Psychophysiology, 49 (2012), 1017–1034. Wiley Periodicals, Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2012.01384.x

COMMITTEE REPORT

Publication recommendations for electrodermal measurements

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Abstract

This committee was appointed by the SPR Board to provide recommendations for publishing data on electrodermal activity (EDA). They are intended to be a stand-alone source for newcomers and experienced users. A short outline of principles for electrodermal measurement is given, and recommendations from an earlier report (Fowles et al., 1981) are incorporated. Three fundamental techniques of EDA recording are described: (1) endosomatic recording without the application of an external current, (2) exosomatic recording with direct current (the most widely applied methodology), and (3) exosomatic recording with alternating current—to date infrequently used but a promising future methodology. In addition to EDA recording in laboratories, ambulatory recording has become an emerging technique. Specific problems that come with this recording of EDA in the field are discussed, as are those emerging from recording EDA within a magnetic field (e.g., fMRI). Recommendations for the details that should be mentioned in publications of EDA methods and results are provided.

Descriptors: Electrodermal measurement, Skin potential, Skin conductance, Skin admittance, Laboratory and field recording

Changes in the electrical activity of palmar and plantar skin, being concomitants of psychological phenomena, can be regarded as one of the origins of psychophysiological recording. Galvanic skin responses or, as called later by a more general term, electrodermal responses (collectively designated as electrodermal activity or EDA) were observed as early as in the last two decades of the 19th century (for an historical overview, see Neumann & Blanton, 1970), at a time when recordings of human electroencephalogram (EEG) were yet unknown. Since then, both phasic and tonic EDA measures have been used extensively in psychophysiological research for a large variety of purposes, and their usage continues even in recent years where the main focus of psychophysiological research has shifted to more direct observations of brain functions.

Over time, a great variety of methods for recording EDA were developed, and a wealth of studies using them in various fields of application have been around for considerably more than half a century. Publication standards recommended in 1981 by a committee appointed by the then editor of this journal (Fowles et al., 1981) have been updated by the present committee, taking into account methodological developments of the past 30 years.

The committee opted for making these recommendations a stand-alone source, enabling readers to get all information they will need for setting up their own EDA recording and evaluation procedures. Those who want to go into more details or get more information on the origins of EDA and fields of EDA application are referred to the Dawson, Schell, and Filion (2007) chapter in the *Handbook of Psychophysiology* edited by Cacioppo, Tassinary, and Berntson and to a recently updated handbook on EDA (Boucsein, 2012).

1. Principles of Electrodermal Measurement

There are three different methods of measuring EDA: (a) without the application of an external current, which is therefore called the

We report with deep regret that Wolfram Boucsein died on January 2, 2012, following a long battle with a blood cancer. His 1992 book *Electrodermal Activity* was the most comprehensive treatise on electrodermal activity ever to appear, and its breadth of coverage and depth of knowledge placed it in a class by itself as *the* standard reference source. A second edition has just been published as we submit the present article. Professor Boucsein provided outstanding leadership of the writing of the present manuscript, for which we all are grateful. Aware of the fragility of his health, he pressed for completion of the manuscript, which was submitted only a few days before his death. We honor him for his contributions to psychophysiology and feel a great loss at his death.

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endosomatic method, and two exosomatic methods which either (b) apply direct current (DC) via electrodes on the skin or (c) apply alternating current (AC) instead.

1.1. Endosomatic Electrodermal Responses

An electrical potential difference can be measured across the palmar and plantar skin in the absence of any applied voltage or current. A single electrode is placed on the active site with a reference electrode at a relatively inactive site such as the forearm (see Section 2.2.). The measured potential is usually negative at the palm, and electrodermal responses (EDRs) are easily seen in these recordings. The endosomatic EDRs (skin potential responses or SPRs) are similar to, and concurrent with, the more commonly measured exosomatic EDRs, albeit with a more complex wave form. In the early literature, a relatively large number of studies examined endogenous EDRs, and theories of mechanisms of EDA have included attempts to explain endosomatic responses. The current condensed summary of the characteristics of SPRs and their relation to skin conductance responses (SCRs) is taken from Fowles (1986) and Edelberg (1993).

SPRs can constitute both negative and positive responses. A negative SPR means an increased negative potential (at the palm), a positive response means a less negative potential. SPRs can be monophasic negative or biphasic, with an initial negative component and a later positive wave. Sometimes the recovery from the positive component goes more negative than the peak of the initial negative wave, making it a triphasic response. However, this late negative component often is viewed as a continuation of the initial negative wave once the positive component has run its course (Fowles, 1986, p. 73). Under some conditions, the SPR appears as a monophasic positive response. Due to this complexity, scoring and interpreting the amplitude of an SPR is difficult, accounting for the limited popularity of endosomatic EDRs in psychological research. Interestingly, these responses, called the "sympathetic skin response," have been used by neurologists in an attempt to assess the functioning of the sympathetic nervous system (e.g., Vetrugno, Liguori, Cortelli, & Montagna, 2003).

The nature of the SPR is systematically related to the amount of prior sweat gland activity (as indicated by EDRs) and to both surface sweating and characteristics of the concomitant SCR (Fowles, 1986, pp. 75, 85). The positive component of the SPR is strongly related to SCRs with a rapid recovery limb (see Section 3.1), to high initial SCLs (due to frequent prior EDRs), and to sweat appearing on the surface of the skin. In contrast, monophasic negative SPRs tend to be associated with low initial SCL (due to infrequent prior EDRs), slow-recovery SCRs, and an absence of visible sweating—all consistent with a filling of the sweat ducts in the corneum (the dead, outer layer of the epidermis) but without sweat reaching the skin surface. Finally, monophasic positive SPRs are associated with recent sweat gland activity (presumably filling the epidermal portion of the sweat duct) as indicated by SPRs (see Figure 4–6 in Fowles, 1986) and with rapid recovery SCRs. These effects can be demonstrated experimentally, eliciting EDRs by fast, deep breaths at variable intervals.

The source of the large negative potential in humans is active reabsorption of Na^+ (with Cl^- following passively) in the sweat gland duct below the epidermis, producing a lumen-negative potential of 50–70 mV across the duct wall (Edelberg, 1993, p. 17; Fowles, 1986, p. 81).[1] The relationship between this ductal potential and skin surface measurements can be understood with Edelberg's (1968; but see Edelberg, 1993) "mosaic (voltage-divider) model" shown in Figure 1. Although considerably oversimplified, the circuit provides a fundamental insight into the circuitry involved. The crucial elements of the circuit are the lumen-negative potential (S) in the duct, resistance (R_s) of the sweat duct between the negative potential and the skin surface, a smaller surface negative potential E from the skin, and the resistance of the epidermis (R_e) between the skin surface and the interstitial fluid. The skin potential *E* is either stable or changes very slowly over time and thus is relatively unimportant for changes in potential. Its primary contribution is to reduce the net voltage applied to the circuit, which becomes $S - E$. The following analysis will neglect the contribution of *E*.

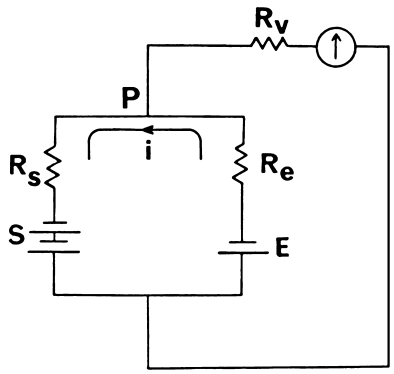

Figure 1. Circuit model for the origin of skin potential. For explanations, see the text. From Edelberg, R. (1968). Biopotentials from the skin surface: The hydration effect. *Annals of the New York Academy of Sciences*, *148*, 252–262. Reprinted by permission of the author.

From Ohm's law, it is apparent that the sweat duct potential is divided between the two resistors in this model. Because the electrode on the surface is connected between the resistors, the measured potential will be affected not only by the size of potential S but also by the relative values of R_s and R_e with some portion of the value of S "lost" to surface recordings by the voltage drop across R_s. If the value of R_e is very high relative to R_s, then little of the potential is lost across R_s between the duct and the skin surface, and the measured potential is reasonably close to the value across the duct wall. In contrast, if R_s increases (e.g., due to emptying of the sweat duct) or if R_e decreases (e.g., due to hydration of the corneum), then the measured potential goes in the positive (or less negative) direction.

According to this model, as the sweat fills the epidermal portion of the sweat gland duct, R_s decreases and a greater portion of the voltage drop is across R_e, increasing the negative potential across the skin. Thus, duct filling accounts for the initial negative component of the SPR. In contrast, anything that increases the value of R_s or reduces the value of R_e will decrease the negative potential across the skin. If this process is fast enough, it will appear as the positive component of the SPR.

1. A more recent study performed by Reddy and Quinton (1994) on electrolyte absorption in the human sweat gland duct revealed that the absorptive function is subjected to rapid regulation, which can be acutely switched on and off by a control system that is common to both absorptive and secretory processes.

In addition to the duct filling just described, three processes have been suggested as influencing SPRs:

- Fowles (1986, p. 84) suggested that hydraulic pressure in the epidermal portion of the duct can become great enough to trigger an increased permeability of the duct wall, providing a "shunt" pathway between the sweat gland lumen and the epidermis. The effect of this decreased resistance would be a rapid positive SPR, which would recover as the pressure dropped and the duct wall recovered. It would also be manifest as a rapid recovery SCR.
- Edelberg (1993) proposed that a poral valve at the top of the sweat gland on the skin surface offers resistance to current flow until it is forced open by hydraulic pressure from the secreted sweat in the duct. At that point, there is a further and sudden decrease in the value of R_s that produces a rapid negative wave (and a rapid increase in SC). Once the sweat has been expelled onto the skin surface, the poral valve closes, increasing the resistance rapidly and producing the onset of the positive component of the SPR.
- Edelberg (1993) suggested that hydraulic pressure forces sweat through the duct walls, producing hydration in the deeper levels of the corneum (which are not hydrated by the electrode gel). The initial effect of this peritubular hydration is to contribute to the onset of a positive SPR, consistent with a decrease in R_e in the voltage divider model. Edelberg further proposes that diffusion of the sweat into the corneum away from the periductal area actually increases epidermal resistance, accounting for the recovery portion of the positive SPR.[2]

The point of this brief excursion into mechanisms is to illustrate the complexity of the factors influencing endosomatic potentials. Because of the voltage divider effect of sweat gland duct and epidermal resistances, changes in resistance sometimes increase and sometimes decrease negativity, making analysis and interpretation of data difficult. Even though the same complex mechanisms also influence SCRs, at least they have the advantage of working in the same direction, permitting an assessment of an overall effect on resistance of the sweat gland ducts and the skin.

With respect to methodology, the same electrodes and gel used for SC recordings are appropriate for endosomatic responses, except that the latter have higher demands on low electrode bias voltage (see Section 2.1). The major difference in technique is that bipolar placement of the electrodes on two active sites is inappropriate for endosomatic responses: Changes in potential will be more or less equal and opposite at the two sites and will cancel each other out. Rather, one needs one electrode on an active site and another on a relatively inactive, reference site (see Section 2.2).

1.2. Exosomatic Measurement with Direct Current

The measurement of EDA as skin conductance using a direct current, constant voltage methodology with silver–silver chloride (Ag/AgCl) electrodes and an electrolyte of sodium or potassium chloride has dominated the EDA literature for many decades. Lykken and Venables (1971) proposed standardization using this methodology, and the earlier committee report on Publication Recommendations (Fowles et al., 1981) for this journal embraced their proposal. The present summary describes a simple, relatively nontechnical methodology that has been applied in the vast majority of publications using EDA.

The basic method is to apply a small voltage (e.g., 0.5 V) to two electrodes placed on the intact palmar surface of the skin and include a small resistor (e.g., 200 to 1000 Ω) in series with the skin. The electrodes should be placed on the same body side to avoid electrocardiogram (ECG) artifacts. Because the resistance of the skin (skin resistance, SR) is of the order of 100 kΩ (1 kΩ = 1000 Ω) or more, the small series resistor is considered negligible with respect to affecting the current flow in the circuit and can be ignored when measuring current flow. As a result, applying Ohm's law, the current (I) flow between the electrodes (and necessarily through the resistor) is $I = E/R_p$ where E is the applied voltage and R_p is the resistance of the participant's skin.

Because *E* has a fixed value, the current varies in proportion to the value of $1/R_p$. This reciprocal of resistance is called conductance (abbreviated *G* for total or a single conductance and g_1, g_2, etc. for individual conductances when more than one conductance is being considered). Consequently, the current flow is alternatively viewed as $I = E \times G_p$, making it clear that current flow through the skin and thus the series resistor is proportional to G or conductance.

The unit of conductance is siemens (S), where 1/1 Ω = 1 S. Because skin resistances are very large, the usual units of scale are kΩ or MΩ (1 MΩ = 1,000,000 Ω). Similarly, skin conductances are small, measured in units of microsiemens (one millionth of a siemens). One microsiemens (μS) is the conductance of 1 MΩ or 1/1,000,000 Ω, and there are 10^6 (i.e., 1 million) μS for 1 Ω of resistance.

The final consideration is that the voltage drop across the small series resistor used to measure current (again using Ohm's law) is $E = I \times R_s$, where R_s is the series resistor. Because the value of R_s is constant, the voltage drop across R_s is proportional to the current flow I, which in turn is proportional to the participant's conductance, G_p. Variations in this voltage drop can be monitored by connecting wires on either side of the resistor and feeding them into a DC amplifier, providing a precise index of variations in the conductance of the skin.

To illustrate this example with concrete numbers, assume an applied voltage of 0.5 V and a series resistor of 1000 Ω or 1 kΩ. The current flow will be $I = 0.5\ V \times G_p$. The voltage drop across the 1 kΩ series resistor is $E = 1000\ \Omega \times I = 1000\ \Omega \times 0.5\ V \times G_p = 500 \times G_p$. If participant's resistance is 100 kΩ, making the conductance 1/100,000 Ω = 0.00001 S = 10 μS, then the voltage drop across the resistor will be $I = 500 \times 0.00001$ S = 0.005 V or 5 mV. From this calculation, the 10 μS participant's conductance yielded a 5 mV signal to the amplifier or 0.5 mV per microsiemens. Thus, the output from this combination of applied voltage and series resistor values is calibrated to yield 0.5 mV for each microsiemen of participant's conductance, and this ratio is true throughout the range of SC. This example shows that application of a constant voltage to the skin produces voltages in the millivolt range across the series resistor that are proportional to SC.[3]

2. Edelberg's poral valve model is also in agreement with the results of Grimnes, Jabbari, Martinsen, and Tronstad (2011, Figure 4), who recorded SP and SC simultaneously from the same electrode.

3. Despite the standardization proposal in favor of constant voltage recording, electrodermal recording systems using constant current are still in use. Advantages and disadvantages of either method are comprehensively discussed by Boucsein (2012, pp. 247–251). In the case of using the constant current method, the current density should be limited to 10 μA/cm^2 to avoid possible sweat gland damage (Edelberg, 1967). The application of a constant current to the skin will produce measurements that are proportional to skin resistance. They can easily be transformed to SC values as follows: *G* (in μS) = 1000/R (in kΩ). This should be performed point by point with skin resistance level data before further parameterization (Boucsein, 2012, p. 177).

1.3. Exosomatic Measurement with Alternating Current

The measurement of EDA with alternating current (AC) instead of DC has been rather infrequently used so far, despite having the property of circumventing some problems with using DC for conductance measurement. Electrodes become polarized by DC current flow as described in Section 2.1. Polarization refers to the counter electromotive force (e.m.f.) that is generated at the electrode metal surface, as a result of which the electrodes behave like a rechargeable battery, with a voltage opposing the applied voltage. Thus, the counter e.m.f. reduces the current and introduces an error in the recording of SC, because it must be subtracted from the applied voltage when the conductance is to be calculated. The constant voltage is recommended to be 0.5 V, but different constant voltage levels will generate different current flows, different electrolysis, and different counter e.m.f.s. It is therefore reasonable to believe that the DC system is nonlinear in the sense that measurements results are dependent on the applied voltage. The size of the counter e.m.f. is unknown, and it is impossible to infer what portion of the recorded change in SC is due to skin conductance changes and what is due to the counter e.m.f. Thus, the DC recording system may be subjected to an unknown drift in electrodermal level (EDL) that is not related to skin tissue changes. Research is needed to determine the significance of this problem under the usual test conditions.

The use of so-called nonpolarizing electrodes (see Section 2.1) may only partially prevent polarization during DC recording. By contrast, electrode polarization is virtually eliminated when AC measurement is used. Because it continuously changes its polarity, AC polarizes the electrodes to a much lesser extent than DC. As a result, the electrolysis occurring before the polarity changes is negligibly small. For these reasons, AC measurement appears to be superior to DC measurement with respect to electrode polarization and also possible effects of the applied voltage on biological membranes (Edelberg, 1967). We have not recommended an immediate change from DC to AC recording because empirical demonstrations of the superiority of AC for typical skin conductance studies are not yet available. However, if such data become available, a switch to AC measurement may well be appropriate. In the meantime, the use of a polarity reversal switch (see Section 2.1) provides a way to partially address this problem.

AC measurements may also provide deeper insights into the electrical processes underlying EDA. The applied voltage influences the capacitive elements in the skin (associated with biological membranes), which have the ability to store electric charge. This ability is measured as their capacitance (*C*). During the application of an AC to the skin, the current flow is reversed during each cycle, thus continuously charging and discharging the capacitors in the skin. The charge on the capacitor increases as long as the current is flowing in a given direction, with the charge reaching its maximum just as the current stops and begins to reverse direction. As a result, the maximum current is reached before the buildup of the maximum voltage in the capacitor (i.e., because current continues to charge the capacitor as long as it flows in the same direction). If electrodermal models such as depicted in Figure 1 are expanded by capacitive elements in the skin (e.g., Yamamoto et al., 1978, Figure 1.1), a lock-in amplifier[4] (Grimnes, 1982) can be applied in order to separate fast responses (e.g., increase of conductance by sweat duct filling) from slow ones (e.g., capacitive changes correlated with the hydration of the stratum corneum).

Within the range used for EDA measurement, the phase shift caused by the combined conductance and capacitance in the skin can be measured or calculated as the difference in the phase of the sine waves for current and voltage. The resulting phase shift is given by the phase angle φ, which can vary between 0° and 90° (see Section 2.5.3).

A full understanding of the outcome of an AC recording requires a little more mathematical comprehension than needed for DC recording. In a nutshell, the resistive part of the output generated by the application of AC is labeled impedance (Z) and measured in kiloohms, whereas the AC conductance is a part of the admittance (Y) and measured in microsiemens.[5] In a complex plane made up by a real and an imaginary axis, the corresponding Y and *Z* vectors may vary in length, but the phase angle φ will have the same numerical value, differing only in its sign (Schaefer & Boucsein, 2000, Figure 2). It has been empirically demonstrated by the latter authors that the phase angle response SφR is independent from using either effective constant voltage (resulting in SY) or effective constant current (resulting in SZ).

1.4. Conclusion

The three methods of measuring EDA described above can be assessed as follows:

- The measurement of *endosomatic* EDRs is the most unobtrusive method and may differentially reflect the various processes taking place during phasic EDA. It does not require special amplifying/coupling systems and can be performed by EEG or electromyogram (EMG) amplifiers that have a large enough input impedance (in case of DC amplifiers) or a long time constant in order not to distort the waveforms (in case of R-C coupled amplifiers). However, the resulting SPRs may be rather complicated for any straightforward interpretation.
- The measurement of *exosomatic* EDA with *direct current*, using a constant voltage system, is the most widely applied method in psychophysiology for observing both phasic and tonic electrodermal phenomena. However, some investigators are concerned that even with "nonpolarizing" Ag/AgCl electrodes (see Section 2.1) there will still be electrode polarization and dependency of the SC on the counter e.m.f. generation at the electrodes (see Section 1.3).
- Measuring *exosomatic* EDA with *alternating current* will circumvent the above mentioned problems of polarization and counter e.m.f. For research purposes, it would permit the determination of possible capacitive changes in both electrodermal levels and responses.

2. Techniques of Electrodermal Recording

Electrodermal recording may require special electrodes, electrode gels, and recording devices, which can be different from those that are convenient for other psychophysiological measures. Only the rather infrequently used endosomatic measurements can be performed with standard recording equipment. Those measurements, however, require a particular choice and pretreatment of an inactive recording site.

2.1. Electrodes

Electrodes constitute a biomedical sensor system. As an important factor for the quality of measurements, they deserve close atten-

4. Lock-in amplifier and phase-sensitive rectifier are synonymous.

5. The letters *Y* and Z were chosen as the last two letters of the alphabet.

tion. Electrodes for electrodermal recording are normally of metal, but can be also from other materials such as carbon. "Metal" is used here as a generic term, as it actually gets corroded at the electrode surface. It is important to use the same metal for the two electrodes in a DC-recording system, because a potential difference will be generated by different metals, different stages of corrosion, or both, which causes a counter e.m.f. and thus electrode polarization. Furthermore, pairs of electrodes should show a minimal bias potential, which can be measured in the absence of an applied voltage (Fowles et al., 1981).

In exosomatic DC recording, an electrode pair is connected to an external voltage of 0.5 V. The electrodes therefore carry a DC current and become anode and cathode in an electric system. The electrodes are polarized by electrolysis (the passage of a direct current through the ionic solution by the applied voltage and the subsequent electrochemical reactions at the electrodes). In endosomatic recording, the electrodes are used to pick up potential differences between skin locations. These electrodes do not carry an imposed current and therefore are not polarized.

For electrodermal recording, the use of sintered silver–silver chloride (Ag/AgCl) electrodes is standard in order to minimize both polarization of the electrode and the bias potential between electrodes. Because of those properties, these electrodes were sometimes labeled "nonpolarizing," a description, however, that is not completely accurate inasmuch as polarization remains a problem. Ag/AgCl electrodes are commercially available with a sintered bulk volume sufficient to make them reusable because the surface can be abraded many times. They are fixed with a double-sided adhesive collar to the skin (Boucsein, 2012, p. 110). These electrodes are much more expensive than disposable AgCl electrodes with very thin layers of silver and silver chloride in order to reduce cost. With large DC currents or low DC current in prolonged use (monitoring), the transferred electric charge may be high enough to strip off the AgCl layer at the cathode and increase the layer at the anode. After some time, large bias voltage levels may result. Fowles et al. (1981) recommended the use of a polarity reversal switch to reverse the DC current flow within a recording session (e.g., every 10 or 15 min), thus minimizing possible polarization effects. The use of a polarity reversal switch reverses the way the electrodes are plugged in, making it as if the electrodes were exchanged with each other. This can, however, only be done between segments of a session, to prevent recording artifacts resulting from the switching process. They also recommended that electrode bias potentials should be monitored every 2 or 3 days, which can be performed by means of the Bias Voltage Test (see Footnote 6). Electrodes made from stainless steel may have the advantages of not corroding and also being mechanically strong, but they are more prone to polarizing effects than Ag/AgCl electrodes. Instead of metal, carbon can be used both for the wires and the electrodes to make them radiotranslucent or to obtain less material conductivity (MRI compatibility).

The following recommendations are given for the three different measurement techniques described in Section 1.4:

- Electrodes for *potential recording* without applied current: Without applied DC current, the electrodes serve only to measure an endosomatic potential difference and the current flow is negligible. It is important to perform the Bias Voltage Test mentioned below. However, the voltage measured should be negligibly small, preferably < 1 mV. Low drift Ag/AgCl electrodes are recommended.
- Electrodes for *exosomatic recording with direct current*: An EDR sensor system consists of at least two electrodes. The two electrodes are supposed to be equal in their properties. An important test for this is to check their half-cell potentials with the Bias Voltage Test.[6] With the applied DC voltage, the current flows and the two electrodes are polarized in opposite directions. The current level will gradually fall because the two electrodes will start to build up a counter e.m.f. (measured in volts) due to electrolysis. As noted above, the two electrodes and the electrolyte act as a rechargeable battery (see Section 1.3). Polarizable electrodes (e.g., bare metal surfaces) will rapidly reduce the current flow. So-called nonpolarizing electrodes (e.g., sintered Ag/AgCl) will be more stable and only slowly reduce the current flow. Ag/AgCl electrodes are recommended because of their stability. Details for making electrodes oneself are found in Fowles et al. (1981).
- Electrodes for *exosomatic recording with alternating current*: The metal–electrolyte contribution to the measured skin impedance SZ is not important for AC recording. The polarization impedance for one wet gel electrode is typically in the order of 400 Ω/cm^2 at 1 Hz, but it may be even lower with rough surfaces (Grimnes & Martinsen, 2008, pp. 264–269). SZ of the skin at a single electrode site is usually higher than 10 $k\Omega/cm^2$ and is, therefore, the dominating impedance (relative to the electrode impedance), as they are connected in series.

The most widely used EDA electrodes contain a metal disc set back in a cylindrical plastic case, which is filled with the electrode gel (see Section 2.3). The electrode–skin impedance is strongly influenced by the size of the electrolyte–skin contact area, also called the effective electrode area (Grimnes & Martinsen, 2008, p. 270) and not by the size of the electrode metal. However, the metal–electrolyte contact area should not be too small, because the artifact-producing generation of any counter e.m.f. increases with small contact areas and higher current densities. A problem that appears with long-term recording is that the effective electrode area may increase because the gel may gradually spread out on the skin, the corneum may become hydrated (and thus more conductive) beneath the adhesive collar used to attach the electrode, or both. This hydration-produced increase in contact area may be indistinguishable from psychologically interesting changes in tonic electrodermal measures and may also contribute to a gradually increasing danger of electrode detachment.

Electrode fixation is effected with adhesive tape or a foam ring around the electrode. Locating the electrode metal back (recessed) in the electrolyte compartment helps to avoid motion artifacts, which might result from the electrode fixation to the skin and the skin curvature at the recording site. It also helps reduce artifacts from movement between gel and electrode metal. Additional tape may be necessary depending on measurement conditions, especially with skin that is wet from sweating. Some electrode constructions involve electrolyte contained in a stiff cup so that outside pressure on the electrode will not squeeze out electrolyte, which

6. In a pair of electrodes that pick up a potential from or apply a current to body tissue such as skin, one electrode together with its electrolyte is called the half-cell of the electrode pair. The Bias Voltage Test is performed as follows: Two electrodes are placed in direct face-to-face gel-to-gel contact (without skin and without applied DC voltage). The measured DC voltage from the pair (bias voltage or difference between the half-cell potentials) should be negligibly small (<5 mV, except for endosomatic measurements, where it should be <1 mV).

otherwise would increase the electrode effective area and penetrate into the adhesive area.

The effect of any pressure, such as that exerted by fixation, the weight of the electrode, and protruding parts (e.g., wires), must be kept as low as possible. The recommended wiring is to use prewired electrodes with a plug or connector to the amplifier remote from the electrode. The electrode wire should not be able to exert any pull on the electrode, irrespective of its hand or foot position. For this purpose, the electrode wires can be fixed by tape to the skin, for example, 10–15 cm from the electrode, and there should be given an extra wire loop between the electrode and the first skin fixation.

Disposable electrodes may have some important advantages. They can be hygienic, hypoallergenic, antiseptic, and latex free. They can have a good fixation system, be stored many months in an unopened package, be produced in large production runs with uniform electrical characteristics, and have a snap-action connector or, even better, be prewired with the connector remote from the electrode. Pregelled models have the additional advantage that the metal–electrolyte interface is stabilized and ready for use. Of course the gel must be EDA compatible (ECG or EEG paste will not work; see Section 2.3).

The choice of electrode type, wiring, and electrolyte are dependent on the intended use. Measurement durations on the order of 30–60 min under close supervision are the typical situation, whereas continuous monitoring for a few days may require somewhat different methods of electrode technique (Edelberg, 1967).

2.2. Recording Sites and Pretreatment

Because nonthermoregulatory electrodermal phenomena can be most reliably and validly recorded from the glabrous (smooth, hairless) skin of palms and the soles, they constitute the preferred recording sites for EDA. Active electrodes are fixed either to the volar phalanges of the fingers or to thenar and hypothenar sites on the palms of the nondominant hand. The distal phalanges of the fingers should be preferred because of their greater responsivity (Scerbo, Freedman, Raine, Dawson, & Venables, 1992) and their greater sweat gland activity as compared to the medial and proximal phalanges (Freedman et al., 1994). For palmar endosomatic recordings, the inactive electrode is placed on the volar (i.e., inner) surface of the forearm. The recommended procedure for pretreatment of this site in the past, slight abrasion of the skin, essentially eliminates all potential and thus provides electrical contact with interstitial fluid. In principle, such abrasion could be limited to the corneum, but because of the risk of deeper penetration, we recommend abrasion only when using sterile electrodes to avoid the danger of transmitting diseases such as HIV or hepatitis.[7] An unabraded site on the volar forearm about two thirds of the distance from the wrist to the elbow provides a relatively inactive reference site (Venables & Christie, 1980, Figure 1.7).

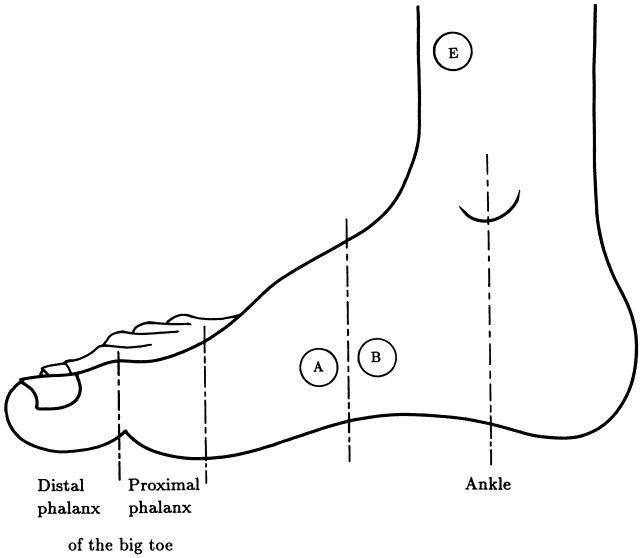

Figure 2. Recommended foot sites for EDA recording. Positions A and B are used for exosomatic recording; position E should be used as the inactive site for endosomatic recording. From Boucsein, W. (2012). *Electrodermal activity* (2nd ed., Figure 2.7, p. 107). New York: Springer. Reprinted by permission of the author and the publisher.

If both hands are unavailable (e.g., if they are needed for computer work), Edelberg (1967) recommended two sites at the inner aspect of the foot, over the abductor hallucis muscle adjacent to the sole of the foot and midway between the proximal phalanx of the big toe and a point directly beneath the ankle, for active electrodes, whereas in the case of endosomatic recording, the inactive electrode is fixed above the ankle (see Figure 2).

EDRs can also be found on nonpalmar–nonplantar sites, and they are, to a variable extent, correlated with the palmar EDRs (Edelberg, 1967). Recently, the volar side of the wrist has been used for electrodermal recording, especially when the whole EDA recording system was located in a wristwatch. Although these sites are not recommended because they reflect thermoregulatory rather more than psychophysiologically relevant electrodermal phenomena, they have been used in ambulatory recording (see Section 4.2).

There is normally no need for pretreatment of active recording sites, but the sites may be washed with lukewarm water prior to the electrode attachment. Washing with soap is not recommended because it may cause swelling of the epidermis. Precautions should also be exerted in using 70% ethanol because this may change the epidermal salt concentration. The latter may be necessary in case of extremely oily skin for preventing detachment of the adhesive tape used for electrode fixation.

2.3. Electrolytes and Skin Contact Area

The contact electrolytes are usually NaCl or KCl in the form of a wet gel or paste. For EDA recording, electrode gel or paste must contain a chloride salt, with NaCl being most often used. Concentrations in the range of 0.050–0.075 molar (0.3%–0.4% by weight) are preferred, because they approximate the concentration of NaCl in sweat that reaches the surface. As a result, any sweat that mixes with the paste is unlikely to appreciably alter the concentration of the NaCl at the interface with the electrode. In ECG recording, the

7. Skin electrodes can become infected by blood-borne diseases, and if applied to a new experimental participant without proper sterilization, can transmit a disease such as hepatitis C or HIV to that participant if the skin is not intact. Because of the long incubation time of some of these diseases, the source of the infection can be difficult to identify. A committee of the Society for Psychophysiological Research published guidelines on safety precautions to prevent such infections (Putnam, Johnson, & Roth, 1992). The danger comes from multiple-use electrodes that contact blood or serum through nonintact skin. This is the case in skin potential recording that establishes a reference by abrading or drilling the skin. Electrodes in such cases must be thoroughly sterilized between uses, not merely washed. In the case of skin conductance recording, the experimenter need only ascertain that the skin is intact where the electrode is placed. We recommend using disposable electrodes when possible, as that avoids any danger of infection.

salt may have a concentration of 3% by weight (0.5 M), not far from sea water that is well tolerated by our skin for many hours. Such salt concentrations are far too high for EDA recordings; therefore, pregelled commercially available ECG electrodes are not suitable for EDA recording. The same holds for gels sold for EEG recording.

The electrolyte and the tissue are ionic conductors, whereas the electrode metal, the electrode wire, and the connector are electronic conductors. At the interface between electrode metal and electrolyte a very thin (in the nanometer range) electric double-layer is formed in the electrolyte. The charge carrier shifts from ions to electrons and vice versa, which occurs in the double layer. The layer has two special properties: The DC half-cell electrode potential is generated there (see Footnote 6) and the layer represents an energy barrier that must be overcome for the electric current to flow and electrolysis to occur.

From the moment of establishing electrode–skin contact, the wet electrolyte penetrates into the stratum corneum. The result is a baseline (tonic) drift (increased SCL) that may take many minutes. Electrolytes may even penetrate into the ducts. It has been shown on nonpalmar–nonplantar sites that a high salt concentration gel results in negative (i.e., decreased conductance) conductance responses (Tronstad, Johnsen, Grimnes, & Martinsen, 2010). The most probable explanation is that the weak sweat electrolyte pushes out the strong electrode–skin-contact electrolyte. We can therefore not exclude the possibility that weak electrolytes such as used in EDA also penetrate the ducts and slow the reabsorption and emptying process of the ducts. To avoid the results of EDA recording being influenced by these processes, the electrodes filled with the electrolyte should be fixed to the skin at least 5–10 min before the recording begins. This delay also allows better electrical contact with the sweat gland ducts for assessing changes in conductance secondary to sweat responses. Individual differences in palmar sweating prior to application of the electrodes will affect the need for this electrolyte-produced hydration: The corneum will already be wet if there has been much sweating and will need to be hydrated if there has not been much sweating. Allowing time before beginning the experiment ensures that all participants will have a reasonable degree of hydration.

In general, EDA recording with dry electrodes, that is, without any electrolyte applied, is not recommended. Covering the skin with the electrode metal will result in a slow humidity buildup under the metal plate, and for a long time the electrode will be unstable and drift toward increased conductance. Also, surface sweating will produce a variable low resistance contact with the metal plate, strongly affecting the measure.[8]

2.4. The Influence of Hydration of the Corneum

Hydration of the stratum corneum is an important factor in SC recordings. The dry corneum conducts electricity poorly, but the conductivity increases appreciably with hydration. If the corneum is very dry, then most of the current necessarily flows down the sweat-filled duct,[9] placing a premium on surface sweating for the production of measurable SCRs. On the other hand, if the surface of the corneum is moderately hydrated, current can flow through the corneum and reach the portions of the duct that spiral through the corneum. With this improved electrical contact with the portions of the duct in the corneum, sweat gland responses that only fill the subsurface portion of the duct in the corneum will become more visible in the SC recording than would be the case with an extremely dry corneum. For this reason, at least moderate hydration of the corneum is desirable. However, extreme hydration promotes swelling of the corneum, producing pressure that, to some extent, makes the pore resistant to opening to permit sweat to reach the surface. According to Edelberg's (1993) model, sweat passing through the surface pores followed by subsequent closing of the pores contributes strongly to rapid recovery SCRs (see Section 1.1). One possible consequence of extreme hydration, then, is to retard this type of response and the release of sweat to the surface. Hence, this phenomenon of poral occlusion may significantly affect the SCRs being measured. It will have a greater effect in conditions of frequent and large sweat secretion (that normally would produce surface sweating) and a lesser effect when sweat gland responses are infrequent and of moderate amplitude (that would not produce surface sweating).

Four factors influencing hydration are important, of which two are natural and important biological phenomena. First, the equilibrium between water in the corneum and humidity in the surrounding air affects corneal hydration. Thermoregulation involving the skin and sweat glands on most body surfaces employs evaporation of water from the corneum to less humid air. The corneum will be more hydrated in humid air. Second, the corkscrew spiral of the sweat gland tube as it passes through the corneum is designed to promote diffusion of sweat laterally into the corneum, increasing peritubular hydration. Third, application of electrode paste provides a source of water that diffuses slowly into the corneum over time. Fourth, both the electrode paste and any collar or other tape used to attach the electrode will prevent normally occurring evaporative water loss, forcing retention of water and promoting hydration. The first process can be controlled by regulating humidity in the room, the second process will vary with the amount of sweating produced by the experimental conditions, and the third and fourth processes tend to increase with time. Needless to say, it is difficult to control these dynamic factors influencing hydration. Given that they will be somewhat systematically related to the passage of time, duration of electrode attachment is an important variable that needs to be controlled when comparing experimental conditions. Therefore, one should be aware that comparing experimental manipulations early and late in long recording sessions may be confounded with hydration (see also Section 4.2).

8. Healthy skin will, to a large extent, tolerate wet gel salt concentrations around 0.5% NaCl even during prolonged contact. In such cases skin reddening and irritation are more often found under adhesive areas than in the electrolyte contact areas. Also *hydrogel* (solid gel), which is used as contact electrolyte in ECG electrodes instead of wet gel, should be investigated as a possibility for future EDA recording. Hydrogel is an ionic material that does not wet the skin, and measurements have shown (Tronstad et al., 2010) that a solid gel may have little free water to exchange with the ducts and corneum. The hydrogel contact therefore will not have any tendency to fill the sweat ducts or disturb sweat reabsorption. The electrode effective area is better defined and stable.

9. Because the sweat glands have variable refractory periods and usually more than 100 ducts are covered by the same electrode, it is very likely that empty, semifilled and filled ducts are recorded simultaneously under most conditions. Because even an empty duct can have sweat films on its walls, its conductance may still be greater than zero. Hence, the concept of filled versus empty ducts oversimplifies a complex continuum, making a statistical approach necessary.

2.5. Recording Devices

The following description of recording devices is technically oriented and does not provide information about certain manufacturers. The devices offered by manufacturers can be checked by their potential user against the recommendations given below.

2.5.1. Endosomatic recording. Recording skin potentials does not require the special circuitry of exosomatic recording devices. An amplifier with a minimum of >10 MΩ, or even better a 100 MΩ, input impedance is required, which nowadays is standard for any EEG or EMG amplifier. However, standard amplifier techniques may not be suitable for SP recording. First, one must be able to lower the amplifier gain enough for SPL recording, which may require a range up to 500 mV per division. Second, in addition to amplifying the potential difference between the two electrode wires, the amplifier needs a third wire that is to be connected to a third electrode, functioning as a floating reference (formerly "ground"). If the participant is also connected to amplifiers recording other biosignals (e.g., EEG), each amplifier may have its own floating reference electrode. Often the most noise-free recording is obtained if each system has its own reference electrode, but selected reference electrodes may also be connected to seek for the best signal-to-noise ratio. This can be tried out in order to find the most noise-free recording in all the systems concerned. Third, because SPRs are of small size compared to the whole range of the SP signal, a backing-off voltage might be advantageous for recording SPRs with high resolution. Bridge circuits cannot be used here because an external voltage is not available. Therefore, backing-off has been accomplished by adding a potential of equal value but of opposite sign to the SPL, so that SPRs are amplified at a higher gain around an arbitrary zero point. Contemporary operational amplifiers combined with a resistor constitute a more suitable solution (see Lowry, 1977, Figure 2). In such a circuit, a current-to-voltage conversion is performed without a zero shift, so the measuring circuit is not disturbed.

2.5.2. Exosomatic recording using direct current. Electrodermal measurement with DC is accomplished by means of operational amplifiers (see Lowry, 1977, Figure 2). Although the circuitry can be used for both constant current and constant voltage recording, the latter is widely preferred in agreement with the recommendations of Fowles et al. (1981). The present committee does not intend to change this recommendation. However, under certain circumstances, constant current may have advantages over constant voltage recording (see Footnote 3).

Today's recording devices commonly use differential amplifiers (Grimnes & Martinsen, 2008, Figure 7.13). The difference between a differential and operational amplifier is that the former needs no feedback resistors. It has three input wires, two for signal pick-up electrodes and one for the floating reference electrode. Operational amplifiers amplify the potential variations of a single input signal with respect to the floating reference, which is common to output and input. The differential amplifier amplifies the difference between two input voltages. This voltage difference is independent of a reference electrode position, although a reference electrode must be used in order to keep the amplifier within its linear range. Because of the independence of a reference point, endosomatic contamination of exosomatic measurement (Edelberg, 1967, p. 27f) no longer is a problem.

Known resistors (with 1% precision) in place of the participant allow calibration of the equipment. Resistors of 1 MΩ and 200 kΩ provide calibration conductances of 1 μS and 5 μS, respectively, which is the range for SCRs. An additional resistor of 50 kΩ provides 20-μS calibration, the approximate range of SCL. Ideally, these tests are conducted and recorded as the session begins but before electrodes are attached and the results retained to document the proper functioning of the equipment in that session. This record of calibration can be invaluable if one should discover that the equipment has not been working properly and need to determine which records are valid.

2.5.3. Exosomatic recording using alternating current. Measurement with AC requires more elaborate instrumentation than DC recording, because the current flowing through the capacitive elements of the stratum corneum is measured in addition to the conductance AC. Because conductance and capacitance are physically in parallel, measurement of current using constant amplitude voltage excitation is preferred. In the simplest case, an AC source with a fixed frequency, for instance, 30 Hz[10] is used as signal source. AC current measuring devices can be constructed using an operational amplifier. The measured current signal is rectified and amplified, and separation of EDR from EDL can be performed similar to the DC recorded signal. An ordinary rectifier is not phase sensitive, so the output contains both conductive and capacitive contributions. A phase-sensitive rectifier can be used to separate these components. If the effective voltage applied to the skin is constant, the resulting voltage corresponds to skin admittance (SY), whereas if the effective current is kept constant, skin impedance (SZ) will be recorded. Such an AC recording device will measure the same phenomena as the usual DC recording and does not record possible capacitive changes in the electrodermal system. Its main advantage is avoiding electrode polarization or counter e.m.f.

If the recording of possible capacitive changes in the electrical properties of skin is desired, in addition to those that are only due to conductance changes, more refined AC measurement devices must be used, such as two phase-sensitive rectifiers, AC bridges, or two-channel lock-in amplifiers (Grimnes & Martinsen, 2008, pp. 237–241). Digital lock-in amplifiers use the multiplication of sine waves, whereas analog lock-in amplifiers are based on a phase-sensitive detector in series with a low-pass filter (e.g., Boucsein, Schaefer, & Neijenhuisen, 1989, Figure 3). For evaluating SZ, the output voltage of the recording device is coupled to an amplifier with adjustable sensitivity, rectified, and low-pass filtered (with 0.1 Hz or 1 Hz). In addition, the phase angle φ between AC current and voltage can be recorded by means of a phase-sensitive detector with the property of continuously adjusting the phase angle, thus acting as a zero-offset for the phase signal. Its output signal is also rectified and low-pass filtered with the same frequency limit as the SZ signal. Schaefer and Boucsein (2000, Figure 6) empirically demonstrated that the phase angle φ can be used for determining features of SφR, which are independent of the application of either constant alternating voltage or constant alternating current. More empirical research on this topic is required.

10. The use of AC frequencies of 10 Hz and more are recommended. Too low a frequency will give time for electrolysis to occur during each half cycle. On the other hand, the current flowing through a capacitor increases with the frequency of the AC current. Thus, frequencies between 20 and 30 Hz are recommended for reducing the capacitive current, which might be considerable at 100 Hz.

2.5.4. Simultaneous recording of skin admittance and skin potential from the same electrode. Using AC techniques also opens up new measurement methods such as the simultaneous measurement of skin potential and AC conductance (i.e., skin admittance SY) at the same electrode (Grimnes et al., 2011). Measuring skin potential has not become popular because the responses are often complex and difficult to interpret (see Section 1.1).

With modern electronic circuitry it is possible to measure conductance and potential simultaneously with the same electrode. Additionally, Grimnes et al. (2011) used a special method for combining SY with SP recordings from a single active electrode at a palmar site together with an indifferent electrode connected to a physiological NaCl bath in which the forearm was immersed. Their recording system used a small AC current, enabling the DC potential and SY to be recorded simultaneously at the same site. They found SPRs with diphasic sharp edges that did not appear in the SYR waveforms. Furthermore, the SPRs were more robust with respect to movement artifacts than the SYRs.

2.6. Signal Conditioning

As noted above, with DC recording the output in millivolts is proportional to the conductance of the participant's skin in microsiemens. A particular problem is that the phasic SCRs are small relative to the SCL on which they are superimposed. Therefore, it is difficult to monitor the smaller SCR changes embedded in the larger SCL. Separation of phasic and tonic parts of the EDA signal can be achieved in various ways. If the hardware and software have enough range and sensitivity to just record the SCL, then the SCRs can be accurately scored off-line.[11] With this solution, it still would be difficult to observe the SCRs on a monitor during data acquisition. However, several recording systems (e.g., Biopac) provide an autoscale function that ensures an optimal range for observing SCRs. If such a system is not available, separation of phasic and tonic components can be performed during recording by means of an automatic voltage suppressor (Simon & Homoth, 1978), which is easy to handle. Alternatively, one can employ one channel with DC recording at a relatively low amplification to measure SCL and a second channel using capacitance (or AC-) coupled input and greater amplification to record SCRs (Edelberg, 1967). The capacitance coupling effectively filters out standing voltages and very low frequencies, allowing only relatively higher frequency components to pass. With an optimal combination of resistance and capacitance, filtering out low frequencies can provide a relatively stable zero baseline without affecting the amplitude of the SCRs. This third option is described in greater detail in the following paragraph.

Separate capacitors are connected to each side of the output from the series resistor between that output and the input to the DC amplifier. Additionally, a resistor is connected between each capacitor and the input to the amplifier. Finally, a connection to the floating reference wire ("ground") is provided between each resistor and the input to the amplifier.

The key parameter for the R-C circuit in question is the time constant, the time required for a given DC voltage input to decline to 37% of its initial value. Short time constants filter out components of the SCR, adversely affecting its measurement. Long time constants allow more of the variation in SCL to pass, creating an unstable baseline that complicates measurement of the amplitude of the SCR. Fowles et al. (1981) considered a 6-s time constant as long enough to accurately measure the SCR while maintaining a fairly stable baseline. The time constant is defined as T (in seconds) = R (in ohms) × C (in farad). A transformation of this equation that is more convenient for EDA uses megohm and microfarad: T (in seconds) = R (in megohm) × C (in microfarad). Thus, a 6-s time constant is achieved with a 2-μF capacitor and a 3-MΩ resistor (connected as described above): $T = 3\ \text{M}\Omega \times 2\ \mu\text{F} = 6$ s.

3. Signal Evaluation

The EDA signal needs appropriate parameterization after being recorded, which is considerably different from other biosignals. Phasic and tonic EDA components need to be evaluated separately. The abbreviations for the extracted parameters should adhere to the nomenclature proposed by a terminology commission of the Society for Psychophysiological Research (Brown, 1967) and amended by Boucsein (2012, Table 1.1, p. 2). The first two letters refer to the method of measurement, that is, SP for skin potential, SR for skin resistance, SC for skin conductance, SZ for skin impedance, and SY for skin admittance. The third letter refers to level (L) or response (R). Nonstimulus-elicited responses are denoted by the prefix NS., for example, NS.SCRs for nonspecific skin conductance responses. Various suffixes can be added, such as freq. for frequency, amp. for amplitude, lat. for latency time, ris.t. for rise time, rec.tc for 63% recovery time, and rec.t/2 for 50% recovery time (see Footnote 12).

3.1. Phasic Electrodermal Measures

Short-lasting changes in EDA are called electrodermal responses (EDRs). They may be elicited by distinct stimuli or may occur in the absence of obvious external stimuli. In the latter case, they are called nonspecific EDRs (NS.EDRs) and are regarded as a tonic measure in the sense that they are used to index EDA over a period of time. In both cases there is a characteristic rise from initial level to a peak, followed by a decline (see Figure 7.5 in Dawson et al., 2007).

In the case of their elicitation by distinct stimuli, the latency of their onset (EDR lat.) can be determined in seconds. The observable range for EDR lat. frequently adopted is from 1 to 4 s after a stimulus change (either onset or offset). However, Levinson and Edelberg (1985) recommended shortening the measurement window to 1–3 s. Latencies longer than 4 s may occur, but latencies shorter than 1 s should be treated with caution because of system-immanent temporal delays, such as time required for processing the stimulus, autonomic nervous system nerve conduction to the sweat glands, and penetration of sweat through the ducts to the epidermis.

After an ascent time from the initial deflection to the peak, which normally varies between 0.5 and 5 s (Grings, 1974) and is seldom used as a separate parameter, the peak amplitude (EDR amp.) is reached. In case of SC measurement, the amplitude is expressed in microsiemens units and is often logarithmically or square-root transformed in order to normalize data.

The onset of a response can be determined by stepping back along the SCR curve to the point of maximum curvature. A method for accomplishing this can be found in the Appendices of Boucsein (1992, 2012), which describe a program SCRGAUGE written by Peter Kohlisch.

11. If the A/D conversion is performed with 16 bits, $2^{16} = 65{,}536$ steps will be available (instead of 4,096 steps with 12 bit A/D conversion). If for the AC-coupled (i.e., coupling with R-C components that form a high-pass filter) SCR, a full-scale value of 20 μS is chosen, the A/D conversion will result in 0.001 μS being represented as three steps of digital information stored in the computer, which can be reliably determined by the evaluation program. Such a resolution is far beyond the normally accepted amplitude criterion of 0.01 μS (see Boucsein, 2012, p. 138).

Sometimes it is important to determine whether a response has occurred—defined in terms of a minimum amplitude to be counted as a response. That need is especially true in the case of NS.EDRs, because (a) there is no defined period for a response to occur and (b) in many studies these responses are counted (sometimes to identify EDR nonresponding). In some analyses of stimulus-specific EDRs, a zero amplitude is entered for nonresponses and averaged with the value of actual responses. In that case, the distinction between no response and a very small response may not be important to determine. However, in other cases, investigators may wish to analyze data only for actual responses, making it necessary to determine whether a response has occurred. Consequently, stimulus-specific EDRs also may need to specify a minimum amplitude to define response occurrence. A minimum amplitude of 0.05 μS was common with hand scoring of EDR records, but with computerized scoring, the definition of the minimum amplitude has been as low as 0.01 μS. It is important to keep in mind the noise level of the equipment to prevent amplifier-created artifacts from being erroneously scored as EDRs. Similarly, if the research participant is active (e.g., performing a task), there may be small movement artifacts that would be scored as responses with a very low minimum response amplitude criterion. Thus, across studies the minimum amplitude varies from 0.01 to 0.05 μS, and the choice will be influenced by experimental conditions and equipment noise level.

Having passed the peak deflection, recovery begins, that is, a decline in the electrodermal reading in the direction of the initial reading before the response. However, EDRs mostly do not quickly reach the level from which they started, because the sweat elicited by EDRs increases the moisture of the corneum and thus the EDL (wet corneum is more conductive than dry corneum; see Section 2.4) or the duct empties slowly or both. Thus, only a portion of the amplitude has been "recovered." In view of this incomplete recovering process, recovery is measured as half-time recovery (EDR rec.t/2) or 63% recovery (EDR rec.tc), which refers to declining by 50% or 63% of the EDR amp.[12] Recovery time is measured in seconds.

In addition to these phasic measures, the area under the EDR curve can be calculated. Although this parameter necessarily correlates with amplitude, it is also affected by the duration of the response. It is much less commonly used than amplitude measures. A possible solution for obtaining area measures from overlapping EDRs has been proposed by Bach, Friston, and Dolan (2010), based on a convolution model of the EDL-corrected time integral.

Some authors prefer using the term *EDR magnitude* instead of EDR amplitude. However, in a strict sense, the term *magnitude* should be reserved for the average EDR amp. calculated from a series that includes zero responses (Venables & Christie, 1980).

Especially under conditions of high-intensity stimulation or stimuli following each other in tight sequence, overlapping EDRs are likely to be observed. Although the traditional evaluation of a superimposed EDR starting from its deflection on the recovery limb of the previous EDR (i.e., from the minimum value on the recovery limb as the new EDR begins) will lead to sufficiently exact results (Edelberg, 1967), mathematical deconvolution models came into use more recently (Benedek & Kaernbach, 2010).

12. The exponential decay of the recovery limb can be uniquely characterized by a parameter known as the time constant, which is estimated well by measuring the time it takes to recover 63% of the amplitude—hence the use of "rec.tc" for 63% recovery. This means recovering down to 37% of the amplitude (63% recovered, 37% not recovered).

3.2. Tonic Electrodermal Measures

There are two principal measures of relatively long-term tonic EDA states: skin conductance level (SCL) and nonspecific skin conductance responses (NS.SCRs). SCL refers to the level of skin conductance in the absence of phasic SCRs, whether the phasic SCR is an artifact or stimulus elicited. If phasic responding were occurring during the measurement of SCL, then the measurement would be artifactually distorted by the SCR. Ensuring that the SCL is not affected by an ongoing SCR requires either manual or automatic detection of the occurrence of phasic responses.

SCL is expressed in microsiemens units but is often transformed to log SCL in order to normalize the data. It is typically computed as a mean of several measurements taken during a specific time period, for example, during a 5-min nonstimulation rest period. During periods of discrete stimulus presentations, SCL may be measured during the silent interstimulus intervals, at the onset of the stimulus before a phasic SCR can possibly be elicited, or at the onset of phasic SCRs before the response has actually developed. In addition to the mean SCL, the within-participant changes in SCL over time—for example, during a rest period of several minutes—can be a useful measure. The change in SCL can be expressed in either absolute microsiemens units or as the slope of change over time.

NS.SCRs are phasic increases in skin conductance that have the same appearance as stimulus-elicited SCRs but are considered tonic measures because they occur in the absence of external stimuli and in the absence of artifacts such as movements and sighs. For this reason, NS.SCRs are sometimes referred to as "spontaneous responses" or "spontaneous fluctuations." Like SCL, NS.SCRs can be measured during periods of nonstimulation or during the silent intervals between stimulus presentations; however it is more common to measure them during a rest period. NS.SCRs are usually expressed as the number of responses per minute and can be computed as an average over several intervals (e.g., the mean of several 20-s periods between stimuli). Although the average amplitude of the NS.SCRs can be computed in addition to the frequency of responses, it is seldom done and it is not clear what unique information amplitude may provide. It is important to note that the measurement of NS.SCRs requires that one define the minimum change in conductance that qualifies as a response, and we recommend this to be between 0.01 and 0.05 μS (see Section 3.1). There is agreement that when a second response occurs before completion of a response, one would count two responses even though they overlap. In most cases the point of inflection in the curve of the first response is obvious to inspection. Mathematically, the inflection is defined as the point at which the slope of the rising portion of the first response stops decreasing and begins to increase (i.e., the second response has begun). Such an inflection is not found in the curve of a single response and thus indicates a second response.

SCL and NS.SCRs have been widely used as indices of sympathetic nervous system arousal, although it should be noted that they are only moderately positively correlated with each other. Nevertheless, consistent with sympathetic nervous system arousal, SCL and NS.SCRs are both heightened by administration of dextroamphetamine (Zahn, Rapoport, & Thompson, 1981), caffeine (Zahn & Rapoport, 1987), and threatening instructions (Bohlin, 1976). Moreover, both SCL and NS.SCRs are relatively stable individual differences, with test–retest correlations generally between .50 and .70 across periods ranging from a few days to a few months. Individuals who exhibit a high frequency of NS.SCRs (usually defined as above the median in response frequency) are considered

EDA "labiles," whereas those that exhibit few NS.SCRs (those below the median) are referred to as EDA "stabiles" (Crider & Lunn, 1971).

3.3. Sources and Removal of Recording Artifacts

Disruptions of the skin–electrode interface can be caused by mechanical pressures on the electrodes, loose electrodes, wire drag, flow of gel, and changes of the skin below the gel caused by the gel (see Sections 2.1. and 2.3). Further sources of artifacts are gross body movements, speech, irregular breathing, and also influences from outside the participant such as ambient noise or other disturbing stimuli (see Section 3.2).

It is desirable to review the record visually so that portions containing artifacts can be excluded from analysis (see Boucsein, 2012, pp. 183–186). In recordings less than 2 h long, it is feasible to scan the entire record and to exclude segments containing artifacts. For ambulatory records help from programs that detect artifacts is advisable. Such programs can locate segments where SCL levels exceed thresholds set for each participant and inform the operator to visualize these epochs and exclude them if they contain artifacts. Even in case of computer-assisted artifact detection and removal, it is advisable to visually inspect the detected suspicious SCRs and accept them or reject them as artifactual (Boucsein, 2012, p. 526). In any case, even semiautomated artifact removal procedures are time-consuming. Therefore, artifact avoidance should be given priority.

For very large data sets, rejection criteria for SCL levels or changes outside amplitude and time thresholds may be applied automatically without confirmation by an operator, in which case reports should specify how many data were rejected in the experimental categories being compared. Programs can detect mechanical electrode artifacts producing large, abrupt (less than a second) SCL changes. For example, Wilhelm and Roth (1996) developed a computerized evaluation method for artifacts based on their unusual steep rise times. They plotted bivariate distributions of SCR ris.t. with both SCR amp. and SCR rec.t/2 to identify outliers falling outside a range of 20% change in slope of the regression. These outliers were regarded as artifacts and were removed from the data before their further evaluation.

As mentioned in Section 4.2, for recordings of several hours or more, measurements from old and fresh electrodes should be compared to detect possible artifacts resulting from electrode deterioration.

4. The Use of Electrodermal Measures in Psychophysiology

Many methodological issues arise in applying electrodermal recording in various areas of psychology. These include, but of course are not limited to, such variables as stimulus characteristics and interstimulus intervals (ISIs) in experimental settings, but also to complex environmental conditions that appear in realistic environments. Similarly, specific problems arise from the increasing use of EDA recording within the magnetic field of a functional magnetic resonance imaging (fMRI) scanner. The following sections review some of the most common methodological issues.

4.1. EDA in Experimental Laboratory Settings

Electrodermal measures have been used in laboratory settings to address a wide range of topics, from the physiological constructs of arousal and pain to psychological constructs such as attention, memory, and decision making. Although an exhaustive list is not possible, the most common applications of EDA found in the literature include orienting responses (ORs) and habituation processes, autonomic conditioning, biofeedback, psychophysiological detection of concealed information, autonomic arousal, attention, temperament or personality, psychopathology (particularly schizophrenia and psychopathy), emotion, and, more recently, the role of emotions in decision making. Although we are unable to review the use of EDA in all of these individual areas (for reviews, see Boucsein, 2012; Dawson et al., 2007), there are important common themes and methodological issues related to EDA measurement in these contexts. In particular, use of EDA to assess a variety of psychological constructs relies heavily on the measurement of phasic EDA as a component of the OR and its habituation. We therefore discuss methodological issues in those areas in more detail.

The OR is a complex of behavioral and physiological responses elicited by novel stimuli or a change in stimulation (e.g., Öhman, 1979; Siddle, 1991; Sokolov, 1963). In the typical OR paradigm, an innocuous stimulus (the standard stimulus) is presented repeatedly with ISIs ranging from 20 to 60 s followed by a single presentation of a different stimulus (the novel or the test stimulus) and then followed by several repetitions of the standard stimulus. Typically, a large response (the initial OR) is elicited by the first stimulus, followed by gradually decreasing responses with repeated presentations (OR habituation) and an enhanced OR to the novel stimulus (OR reinstatement). Although many physiological measures have been identified as OR components, EDA measures are more consistent with OR theory than other OR components. For example, cardiovascular measures did not always display the expected habituation (e.g., Furedy, 1968). Furthermore, according to Barry's preliminary processes theory (e.g., Barry, 1988), the electrodermal response is the only clear-cut OR index.

Both initial OR and OR reinstatement have been assessed primarily by skin conductance amplitude, although other phasic response parameters (e.g., response latency) have also been applied. Measurement of habituation is, however, more complex, and researchers have used different definitions and measures to assess it. These definitions can be broadly classified into two types: (a) measures of the slope of the habituation curve, either by function fitting or by simply looking at differences in EDR amplitude between different points of the habituation series, and (b) measures of the completion of the habituation process, typically reflected by the number of trials until no responses are observed.

These two types of measures may yield different and sometimes inconsistent results. Furthermore both types have weaknesses. Fitting a function (typically a negative exponential function) for each participant is quite difficult because estimates of single responses at each trial are not sufficiently reliable. Estimating habituation functions for groups of participants is more reliable and can be used to examine the effect of various variables (e.g., stimulus intensity and stimulus significance) on the habituation. Typically, habituation functions are estimated by linear regression of response magnitude on the logarithm of the trial number. However, such a procedure yields estimates of slope (i.e., habituation rate) and intercept (i.e., initial OR) that usually are strongly correlated. This problem as well as attempts to estimate the absolute habituation rate are discussed by Siddle, Stephenson, and Spinks (1983). The completion of the habituation process is typically defined as the two or three consecutive trials that fail to elicit SCRs above a minimal level of responsivity (typically SCR amplitude of less than 0.01 μS; see Section 3.1). Both Barry (1990) and Levinson and Edelberg (1985) recommended the use of just two trials. Although this index can be

easily computed at the individual participant level, it is vulnerable to random fluctuations of the EDA. Because measures of EDA responsivity and habituation rely on the quantification of nonresponses, it is critical that researchers report their recording parameters and smallest recordable response value clearly so that data reported on nonresponding rates, trials to nonresponse, or both can be easily compared across studies.

Another important methodological issue that is linked to the issue of habituation is the order of stimulus presentation. In studies of simple orienting and habituation, a single type of stimulus is presented repeatedly, and the habituation rate is a relatively straightforward comparison of early trials to later ones. However, in more complex designs in which EDA is used to assess responses to different categories of stimuli, either with different signal values or emotional significance, it is imperative that the stimulus sequence be balanced such that habituation processes that may overlay or interact with the processes of interest do not differentially affect one stimulus category over another.

An aspect of OR theory that has attracted a great deal of attention is that stimuli that are significant or important for the individual elicit larger ORs, which habituate more slowly. Sokolov (1963) used the term "signal value" to describe these stimuli, but "significant stimuli" is more common. Significance can be defined in several ways, for example, by a classical conditioning procedure or by instructing participants to pay special attention to a particular stimulus. Indeed, research in classical autonomic conditioning has made an extensive use of EDA measures (e.g., Öhman & Soares, 1998). The stimulus significance effect on OR has been the focus of a theoretical debate (e.g., Bernstein, 1979; Maltzman, 1979; O'Gorman, 1979), and is the basis for one of the most promising applications of psychophysiology, namely psychophysiological detection of concealed information (known as the Guilty Knowledge Test [GKT], or the Concealed Information Test [CIT]; see Lykken, 1974, and more recently, Verschuere, Ben-Shakhar, & Meijer, 2011).

The CIT utilizes a series of multiple-choice questions, each having one relevant alternative or probe (e.g., a feature of the crime under investigation) and several neutral (control) alternatives, chosen so that an innocent suspect would not be able to discriminate them from the probe (Lykken, 1998). The relevant items are significant only for knowledgeable (guilty) individuals, and thus if the suspect's physiological responses to these items are consistently larger than to the irrelevant items, knowledge about the event (e.g., crime) is inferred. Although many autonomic measures have been used in the CIT paradigm, SCRs produced the most efficient differentiation between knowledgeable and unknowledgeable individuals (e.g., Gamer, 2011). A meta-analysis of GKT studies employing EDRs has yielded impressive estimates of detection efficiency (Ben-Shakhar & Elaad, 2003).

In both the autonomic conditioning and the CIT paradigms and in several other research paradigms, the major focus is on differential electrodermal responses (e.g., responses to CS+ vs. CS– stimuli or responses to the crime-related vs. neutral items). The use of differential or relative response measures is particularly important due to the large individual differences in EDRs. For example, a typical given SCR value can be large for one individual and small for another. Thus, when comparing different groups (e.g., in experiments using between-subjects designs) it can be helpful to transform raw SCRs into relative values. Several transformations of both tonic and phasic electrodermal measures have been proposed to deal with this problem. Lykken and colleagues (Lykken, 1972; Lykken, Rose, Luther, & Maley, 1966; Lykken & Venables, 1971) proposed a range correction procedure by which tonic responses of a given individual are divided by the *range* of tonic responses of this individual (i.e., the maximal SCL minus the minimal SCL) and OR-EDRs should be divided by the individual's maximal EDR. Although range correction can reduce error variance, thus increasing statistical power when comparing groups of participants, it relies on estimating maximal and minimal responses, which may be insufficiently reliable. An alternative method suggested by Ben-Shakhar (1985) uses within-individual standard scores or other transformations that rely on the mean rather than the individual's maximal response. An empirical comparison of range correction and standardization on data derived from the CIT paradigm showed that the latter has larger statistical power. Furthermore, several studies demonstrated that the use of standard scores computed within blocks of stimuli may reduce SCR habituation and consequently maintain the effects of the manipulated factors even when many stimuli are presented repeatedly (Ben-Shakhar & Dolev, 1996; Elaad & Ben-Shakhar, 1997).

Another methodological issue concerning phasic EDRs is the choice of ISI. Traditionally long ISIs have been used (e.g., between 20 and 60 s) in order to differentiate responses to consecutive stimuli. However, long ISIs have various disadvantages because they lead to a significant lengthening of the experiments and limit the number of stimuli that can be presented. In addition, long ISIs are inappropriate for other measures of interest. For example, response time and event-related potentials are typically recorded with much shorter ISIs, and attempts to use SCRs in combination with these other measures in the same experiment leads to suboptimal measurement conditions for one or all measures (see, e.g., Gamer & Berti, 2010).

Recent attempts to overcome these difficulties and apply SCR measurement to much shorter ISIs (i.e., 2–3s) have relied on mathematical deconvolution models (Alexander et al., 2005; Benedek & Kaernbach, 2010) or on modeling the SCR waveform with a combination of a sigmoid function and an exponential decay function, which are fitted to the data (Lim et al., 1997, 1999). In addition, Breska, Maoz, and Ben-Shakhar (2011) demonstrated that shortening the ISI within the CIT paradigm by 50% (from an average of 20 s to an average of just 10 s) has no effect on differential SCRs. Consequently, they recommended that when the focus of the study is on differential responding to one type of stimuli relative to others (e.g., novel stimuli, significant stimuli, conditioned stimuli, or targets vs. nontargets), the ISI can be relatively short. However, when the research is focused on overall SCR responding (e.g., comparing electrodermal responding of different populations or under different emotional conditions), the use of shorter ISIs may unduly attenuate the responses, and it is thus not recommended.

A final issue with regard to phasic EDA pertains to its use in the assessment of emotional processing. Here there is much interest in comparing emotional responses that occur outside of conscious awareness to those under volitional influence and regulation. In this case, researchers must be careful to employ designs that can distinguish emotional responding from more general orienting or attention or effort-based responses and must take care to equate the emotional stimuli on the arousal dimension.

In addition to phasic EDA measures, tonic measures have also been used to assess a wide range of psychological constructs. SCL and NS.SCRs have been particularly popular in studies of individual differences variables such as personality (e.g., Crider, 2008; Norris, Larsen, & Cacioppo, 2007), health vulnerability (e.g., El-Sheikh & Arsiwalla, 2010; El-Sheikh, Keller, & Erath, 2007),

and aggressive or antisocial behavior (e.g., Gatzke-Kopp, Raine, Loeber, Stouthamer-Loeber, & Steinhauer, 2002). The methodological issues surrounding the use of tonic measures are essentially the same as for phasic measures. For example, SCL and NS.SCRs both show patterns of habituation with stimulus repetition that are similar to the patterns observed with phasic EDA measures. However, because tonic measures are so frequently used in the study of individual differences, particular attention must be paid to the issues noted above regarding the transformation of EDA variables if individuals with significantly different baselines or range of responses are to be meaningfully compared.

4.2. EDA in Ambulatory Recording

Most studies using electrodermal measures take place in laboratories, where experimental conditions are carefully controlled. In this setting, standardized stimuli can be presented and the reactions of the experimental participant meticulously measured. Laboratory recording is limited in that the laboratory affords only an artificial representation of everyday life, and the time that a participant is willing to spend in the laboratory during waking periods is seldom more than 2 h. On the other hand, when situations are not structured and participants do their normal activities, uncertainty arises as to what to attribute variations in SC. A socially engaging conversation or an interesting new environment may cause fluctuations in SCL as great as might be elicited by stress or fear. Simultaneous video and audio recording or frequent self-reports might be necessary to understand the psychological meaning of those fluctuations. Intermediate between 2-h laboratory recording and unfettered 24+-h recording are structured situations with predictable timing, during which activities such as automobile driving or parachute jumping are performed.

Technical developments in the last few decades have made ambulatory recording of SC ever easier. Several companies have offered portable multichannel physiological recorders that include an SC channel. Ordinarily two electrodes are placed on the hand or fingers and cables go up the arm and down the trunk to a battery-powered amplifier–digital recorder attached to the waist. One company (Affectiva) makes a device where the amplifier–recorder is worn on the wrist like a watch with a dry electrode in contact with skin on the ventral wrist (for limitations, see Section 2.2).

Important issues in ambulatory SC recording are the stability of the electrodes and the influence of temperature (see Section 5.2) and physical activity. Turpin, Shine, and Lader (1983) compared a 0.05 M KCl solution in hydrating (methyl-cellulose) versus nonhydrating (polyethylene glycol) bases. When old and freshly applied electrodes were compared, no effect could be found over 3 h of recording in SCL or in the number and amplitude of SCRs to a reaction time task. The hydrating medium, however, resulted in significantly fewer and smaller SCRs after 3 and 6 h compared to the nonhydrating gel. Using a hydrating isotonic gel, Boucsein, Schaefer, and Sommer (2001) obtained reliability estimates of SCRs in different auditory habituation sequences from old compared to fresh electrodes after 24-h monitoring from 12 young women. The authors concluded that the ambulatory recordings lacked both reliability and validity after 24 h. More recently, Doberenz, Roth, Wollburg, Maslowski, and Kim (2011) found a decrease in SCL with an isotonic hydrating gel over 24 h that averaged somewhat less than 20%. Although dry electrodes have been avoided because of their uncertain contact with skin (see Section 2.3), they may warrant reexamination for their usefulness in longer recordings, where they may alter the skin less than wet electrodes.

Unlike heart rate, physical activity measured by an accelerometer correlated little with SC level in a study by Doberenz et al. (2011), which is consistent with Turpin et al. (1983), who examined the effects of somatic activity on SCL and SCR frequency and amplitude but found no significant correlations. Yet, if participants engage in strenuous physical activities for a minute or so, sweating and SCL will rise to dissipate the body heat generated. Taking into account more strenuous activity would require sensors that register quantitative and qualitative features of activity that are usually missed by current recording systems.

Ambulatory recording often lasts long enough to include both sleeping and waking periods, which need separate analysis and interpretation. Although sleep stages cannot be distinguished electrodermally, SCL as measured at the finger falls considerably during nighttime sleep. On the other hand, SCL at the wrist (and probably other areas of the body where temperature regulation effects predominate; see Section 2.2) falls little but shows prominent rises (sometimes called "storms," e.g., Lester, Burch, & Dossett, 1967) lasting 30 min or so, especially in the earlier part of the night (Roth et al., unpublished observations). These may represent thermal sweating, which is interrupted by REM sleep, during which temperature regulation is temporarily switched off (Heller, 2005).

Summarizing, emotional effects on SC are more sensitively recorded from electrodes on the palmar surface of the fingers or hand than from the ventral wrist, which is more affected by thermoregulatory changes. Because of uncertainty in the extent of electrode deterioration with wet electrodes, in recordings longer than 2 h it is advisable to test for deterioration in each participant by applying fresh electrodes at the end of the recording and compare levels between the new and old electrodes. Ambient temperature and physical activity should be recorded simultaneously with SC to allow for exclusion of periods where environmental temperature is significantly higher or lower than average and during and immediately after periods of strenuous activity. The effects of psychologically significant events and states during recording can only be understood if these events and states are assessed in synchrony with electrodermal measures. Participants should be able to report with button or key presses when such events or states occur.

4.3. Electrodermal Recording in a Magnetic Field

There has been an increase in using EDA recording in the magnetic field of an fMRI system. One of the primary challenges to such recording is that metal objects influence the magnetic field and vice versa. One solution is to take the EDA coupler and amplifier outside the fMRI scanner. In this case, precautions should be taken not to move the electrode wires, as moving a conductor in a magnetic field changes this field. Furthermore, long electrode wires serve as antennas for the high-frequency gradients used for the image acquisition, resulting in EDA signal loss due to amplifier limitations. One possible solution is using a custom-made nonmagnetic EDA recording device that can be placed in the magnetic field close to the individual to be measured (e.g., Blecker, Kirsch, Schaefer, & Vaitl, 2001).

Post hoc removal of the repetitive EDA signal contamination from the fMRI's high-frequency noise as performed by Critchley,

Elliott, Mathias, and Dolan (2000) may restrict the recording to larger SCRs (Williams et al., 2001). Therefore, Williams et al. (2000) used a fiber-optic system instead of metal electrode wires to protect the SCR recording from interference from radio frequency impulses in the fMRI. In addition, the loud noise generated by switching on and off the magnetic field can mask auditory stimuli given by the experimenter and is generally stressful for participants.

5. Influences on Electrodermal Recording

Other issues in electrodermal recording are demographic differences between participants (here called "internal variables") that might affect the data collected; external physical influences such as temperature, clothing, and relative humidity; and the effects of medication. The following sections address these issues.

5.1. Internal Variables

There are wide individual differences in both tonic and phasic EDA related to demographic variables such as age, gender, and culture. For example, older adults generally have lower tonic arousal levels and smaller phasic responses than do younger adults when tested across a wide range of ages (e.g., between 20 and 60 years of age). This pattern of results has been found for SCL (Barontini, Lazzari, Levin, Armando, & Basso, 1997) and for the frequency of NS.SPRs (Surwillo & Quilter, 1965). Phasic SCRs have also been found to be smaller in older adults than younger adults during auditory habituation and discrimination conditioning (Shmavonian, Miller, & Cohen, 1968) as well as during the presentation of highly arousing negative visual stimuli (Gavazzeni, Wiens, & Fischer, 2008). Age effects in infants and children have been less frequently studied, although there is evidence that children less than 5 years of age exhibit smaller phasic changes than older children. For example, Gao, Raine, Dawson, Venables, and Mednick (2007) measured phasic SCRs to neutral auditory stimuli in a longitudinal study of children at five different ages (3, 4, 5, 6, and 8 years of age). They found that SCR frequency and magnitude were significantly greater in the 6- and 8-year-olds than in the younger children and concluded that the greatest developmental increase in SCR orienting occurred between 5 and 6 years of age.

The effects of age may be due to peripheral or central nervous system changes with age, or both. At the periphery, the number of active sweat glands is lower in older adults (mean age of 69.5 years) than in younger adults (mean age of 25.3 years), which may partially account for the lower tonic and phasic findings (Catania, Thompson, Michalewski, & Bowman, 1980). Aging is also generally associated with reduction of brain gray matter including areas important for electrodermal activity (cortex, hippocampus, amygdala, and hypothalamus; Sequeira & Roy, 1993).

Gender differences also have been reported in tonic and phasic EDA, although the size and direction of the effects seem to vary depending on the nature of the stimulus situation. Women have been found to show larger SCRs to unpleasant pictures than men (Bradley, Codispoti, Sabatinelli, & Lang, 2001), and this has also been found among prepubescent girls (7–10 years of age) compared to boys (McManis, Bradley, Berg, Cuthbert, & Lang, 2001). These results have been interpreted as indicating that women generally respond with greater defensive activation than men to affective pictorial stimuli, although exceptions have also been found (Kring & Gordon, 1998). Whether gender differences in EDA reactivity are due to sociocultural or biological differences, or both, is yet to be determined. In contrast to unpleasant stimuli, men and women respond electrodermally similarly to pleasant pictures except for erotic stimuli, where men show significantly larger SCRs than women (Bradley et al., 2001). Gender differences in EDA laterality have also been reported. Males, unlike females, have been reported to display greater asymmetry between the hands with larger NS.SCRs and specific SCRs in the left hand (Martinez-Selva, Roma, Garcia-Sanchez, & Gomez-Amor, 1987), although the psychophysiological implications of this difference are not clear.

Ethnic differences have also been observed in EDA. For example, early research found higher resting SRL (lower SCL) in African-American children (mean age 7 years) and adults (mean age 22.9 years) than in age-matched Caucasian American children and adults (Johnson & Corah, 1963). The fact that there was no ethnic difference in other measures (EEG, heart rate, skin temperature, blood pressure, frequency of NS.SCRs) led the investigators to suggest that the basal EDA difference was due to peripheral effects such as thickness of the stratum corneum or the number of active sweat glands. Subsequent research has replicated the finding of lower SCLs among African Americans and generally, but not always, confirmed a lower density of active sweat glands (Juniper & Dykman, 1967).

Although the demographic effects reviewed here are not always consistent or large, it is clear that one should control or balance these differences across groups for which EDA is being compared. For example, if one compares EDA in groups with high and low anxiety levels, age, ethnicity, and gender should be equalized across groups. A more controversial method is to exclude certain participants from study because of demographic differences (e.g., to limit the study to male participants). However, depending on the goals of the specific experiment, it may be unethical to exclude participants due to ethnicity, gender, or age, in which case one should match groups on these variables. If the sample size is sufficiently large, one should separately analyze the effects based on age, ethnicity, and gender to test for generality of effects.

5.2. External Variables

Certain external environmental variables such as temperature and humidity have been investigated as sources of variance in EDA. Although the hands are not principal areas of thermoregulatory sweating, the effects of temperature on EDA have been studied in various ways, including manipulation of body temperature, manipulation of ambient temperature, correlation with ambient temperature, and correlations with seasons of year. For example, Maulsby and Edelberg (1960) manipulated the temperature of water in which the participant's finger was immersed while measuring skin resistance and skin temperature. They found that basal SRL varied inversely with skin temperature by 3% per degree of centigrade change. Although the relationship between log SRL and skin temperature was linear over a range from 20°C to 40°C, the effect of changes in skin temperature on elicited phasic skin resistance responses (SRRs) was more complex. Skin cooling initially increased SRR amp. whereas warming reduced the SRR amp., but these effects lasted only a few minutes and then were reversed.

The effects of manipulating ambient temperature on palmar SRL, sweat gland activity, and skin temperature recorded from the palm and the chest were studied by Wilcott (1963). Recordings were obtained from male participants before, during, and after they entered a heating cabinet where the air temperature was 150°F (65.6°C). Skin resistance declined, whereas sweat gland activity

and skin temperature increased significantly at both the palmar and chest sites when exposed to the high environmental temperature. Although the changes in sweating and SRL at the chest were greater than those at the palm, the results demonstrate that palmar EDA is sensitive to large changes in environmental temperature. In another study, SCR amp was found to increase when ambient temperature was increased sufficiently to raise deep body temperature by approximately 1°C (Lobstein & Cort, 1978).

Long-term ambulatory recording of skin conductance outside of a temperature-controlled laboratory has also found EDA measures to be positively correlated with changes in ambient temperature (Turpin et al., 1983, recorded for up to 7 h continuously; Doberenz et al., 2011, recorded for up to 28 h continuously; see Section 4.2). Both of these studies found increased frequency of NS.SCRs with rising ambient temperature, but only on a between-subject basis. Whereas Turpin et al. did not find temperature to be correlated with SCL, Doberenz et al. obtained strong within-subject correlations of ambient temperature with SCL, SCL standard deviation, coefficient of SCL variation, and frequency of NS.SCRs. The authors suggest that the stronger within-subject effects were apparent because the EDA and ambient temperature were measured over short time periods (1-min epochs), whereas the between-subject effects involved much longer time periods (hours).

Outside temperatures change with season of year and may influence EDA even when tested within the laboratory. Wenger, for example, found that autonomic measures varied with season of the year to such an extent that he discontinued testing during the summer months (cited by Wenger & Cullen, 1972, p. 537). Wenger's laboratory was in the state of Ohio, in a temperate climate. Venables and Mitchell (1996) examined effects of season of year in their study of children and young adults in the Island of Mauritius, which has a southern tropical climate. Although laboratory temperature was kept relatively constant, there was a significant interaction between season of testing and gender of the participants. In the hot season, females exhibited larger SCR orienting responses than in the cold season, whereas this was not true for males. The authors note that this may be a chance finding or it may indicate that females are more responsive to environmental temperatures than males.

All in all, although palmar eccrine sweat glands are not as sensitive to temperature as those on other body sites, they are definitely influenced by temperature. Therefore, in the laboratory study of EDA it is important to keep temperature as constant as possible and, in studies outside the laboratory, it is important to statistically correct for differences in ambient temperature.

Relative humidity may also influence EDA results. Venables (1955) reported a curvilinear relationship, that is, a negative correlation between SCL and humidity from 54% to 66% but positive correlations below 54% and above 66% relative humidity. No connection between EDA and humidity was found by Fisher and Winkel (1979). In their Mauritian study, Venables and Christie (1980) obtained age-dependent correlations between various EDA parameters and humidity. The influence of air pressure on EDA is even less clear. Wenger and Cullen (1962) found a significant, albeit low, correlation between air pressure and SCL only for their male participants.

5.3. Medication Effects

In both laboratory and ambulatory recording, medication is a serious source of possible artifact. Both prescription and over-the-counter medications can exert significant effects on skin conductance levels, and probably on reactivity as well. In developed countries at least, adult volunteers for scientific studies typically have taken one or more medications, intoxicating substances, and caffeine-containing drinks in the 72 h before testing. Many common medications have anticholinergic side effects affecting SC directly, whereas others influence emotion, cognition, or sleep in a way that affects SC indirectly. Nonpsychiatric medicines with marked anticholinergic side effects include medications for allergies, colds, insomnia, stomach upset, and glaucoma. Psychiatric medications with anticholinergic properties include first- and second-generation antipsychotics and antidepressants. Not just tricyclic antidepressants have anticholinergic properties but also selective serotonin reuptake inhibitors (SSRIs) and other types of antidepressants. Whether a specific medication has anticholinergic properties can be looked up in annually updated lists of information about prescription and nonprescription medications (e.g., Hamilton, 2012).

Because the experimenter cannot ethically prohibit medically prescribed medications and because short-term omission of doses can lead to withdrawal and rebound effects, one cannot avoid medication effects by simply forbidding participants to take medications even for a short period. At the least, the experimenter should ask participants to list the names, doses, and times of all medications taken in the week before testing and the day of testing. Experimenters should summarize this information in their reports. Unfortunately, it is usually impractical and expensive to confirm what the participant said with urine or blood testing. Participants who have taken medicines with moderate or strong anticholinergic properties at the time of testing must be excluded from analysis. In the case of SSRIs with mild anticholinergic properties, potential bias toward finding lower skin conductance levels should be acknowledged in the report.

6. Summary of Publication Recommendations

Published reports must contain sufficient detail to allow other experimenters to try to replicate the reported results and to help explain failures of replication. Given the limited space that journals provide, recommendations will be summarized below for both necessary and optional recording and environmental procedures to be reported in publications of studies using EDA.

First and above all, the *method of measurement* has to be specified: endosomatic or exosomatic, direct or alternating current (if any) applied to the skin, and constant voltage or constant current. The applied voltage (or current) must be noted. If commercially available instrumentation has been used, the manufacturer and instrument type should be mentioned. Furthermore, calibration procedures should be specified.

Second, methods of *signal conditioning* and storage need to be specified, including procedures for separating EDL from EDRs, if applied, time constants of amplifiers, separate grounding procedures, if used, A/D conversion rate, and sampling frequency (for EDL and EDRs if stored separately).

Third, *recording sites* should be specified for active and inactive electrodes (if applicable). If the sites were pretreated, the procedure should be reported in detail. Also essential is providing details for *electrodes* and *electrolytes* that were used, such as electrode metal (e.g., sintered Ag/AgCl), area of contact (either in square centimeters or diameter), method of fixation (e.g., double-sided adhesive tape), details of the used electrolyte, such as type of gel or base, ionic type and concentration (e.g., 0.08 M or 0.5% NaCl), or, in the case of disposable electrodes, brand and type plus as much of the above mentioned information as is available from the manufac-

turer. It is important to know how long electrodes were attached before the recording started and how long they stayed in place. Details of how polarization was controlled and how electrodes were stored should be given if available. In the case of DC recording, we recommend using a polarity reversal switch between segments within a session.

Fourth, *signal evaluation* needs to be reported in detail, whereas the sampling rate (for tonic and phasic measures separately, if different) and specification of time windows for tonic and phasic measures (e.g., latency windows for EDR onset being 1–4 s after stimulus onset) are mandatory. For EDRs, a minimum amplitude criterion must be specified and reported (e.g., 0.01 μS for SCRs to be scored). The standard terminology mentioned in Section 3 should be adhered to. The term *EDR magnitude* should be reserved for the average amplitude calculated from a series of responses that include zero amplitudes. Any treatment of superimposed EDRs should be specified. Methods of detection and elimination of recording artifacts should be described if applicable.

Besides the usual details to be reported about procedures for laboratory and field settings, it is important for EDA measurement to specify *baseline conditions* in detail, including length and statistical treatment during EDA data evaluation. The *gender*, *age*, and *ethnicity* of the participants (e.g., number, range or mean, and standard deviation) are essential for comparison with EDA results from other studies. *Medication* or *drug use* (including caffeine intake before participation in the study) need to be reported as well. Clothing as well as inside and outside *temperatures* and their possible changes during the recording periods should be reported in as much detail as possible. If available (e.g., in case of room air-conditioning), *relative humidity* should be reported as well.

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(Received February 28, 2012; Accepted March 1, 2012)