selectively the primary and clearly undesirable source of phasic-tonic correlation. The corrected tonic and phasic measures can then be examined for residual correlation and further statistical manipulations employed if appropriate in relation to the questions one wishes to answer.

(3) A third source of phasic-tonic correlation comes closer to the original concept of the LIV. If SCL is already very high (with respect to *S*'s own upper limit, i.e., if ϕ_{sc} is approaching 1.00), then presumably the maximum possible SCR will be limited also. With cardiovascular variables, we would be talking here about homeostatic restraint but, in the case of SCL we are probably dealing with a simple physiological limit. If we are using a strong stimulus which elicits large SCRs, then we must expect that these SCRs will begin to decrease in amplitude as the tonic SCL rises above a certain level. That is, this particular factor by itself will tend to produce negative SCL-SCR correlations when SCL is high, no correlation when SCL is low, and larger correlations overall for strong stimuli than for weak. (These relationships will be seen within individual *S*s but not necessarily across *S*s unless range-corrected units are employed.) There is no general way of avoiding this effect, if one wants to avoid it, except by avoiding very high levels of tonic SC. Plotting one's data in terms of range-corrected units will at least allow one to observe when this effect is present. It is ironic that, while covariance procedures are advertised for use with this source of covariation (methods to "undo the LIV"), they are particularly unsuited to the job since the expected relationship is far from linear.

(4) A fourth source of phasic-tonic relationship is the fact that different levels of tonic SCLs represent different states of the organism, e.g., a subject is in a state of higher arousal when his SCL is high than when it is low. It is natural to expect that reactions to specific stimuli will be different, i.e., the central or psychological reactions themselves, as a function of the concurrent level of arousal. It is probably *not* reasonable to make any very general assumptions about the form of this relationship because this may very well depend upon the specific nature of the stimulus and may be quite complex. For example, it might not be surprising to discover that the SCR to a moderately painful shock was high for a drowsy *S*, lower for a moderately alert *S*, high again for an excited *S*, and low again for a *S* excited to near his upper

limit. No standard covariance procedure can cope with such functions. Moreover, it is not the case that one should always want to "undo" such relationships since, for example, it is probable that the 'subjective intensity' of the shock truly was stronger for both the drowsy and excited *S*s than it was for the *S* who was only moderately aroused.

Summary

In the interests of improving the state of the art and providing greater comparability among laboratories, we propose the following:

1. The term "tonic SCL" will refer to the average SC level, exclusive of phasic activity, during a specified time period; the term "basal SC" is misleading and should be avoided. "GSR" is a time-honored generic term for phasic electrodermal changes; the phasic change in skin conductance will be referred to as an "SCR."

2. Since much evidence indicates that skin conductance bears a simpler relationship to the underlying activity of interest to the psychologist, conductance should be measured in preference to resistance. SC should be measured directly using a constant-voltage circuit as described herein, limited to about 0.5 volts.

3. Silver silver-chloride electrodes should be used together with an electrode paste containing 0.5 percent KCl or an isotonic mixture of KCl and NaCl equivalent to physiological saline. The area of skin in contact with the electrodes should be controlled and the measurements should be reported in terms of specific conductances as described in the text. For most purposes, electrodes should be applied to the palmar surface of the distal phalanx of the first and second fingers of one hand.

4. Whenever comparisons are to be made between individuals (including correlations with other variables), measurements of tonic SCL should first be corrected for individual differences in range of SCL variation. This will require obtaining estimates of each *S*'s maximum and minimum SCL as described in the text.

5. Also for inter-individual comparisons, measures of SCRs should first be corrected for individual differences in range of SCR variation. This may be done simply by dividing each SCR by that *S*'s SCR_{max}, i.e., the largest SCR he produces in response to some strong startle stimulus.

6. Having followed the above procedures, the investigator will seldom wish to attempt any further manipulation of units, e.g., for the purpose of reducing correlation between SCR and SCL. Before employing the covariance procedures which have recently been popular, he should be sure that he fully understands the various considerations advanced in this connection in the text.

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