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MEASURING ELECTRODERMAL ACTIVITY AND ITS APPLICATIONS IN JUDGMENT AND DECISION-MAKING RESEARCH

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The skin has electric properties that change on the relatively short time-scale of seconds and are closely related to psychological processes. These characteristics of skin, known for more than 100 years, have been widely used in research (see also Chapter 13). Changes in electrodermal activity (EDA) and skin conductance are related to changes in eccrine sweating which are, in turn, related to activity in the sympathetic branch of the autonomic nervous system (ANS). Accordingly, EDA measures have been used to study psychological processes related to sympathetic arousal. For example, skin conductance has become an important tool in studying affective processes because the ANS plays a significant role in emotion and motivation. While increasingly direct methods of assessing neural activity have been developed recently (e.g., fMRI and PET), skin conductance is still often used as a proxy for neural and brain activity because it is relatively cheap and can be measured unobtrusively, reliably, and accurately.

It is important to note that skin conductance is a multifaceted phenomenon and does not reflect a single psychological process. Thus, EDA and skin conductance have been used in a wide array of behavioral and neuroscientific research, serving as an indicator of attention, habituation, arousal, and cognitive effort in many different subdomains of psychology and related disciplines. In judgment and decision-making (JDM) research, skin conductance is often used as an indicator of affective processes and emotional arousal. Therefore the renewed interest in skin conductance in JDM is most likely related to the renaissance of affect and emotion in JDM in general, as part of what has been termed the emotions revolution (Weber & Johnson, 2009).

Skin conductance is well suited as a process tracing method. It can be measured virtually continuously and relatively unobtrusively. Further it provides information about otherwise hidden cognitive and affective processes that reflect the ways in which people make decisions and form judgments. It follows that skin conductance is a viable method in process tracing studies as it can serve, for example, as an indicator of the involvement of affective and emotional processes in judgment and choice. However, there are several peculiarities about the nature of skin conductance that one has to be familiar with and take into account in order to measure and interpret it successfully. The main goal of this chapter is to give an introduction to the use of skin conductance in JDM research with a focus on providing concrete and hands-on advice for the researchers who are unfamiliar with this psychophysiological measure but are interested in using it in their own research.

In this chapter, we focus on the type of EDA measurement and indicator most commonly used in JDM research—the skin conductance response (SCR). Concentrating primarily on advice regarding the practical steps involved in using skin conductance, we give only a brief overview of the physiological background of EDA, and then delve into pragmatic issues concerning its assessment. Our discussion of practical concerns starts with a description of the needed equipment, the setup of the skin conductance acquisition, and electrode placement, followed by considerations regarding task and study design, and ends with explanations of approaches for the preprocessing and statistical analysis of skin conductance data. We give most attention to more traditional and standard ways of study design and data analysis. However, we also briefly outline more recent—sometimes called model-based—data analysis approaches and we give some pointers towards the relevant literature and toolboxes so that researchers interested in using these more advanced methods have some starting points to delve into these approaches. It is important to mention that there is compelling evidence that some of these more recent methods may outperform more conventional analysis in terms of their sensitivity (see, e.g., Bach, 2014). Furthermore, these newer approaches are likely to be appropriate for a wider range of experimental designs (such as rapid-event designs). We hope that our chapter can help the reader make an informed decision about how to approach their analysis. Thus, while we focus here on the more conventional analysis approach (see also the 2012 recommendations by the Society for Psychophysiological Research, published in Boucsein et al., 2012), we strongly recommend that readers also look into the more recent analysis approaches. In the last section of our chapter, we list some recommended literature, including the excellent volume by Boucsein (2012) which gives detailed information about virtually all aspects of EDA.

Electrodermal Activity and Skin Conductance: Terminology and Background

Different terms have been used in the literature to refer to aspects of electrodermal activity and skin conductance, sometimes interchangeably. Thus, some clarification is in order. In 1967, the Society of Psychophysiological Research (Brown, 1967; see also Boucsein, 2012; Boucsein et al., 2012) published a proposal for a standardized terminology that has been widely accepted. The term electrodermal activity (EDA) was introduced by Johnson and Lubin (1966) and refers most generally to all (passive and active) electrical phenomena in the skin, while skin conductance is one form of EDA. Specifically, the term skin conductance refers to how well the skin conducts electricity when an external direct current of constant voltage is applied. Skin conductance is measured in microsiemens (μS).[1] Other measures of EDA are distinguished based on technical aspects of the assessment: EDA recordings that do not use an external current are called endosomatic, while recordings that do use an external current (such as skin conductance) are called exosomatic. Exosomatic techniques are further distinguished by whether a direct current (DC) or an alternating current (AC) is used. DC measurement that keeps the voltage constant is called skin conductance, as it reflects how well the skin conducts a current. DC measurement that keeps the current constant is called skin resistance, as it reflects the electrical resistance of the skin. For the case of AC, keeping effective *voltage* constant results in the measure of skin admittance, while keeping effective *current* constant results in skin impedance.

As previously mentioned, skin conductance is the most commonly used measure in JDM and thus we focus on it here. Skin conductance can be divided into tonic and phasic phenomena. The main differences between these phenomena are related to their time-scale and their relationship to the evoking stimuli.

Figure 11.1 shows a raw skin conductance signal from one participant in a risky decision making experiment using the "hot" Columbia Card Task (CCT; Figner et al., 2009; Figner &

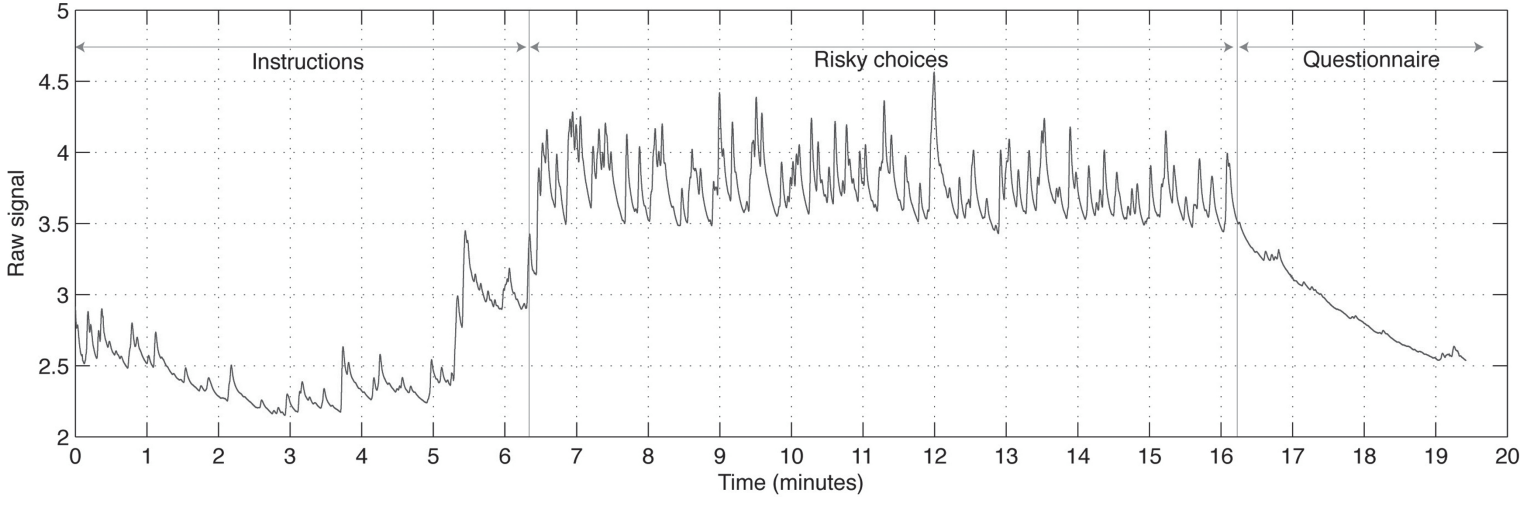

FIGURE 11.1 Raw skin conductance signal from one participant over the course of an experiment using the hot version of the Columbia Card Task (see Figner, Mackinlay, Wilkening, & Weber, 2009; Figner & Weber, 2011).

Weber, 2011).[2] The first 6 minutes of the session were used for administrative tasks, instructions, and practice trials. Then, starting at minute 6.2 and ending at minute 16.2 (see the area between the left and right vertical gray lines in Figure 11.1), the participant made incentivized risky choices in the computer-based hot CCT, which gave the participant real-time feedback regarding the outcomes of their choices. From minute 16.5 on, the participant filled out a questionnaire. In these 20 minutes of skin conductance data, one can see an overall and relatively slow drifting of the signal on which there are superimposed short (i.e., over the span of a few seconds) changes in skin conductance (seen as sharp peaks in Figure 11.1).

The longer-term manifestations are tonic, seen in the relatively low overall level in the "Instructions" and the "Questionnaire" phases versus the relatively elevated level during the "Risky choices" phase. The most common measure of this aspect of the data is the skin conductance level (SCL). This measure describes the overall conductivity of the skin over longer time intervals, typically ranging from tens of seconds to tens of minutes.

Within (and largely independent of) these different SCL levels, many sharp peaks in skin conductance can be seen. These short modulations in the signal are phasic phenomena and each peak represents an individual skin conductance response (SCR).[3] An SCR is a discrete and short fluctuation in skin conductance that lasts several seconds and usually follows a characteristic pattern of an initial, relatively steep rise, a short peak, and then a relatively slower return to baseline (see Figure 11.2). SCRs reflect the higher-frequency variability of the signal that is modulated on top of the slower changes in SCL.

In traditional analyses, SCL is typically operationalized by taking the average of several discrete measurement points distributed across the time window of interest (Boucsein, 2012). These measurement points should not be taken during an SCR (as this would lead to an overestimation of SCL), complicating automated approaches to quantify SCL.[4] In contrast to the SCRs, it is assumed that the SCL is *not* directly related to particular stimuli, but indicative of a more general level of arousal. Accordingly, since not all observable SCRs are directly related to an observable stimulus, a second, though less common, measure of *tonic* skin conductance has been suggested—the frequency of sometimes called non-specific (also called spontaneous) SCRs per time unit (usually per minute; typically, 1–3 per minute of these non-specific SCRs are observed during rest, Dawson, Schell, & Filion, 2007). As pragmatic criterion whether a SCR is specific (i.e., related to a stimulus) or non-specific, Boucsein (2012) suggests that SCRs that start more than 5 seconds after the end of a stimulus should be categorized as non-specific. We focus on SCR, the main indicator of *phasic* changes, because it is more commonly used in JDM research and typically will be better suited for process tracing studies due to its relatedness to specific events. SCR can also be operationalized across shorter time intervals than SCL (for a study using both SCL and SCR, see Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004). SCRs have been quantified using various characteristics and measures (see Figure 11.2, and Boucsein, 2012). The onset latency (lat.) is the time between the onset of the stimulus and the start of an SCR, typically 1 to 3 sec. The rise time (ris.t.) is the time between the onset of the SCR and its peak amplitude, typically also 1 to 3 sec. The amplitude (amp.) is the difference between the conductivity at the onset (the baseline) and the peak. The recovery half time (rec.t/2) is also sometimes used but it is highly correlated with rise time and therefore somewhat redundant (Venables & Christie, 1980). Frequency (freq.) of SCRs per time unit is another measure to quantify skin conductance responses. We will focus on the measures most commonly used in JDM research, which are amplitude (particularly in older research) as well as the more recent indicator *area bounded by a curve* (see Figure 11.6 and explanations later). This latter measure is better suited for automated data analysis as it captures both the amplitude and

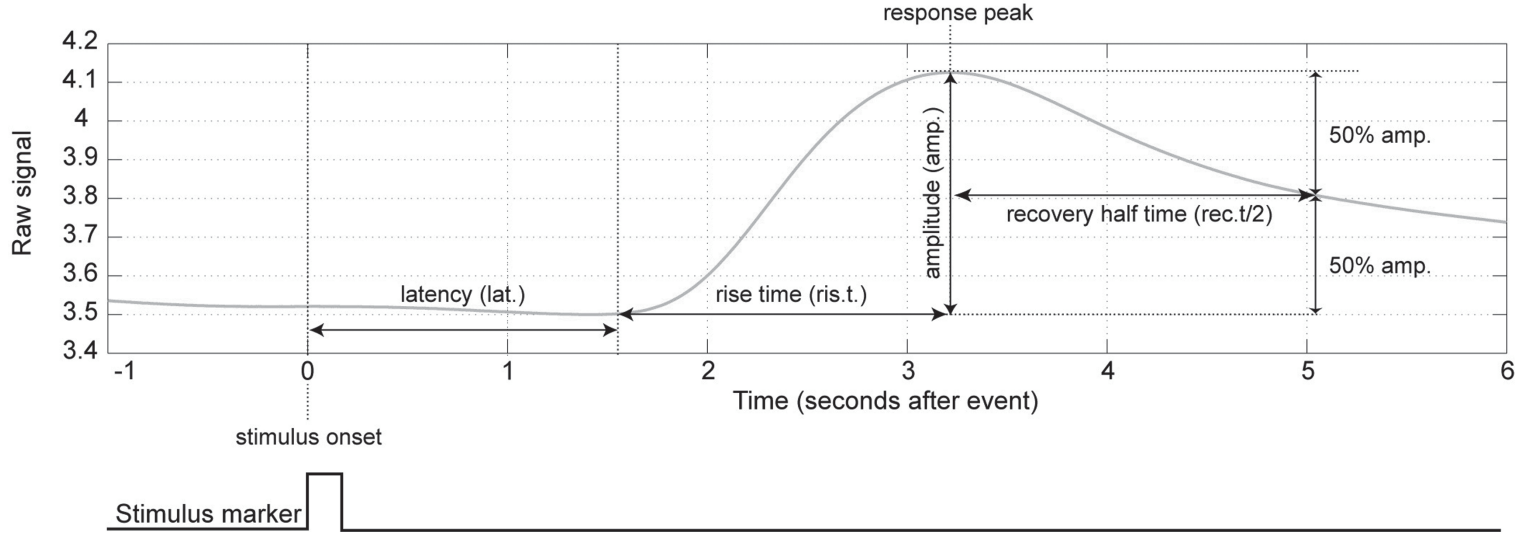

FIGURE 11.2 Raw unfiltered skin conductance signal, showing components of an SCR that can be used to quantitatively characterize SCRs. A stimulus marker corresponding to the participant turning over a loss card is also shown as part of the time course.

temporal characteristics of an SCR, and therefore is likely to be a more valid indicator than either aspect alone.[5]

Physiological and Psychological Processes

Changes in skin conductance are related to the activity of eccrine sweat glands, innervated by sympathetic nerves. Changes in skin conductance reflect secretion of sweat from these glands. As sweat is an electrolyte solution, the more the skin's sweat ducts and pores are filled with sweat, the more conductive the skin becomes. The sympathetic branch of the ANS controls eccrine sweating, and thus skin conductance reflects the arousal of the sympathetic ANS that accompanies various psychological processes. The mechanisms and pathways involved in the central nervous control of eccrine sweating are relatively complex (Boucsein, 2012; Critchley, 2010). A recent fMRI study suggested that SCL and SCR are related to activity in different brain areas (Nagai et al., 2004).

While the central origins of the ANS are within the hypothalamus and the brainstem, other parts of the brain such as the amygdala, the hippocampus, the basal ganglia, and the prefrontal cortex have been found to be involved in the control of eccrine sweating. These "higher" areas are part of the limbic and paralimbic networks, which are crucially involved in affective processes. Thus it is not surprising that skin conductance is often used as an indicator of emotional arousal and other affective processes. Interestingly, it has been shown that these higher brain areas are not necessary for reflex SCRs to non-emotional stimuli such as deep breaths and orienting stimuli such as a loud noise, but they are necessary for SCRs in response to stimuli that have acquired emotional value through experience, e.g., in classical conditioning (Naqvi & Bechara, 2006; Tranel & Damasio, 1989, 1994).

Typically, skin conductance is measured from the volar[6] surfaces of the fingers or the palms of the hand. For example, two electrodes are attached to the index and middle finger of the non-dominant hand (thus allowing the participants to use their dominant hand to handle a computer mouse, fill out a questionnaire, etc.) and a small constant voltage is applied. The current is imperceptible to the participant. Differences in skin conductivity are revealed by the amount of current that passes between the electrodes. As an alternative to measurement on the palms of the hands, skin conductance can also be recorded from the soles and inner sides of the feet; this method is called *plantar* skin conductance, in contrast to *palmar* skin conductance recorded from the inner surface of the hands. Plantar skin conductance is used, for example, when the participant needs both hands for the experiment or sometimes in fMRI studies when the electrodes or their leads might interfere with the scanner environment. The palms of hands and soles of the feet are best suited for measuring skin conductance as they are easily accessible and also have a high density of eccrine sweat glands. Importantly, eccrine sweating on the volar surfaces is different from other locations, as it has been suggested that sweating in these skin parts is strongly related to mental processes (*emotional sweating*, e.g., in response to both positive and negative events as well as for anticipated and experienced outcomes; Boucsein, 2012), rather than thermoregulation.

In the psychological literature, EDA measures have been used in both normal and clinical populations as indicators of a wide range of underlying psychological processes, such as orienting responses (e.g., Uno & Grings, 1965; Williams et al., 2000), habituation (e.g., Sokolov, 1963), classical and operant conditioning (e.g., Delgado, Gillis, & Phelps, 2008), and as indicators of information processing and cognitive effort (e.g., Dawson, Filion, & Schell, 1989; Nikula, 1991). In JDM research and related work, it appears that SCR is most often used as an indicator of affective processes, and in the following section we will present some of the more recent work, including our own. Here, it is important to note what can and cannot be assessed with skin conductance. It

is well established that SCR covaries with the arousal dimension of affect, indexing its *intensity* and changes thereof. In contrast to this quantitative aspect, the qualitative aspects of affect, such as its *valence* (positive/negative, approach/avoidance) or *which* emotion is present (e.g., fear versus anger versus joy versus disgust, etc.) are not reflected in EDA and have to be inferred from other sources. Often these qualitative aspects of affect, e.g., whether an affective response is negative or positive, might be clear and do not need additional measures, for example, when the participant experiences a gain versus a loss. In more ambiguous situations, or if finer-grained distinctions are of interest, it is necessary to assess these qualitative aspects either via the use of other physiological measures (e.g., electromyogram of facial muscles involved in smiling or frowning responses; Cacioppo, Berntson, Larsen, Poehlmann, & Ito, 2000; Rainville, Bechara, Naqvi, & Damasio, 2006) or—perhaps more reliable but obtrusive—a self-report measure such as an affect valence rating scale.

The studies by the Iowa group were pioneering in their use of skin conductance to investigate questions related to decision making. Damasio, Bechara, and colleagues have used SCR measures as tracers for otherwise unobservable implicit processes, both with healthy and brain-lesioned participants. Research with the Iowa Gambling Task (IGT; Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, Damasio, & Lee, 1999) has shown that participants not only exhibit SCRs to the outcomes of their choices (gains versus losses, reflecting experienced utility) but, over the course of repeated trials, healthy participants also develop *anticipatory* SCRs, assumed to index emotional arousal before and while they make their choices (reflecting anticipated and decision utility). These anticipatory SCRs were predictive of whether the participant would make an advantageous versus a disadvantageous choice. According to the Somatic Marker Hypothesis (SMH; Bechara, Damasio, Tranel, & Damasio, 2005), these anticipatory SCRs seem to develop *before* participants have explicit knowledge of the advantageousness of the different choice options. Thus, such autonomic arousal has been interpreted as guiding and influencing the participants' choice behavior. The SMH is the object of a lively debate and, together with the IGT, continues inspiring research with healthy normals as well as developmental and clinical populations, typically measuring anticipatory and outcome-related SCRs (e.g., Crone, Somsen, van Beek, & van der Molen, 2004; Jenkinson, Baker, Edelstyn, & Ellis, 2008; Luman, Oosterlaan, Knol, & Sergeant, 2008; Wright, Rakow, & Russo, 2017; for a review see Dunn, Dalgleish, & Lawrence, 2006). In summary, work by the Iowa group has demonstrated how SCRs can be used as a process indicator of affective processes before, during, and after making decisions that would otherwise be difficult to observe in an equally unobtrusive manner.

Other, more recent JDM work using SCR includes Reid and Gonzalez-Vallejo (2009) who used SCR in an innovative way as an indicator of affective processes, showing that decision weights derived from SCR magnitudes can improve choice models that try to capture how participants integrate symbolic and affective information during decision making. Holper, Wolf, and Tobler (2014), and Holper and Murphy (2014), have used EDA recordings to show that skin conductance appears to reflect objective (i.e., preference-independent) risk processing while lateral prefrontal cortex activity (assessed using functional near-infrared spectroscopy) appears to reflect subjective (i.e., preference-dependent) risk processing. In our own research, we use measures of skin conductance in combination with the CCT (Figner et al., 2009) as well as with a task involving morally challenging and ethical dilemma decisions (Krosch, Figner, & Weber, 2012). By using SCR, we were able to show that our two versions of the CCT—the affect-charged hot and the deliberative cold—indeed differed in the involvement of affective processes, explaining their differential developmental patterns in risk taking across childhood, adolescence, and adulthood. In the study on morally challenging choices, we found that increased affective arousal indexed by SCR during the dilemma-like choices predicted participants' reported decision difficulty as well as their projected future worry about their decision.

In more clinically oriented work, Siegel and colleagues (Siegel & Gallagher, 2015; Siegel & Weinberger, 2012; Siegel, Warren, Jacobson, & Merritt, 2017) recently have shown that repeated exposures to masked phobic stimuli (e.g., pictures of spiders) can reduce avoidance behavior of phobic persons when the stimuli were presented briefly enough not to increase SCLs. This is important because earlier work (Öhman & Soares, 1994) had shown that even subliminal presentation of phobic stimuli can elicit SCRs and negative affect ratings. Thus, Siegel and colleagues' findings that very brief exposures to phobic stimuli can reduce fear (and thus arguably affect evaluations) suggests the existence of a non-conscious pathway that appears to operate independently of physiological affective systems, as indicated by the absence of SCRs.

In the following part of the chapter, we describe the steps necessary to conduct research with skin conductance. We provide descriptions of equipment, laboratory setup, task structure, and data analysis techniques, and discuss important considerations for planning and conducting research with skin conductance measures.

Equipment

There are several commercially available systems to measure skin conductance. For our own studies reported earlier, we used a Biopac system, consisting of a base module in combination with modules for skin conductance and cardiovascular activity. A desktop or laptop computer is needed to run the AcqKnowledge software that comes with the Biopac system. The AcqKnowledge software is used to set up the acquisition parameters, allows for real-time monitoring of the measurements, records the data to a hard drive, and can be used for data filtering and analysis. A second, separate desktop or laptop computer is typically used to administer the computer-controlled experimental task.

Parameters and Filters

To illustrate how a recording might look in one of our own studies, Figure 11.3 shows a screenshot of the AcqKnowledge software processing six channels of data: Channel A represents raw cardiovascular activity (with channel F being heart rate, estimated beats per minute, derived from the signal of channel A). Channel B records and displays the raw skin conductance signal, i.e., no filtering is applied.[7] This channel is similar to traditional skin conductance measurements and reflects both slow tonic and fast phasic changes (i.e., SCL and SCR). A second skin conductance channel is set up in AcqKnowledge to record the skin conductance signal, but this time with a software-based 0.5 Hz high-pass filter applied (shown on channel E). The high-pass filter effectively removes the tonic component of the raw skin conductance signal and shows only phasic changes, in effect isolating SCRs. Notice the strong phasic change on the right part of the figure—this corresponds to the participant turning over a loss card in the CCT and realizing a loss of money. Other ways to isolate the phasic changes and reduce or eliminate the slow drift present in the SCL signal are by using a difference function (see Naqvi & Bechara, 2006) or by computing a derivative of the raw signal (Nagai et al., 2004). Finally, channels C and D in our setup correspond to task markers in our experimental tasks.

Sampling Rate

When data storage capacity of several hundreds of megabytes is not a problem, we suggest that the sampling rate should not be lower than 100–200 Hz.[8] While such high sampling rates are not imperative to veridically represent a relatively slow signal like skin conductance, more complex analysis approaches and smoothing procedures can benefit from higher sampling rates; if a lower sampling rate is required, the signal can easily and quickly be downsampled during the

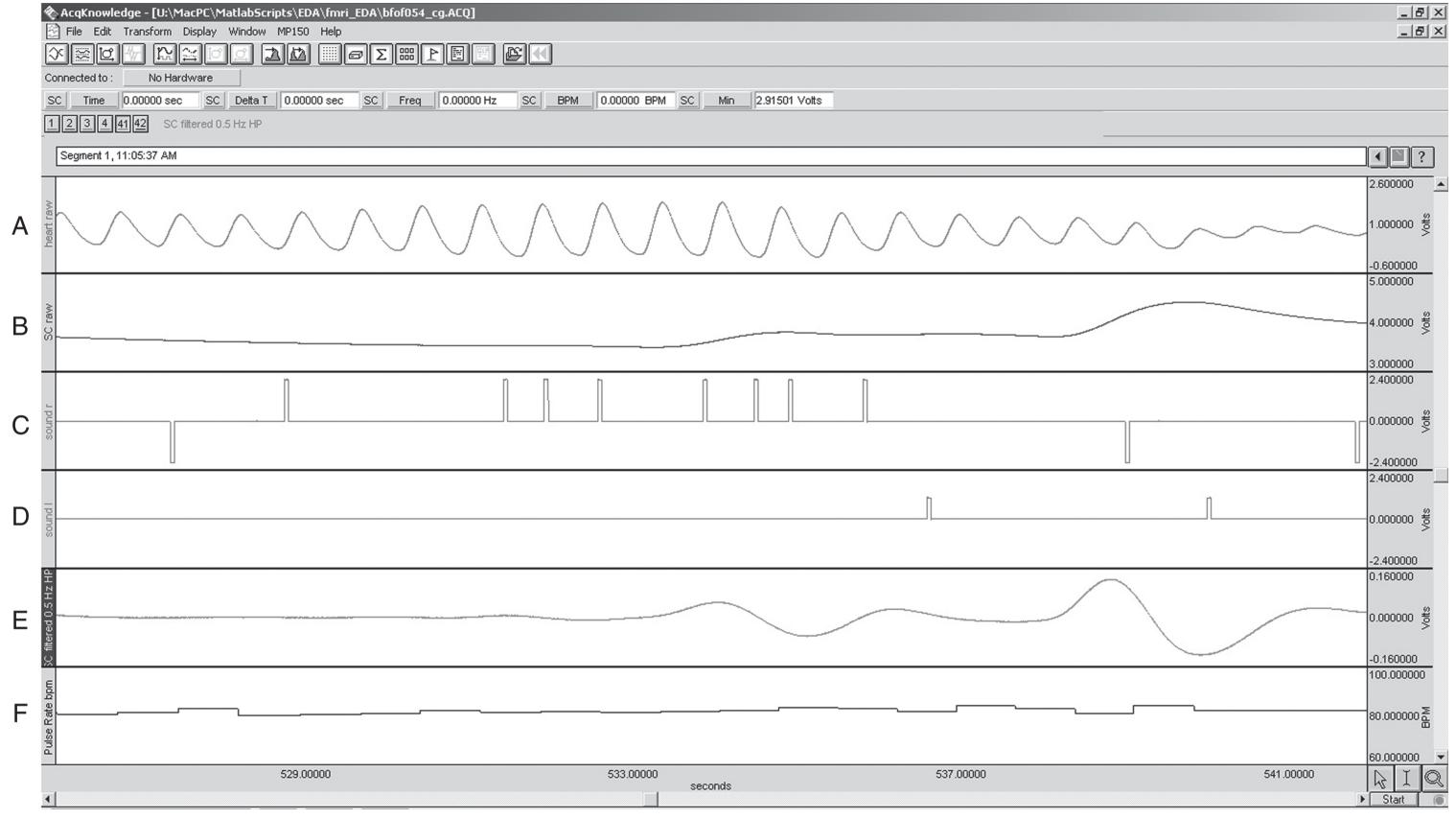

FIGURE 11.3 Screenshot of the AcqKnowledge software. Six channels of data are recorded and displayed here (see explanations in the main text).

data-processing stage. Since sampling rates can easily be set as high as 1 or 2 kHz without running into problems of computing resources or data recording speeds in modern computers, we usually sample at 1 kHz.[9]

Electrodes

Two main types of electrodes are available to be used for skin conductance measurement. Reusable electrodes must be cleaned after each use and are used in combination with an electrode gel for EDA use. Disposable electrodes are pre-gelled and do not require preparation or cleaning and disinfection after each use. This is particularly practical when doing research outside of the laboratory (e.g., at a school or workplace).

After participants provide informed consent, we first attach the electrodes to give the electrode gel enough time to soak into the skin and thereby result in a good and stable electrical connection. The electrodes are placed on the non-dominant hand, so the participants can still write or handle a computer. Before attaching the electrodes, we first clean the locations of electrode placement with small disposable alcohol pads as we observed that, if a participant applied hand cream shortly before coming to the laboratory or has otherwise very oily skin, the oil can prevent the electrodes from sticking to the skin[10] as well as prevent the electrolyte gel from establishing an electrical connection, which might result in a poor skin conductance signal.

However, there are various and contradicting recommendations in the literature regarding pretreatment, including no pretreatment at all, only water, water and soap, or alcohol (e.g., Naqvi & Bechara, 2006; Venables & Christie, 1980). As far as we know, no research has investigated the effects of these pretreatment methods on EDA signal quality. Regardless of which pretreatment is chosen, the same procedure should be used within an experiment and ideally reported as part of a corresponding methods section.

After briefly letting the alcohol dry, we put the electrodes on the distal (first) phalanges of the index and middle finger (see Figure 11.4).[11] Others have used the medial (second) phalanges or the palm of the hand (usually the thenar and hypothenar eminence). There is no agreed upon standard placement. It is again highly advisable that, within an experiment, the same electrode placement be used across all participants. It has been reported that SCR amplitudes from the distal phalanges were about 3.5 times larger than those from medial phalanges and SCLs were about twice as large from distal phalanges, compared to medial phalanges; in addition, SCRs from distal phalanges were more sensitive to habituation (Scerbo, Freedman, Raine, Dawson, & Venables, 1992; as cited in Boucsein, 2012). Some have argued that placement on the distal phalanges might increase the chances of movement artifacts, compared to the medial phalanges (Venables & Christie, 1980). Independent of actual electrode location, the experimenter should make sure that the participant can comfortably rest their hand either in their lap or on the desk using a pillow or a blanket to support the arm and hand to avoid signal artifacts, which may arise from movement of the hand to which the electrodes are attached. Finally, as temperature and humidity can influence skin conductance (Boucsein, 2012), we record the temperature and humidity at the start and end of each participant's session using an inexpensive combined hygrometer/thermometer (to determine whether there is a systematic relationship, and if so, to be able to statistically control for this potential influence on the EDA signal).

Event Markers

To enable a meaningful analysis of the skin conductance data and to be able to relate the stimuli and the participant's behavioral responses to the skin conductance signal, the physiological data

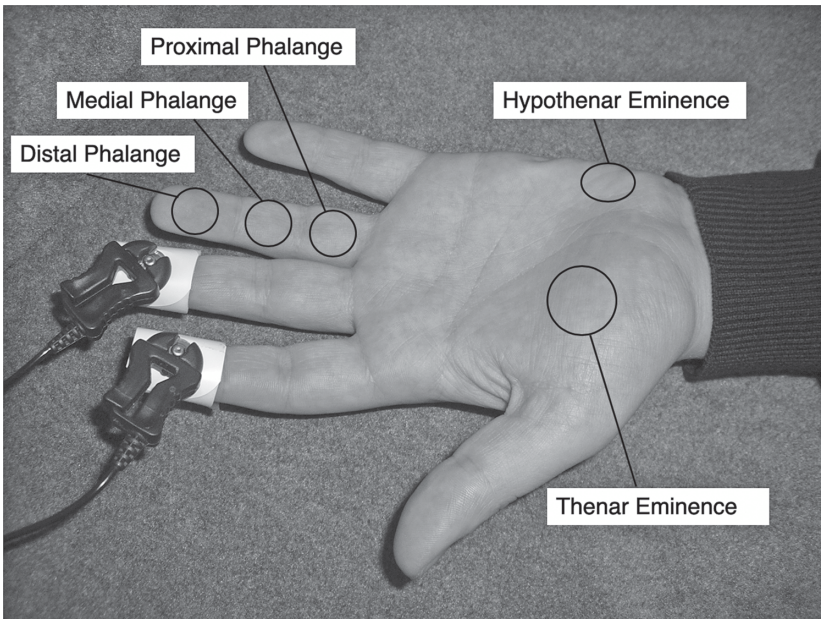

FIGURE 11.4 Electrode setup and terminology for common electrode placement locations.

recording, the stimulus display, and the participant's behavior all have to be synchronized somehow, preferably by recording these events on a common timeline. AcqKnowledge and Biopac allow for a direct interface with various commercial task-administration software packages (such as Direct RT, E-Prime, MediaLab, Presentation) so that task markers are recorded along with the physiological data. In our own studies, we opted for a customized solution that gives us maximal flexibility in the software we use to program experimental tasks. For example, the CCT version we used in Figner et al. (2009) was programmed using Microsoft's Visual Basic and plays custom-made sound files every time a participant makes a decision or a new round starts. These sound signals are not audible to the participant but are fed directly from the analog sound output of the stimulus computer into the analog inputs of the Biopac base module. The event markers are visible in Figure 11.3 as channels C and D.

Experimental Procedure

The electrodes should be attached at least 5 minutes prior to recording the physiological data to ensure that a good and stable electrical connection is achieved. We check whether everything is working by having the participant take a couple of deep sharp breaths, as this reliably results in very clear SCRs.[12] If there are no clear SCRs observed, it is possible that the gel needs more time to soak into the skin. Therefore, we would continue giving instructions and check a second time immediately before the critical part of the study is to begin. One could use the recording up to this point as a baseline. However, because the electrical connection might not yet have reached a steady state, it is more advisable to have a (second) baseline period towards the end of the experiment, e.g., while participants fill out some questionnaires. Naqvi and Bechara (2006) recommend the recording of—in addition to a resting baseline—an active baseline (the responses to a series of quick, sharp, deep breaths), which can be used to exclude non-responders or as covariate to account for individual differences in SCR magnitude.

Before the critical part of the experiment starts, we again check whether the skin conductance is recorded properly, having the participant take a deep breath. If there is a problem, one can try to remove the electrodes, clean the skin again, and start over. If participants have very cold hands, this can also reduce electrodermal activity (Boucsein, 2012).[13] If the second try fails again, it is likely that this participant is a non-responder[14] and the experimenter has to decide whether it is worth collecting the data (most probably resulting only in a meaningful behavioral but not a meaningful physiological data set) or to abort participation.

Experimental Design and Task Structure

As described earlier, skin conductance is a relatively slow signal. Not only does it change in the range of seconds but it is also *time-lagged*, i.e., between the occurrence of a stimulus and the resulting SCR, there is a latency of about 0.5 to 5 sec (most often, the latency of SCRs is between 1 and 2 sec; Boucsein, 2012). This makes the signal similar to the blood oxygenation level dependent (BOLD) response in fMRI research, which is also slow and time-lagged. While there are several differences between SCR and BOLD, similar considerations have to be taken into account when planning the study and the task. For example, a one-shot design, i.e., one single SCR measurement per participant per experimental condition, might result in data too noisy to yield any reliably discernable effects. In addition to other factors, the number of repetitions needed depends crucially on the stimuli (namely how reliably they trigger SCRs and how strong those SCRs are). Strongly aversive stimuli, such as an electrical shock in a conditioning experiment or a loss of a substantial amount of money in a risky choice task, can be expected to more reliably trigger strong SCRs compared to more subtle stimuli. To address the time-lag problem, SCR studies often use relatively long interstimulus intervals (ISI) of 6 to 12 sec or more between trials to make sure skin conductance has returned to baseline before a new trial starts (e.g., Bechara, Tranel, Damasio, & Damasio, 1996; Breska, Maoz, & Ben-Shakar, 2011; Reid & Gonzalez-Vallejo, 2009).

fMRI researchers came up with different ways to optimize their task designs in response to methodical challenges, which can be applied to skin conductance studies (for basics in fMRI research see Huettel, Song, & McCarthy, 2004). In *blocked designs*, longer periods of a specific task are counted as one period of interest (*block*), assuming that during the block relatively constant processes are engaged. We used this approach in Figner et al. (2009) to compare SCRs during a longer time period across the hot and the cold CCT, and to a baseline measure. Here, the whole risky choice phase of the (hot or cold) CCT counted as one block. Sufficient for the purpose of our manipulation check (that the hot CCT involved stronger affective processes than the cold CCT), we used a simple between-subject design in which each participant had only one block of interest, plus a baseline measure. More elaborate designs can be used to increase statistical power, e.g., repeatedly administering the blocks of interest within-subject, in random or counterbalanced order, with blocks of rest between the active blocks.

However, in many studies, investigating shorter time intervals (such as single trials) might be more appropriate. For such questions where the unit of analysis has to be shorter, we are confronted again with the problems regarding the slowness and time-lag of the skin conductance signal. Potential improvements from such designs can be found again in fMRI paradigms. While designs looking at relatively short time periods are generally called *event-related designs* (as the physiological data are analyzed with respect to single events, not blocks containing multiple events), so-called *rapid event-related designs*, wherein a train of stimuli follow each other in a tight sequence, are most interesting for our purpose. Such designs are likely to generate superimposed SCRs, i.e., overlapping SCRs in the sense that a new SCR starts before the previous SCR has ended; this has the effect that the two

(or more) SCRs add up to what might look similar to one single larger and/or longer SCR, making it difficult to clearly say where each individual SCR starts and/or ends. Traditionally, this has been handled by measuring a superimposed SCR starting from its minimum value on the recovery limb of the prior SCR (Edelberg, 1967). More recently, mathematical deconvolution models have been proposed (i.e., methods to analytically disentangle the superimposed SCRs; see Alexander et al., 2005; Bach, Flandin, Friston, & Dolan, 2009; Benedek & Kaernbach, 2010a, 2010b; Lim et al., 1997). Two common toolboxes that provide such model-based analysis methods are the MATLAB toolbox *PsPM* (Psychophysiological Modelling; previous versions were known as SCRalyze) by Dominik Bach and colleagues (for more information, see http://pspm.sourceforge.net/reference/), and the MATLAB toolbox *Ledalab* by Kaernbach and Benedek (for more information, see www.ledalab.de/). For an excellent brief outline of the general approach and an empirical comparison of these two model-based analysis approaches and a traditional method, see Bach (2014). Importantly, such designs and the corresponding analysis approaches are based on the assumption that such repeated and overlapping and thus superimposed physiological responses aggregate linearly (in our case several SCRs; in fMRI, several BOLD responses).[15] If this assumption holds, separate events of interest do not have to be divided by long ISIs (the assumption of linearly additive SCRs seems to hold for ISIs that are approximately 2 sec or longer: Bach et al., 2010; shorter intervals are likely to induce non-linearities, which would require somewhat different modeling approaches, which are currently not implemented, e.g., in PsPM). Instead, responses can be allowed to overlap, as they can be deconvoluted statistically. In such an analysis, the dependent variable would be the continuous SCR data. Several independent regressors can be built for different types of events of interest, such as, in the CCT, a regressor coding each time the participant turns over a loss card; a second regressor codes each instant of turning over a gain card; a third regressor represents the decision to end a trial voluntarily, etc. Some regressors may have only two different values (0 and 1), coding whether the event is present or not. Other regressors can be parametrically varied (e.g., coding different loss magnitudes). As in fMRI analysis, these regressors are simple delta (i.e., stick) functions, being 0 for all time points without the event of interest and being some number greater than 0 for the events. Before they are used in the following GLM analysis, the delta functions are convoluted with a "canonical" SCR that can be taken from, for example, an averaged SCR (the mentioned toolboxes contain such canonical SCRs). Just as in fMRI analysis, the estimated weights and error indicators of the regressors from the individual-level analysis can then be transferred to the group analysis.[16]

Importantly, the intervals between events do not need to be long but they should be jittered (i.e., of unequal length). This can be achieved by programming randomly jittered ISIs as part of the computer task, or by using the self-pacing of the participants, an approach that we adopted in our CCT studies (although one has to keep in mind that subsequent events that are separated by less than 2 sec in time likely lead to non-linear aggregation and thus pose a problem for the currently available analysis approaches). These more recent model-based approaches allow stimuli to be presented closer in time, compared to more traditional analysis approaches, thus giving more freedom in task design. Accordingly, these approaches support more natural task designs that cannot be realized pragmatically with long ISIs. A second advantage of these model-based approaches that is at least as important is that they promise increased statistical power and greater sensitivity, without increasing the Type I error rate. While there appear to be differences across different modeling approaches (for a comparison, see Bach, 2014), the new methods clearly have the potential to outperform traditional analysis approaches. Therefore, we recommend considering using these more advanced analysis methods. That being said, there may be trade-offs for the user,

for example, the conventional analysis approach is likely more intuitive and easier to understand for non-experts, is relatively model-free (though no analysis approach is completely model-free), and may require less time investment in terms of becoming familiar with a new toolbox. Since these model-based approaches are not the focus of our chapter and since there is a growing literature with excellent papers discussing them in more detail,[17] for the remainder of the chapter, we will focus on the traditional analysis method, assuming sufficiently long ISIs.

Data Management and Analysis

The data that result from skin conductance measurement are substantial. Assuming a sampling rate of 1 kHz, one participant taking part in a 20-minute experiment yields over 1 million (20 minutes × 60 seconds × 1000 observations per second = 1,200,000) numbers corresponding to the conductivity of their skin over time. This ordered vector of numbers is from just one channel and forms the raw signal that can be processed and analyzed on its own or in conjunction with other variables recorded along the same time course on different channels. We use MATLAB for the analysis, a powerful and flexible software package capable of dealing with large data sets (some possible alternatives are R or Octave). The proprietary AcqKnowledge files (.acq) can be exported into a generic tab delimited format compatible with MATLAB (.mat) where each row corresponds to one of the samples, and each column corresponds to a separate channel.[18]

Preprocessing

We first verify that the data were recorded properly during the experimental session by generating and examining plots of each of the channels over time. For example, the raw skin conductance signal should yield a plot that looks something like Figure 11.1. Examining the plots of each channel can reveal serious problems with a data set that would invalidate later results from the experimental session, e.g., if an electrode fell off a person's finger during the experiment or a wire becomes disconnected. For the remainder of the analysis, we focus on the high-pass filtered SCR data channel (channel E in Figure 11.3).

As high-frequency noise is likely to be present in the skin conductance signal, steps are often used to eliminate this source of error variance. For example, in the laboratory we used for Figner et al. (2009) and Krosch, Figner, and Weber (2012), the Biopac picked up electromagnetic disturbances (from sources such as the overhead florescent lights) and hence recorded a persistent low amplitude 60 Hz sub-signal. Such noise can be eliminated by administering a low-pass filter or a smoothing function (for our data collected with a sampling rate of 1 kHz, we use a simple moving average across 500 msec). By treating the raw signal with both a high-pass filter (thus removing tonic changes and slow drifts), and then a low-pass filter (to remove high-frequency noise), the result is a band-pass filtered signal.[19] This signal is the basis of subsequent analyses as it isolates the phasic SCRs that are of interest to us in our research. In Figure 11.5, we show the effects of high-pass and low-pass filters on a raw skin conductance signal.

In addition to processing the skin conductance signals, the task marker channels are processed. The channels are smoothed with the same moving average function to mitigate noise, and then a peak detect function is run on the channels. The result is a series of several binary markers that indicate when in the time course the participant performed a particular action or there was a particular event or outcome in the task. These markers are used to isolate portions of the SCR signal that are of particular interest (i.e., to define the measurement windows, see later).

Main Analysis

There are a variety of different ways to quantify SCRs and score the response as a single number. Traditionally, the most common indicator (using the unfiltered raw skin conductance signal) has been the SCR *magnitude*, reflecting the peak amplitude of the SCR. In order to quantify this variable, a latency onset window has to be defined. A typical criterion is that the onset of an SCR has to be between 1 and 3 sec after stimulus onset.[20] Then, the peak amplitude of this SCR is quantified by computing the difference between skin conductivity before the SCR onset and the skin conductivity at the peak of the SCR (Boucsein, 2012; Boucsein et al., 2012). In the literature, the variable SCR *magnitude* includes SCRs with 0 amplitude, whereas SCR *amplitude* only includes cases in which an actual SCR was observed (i.e., excluding cases in which no discernable SCR occurred in the time window).

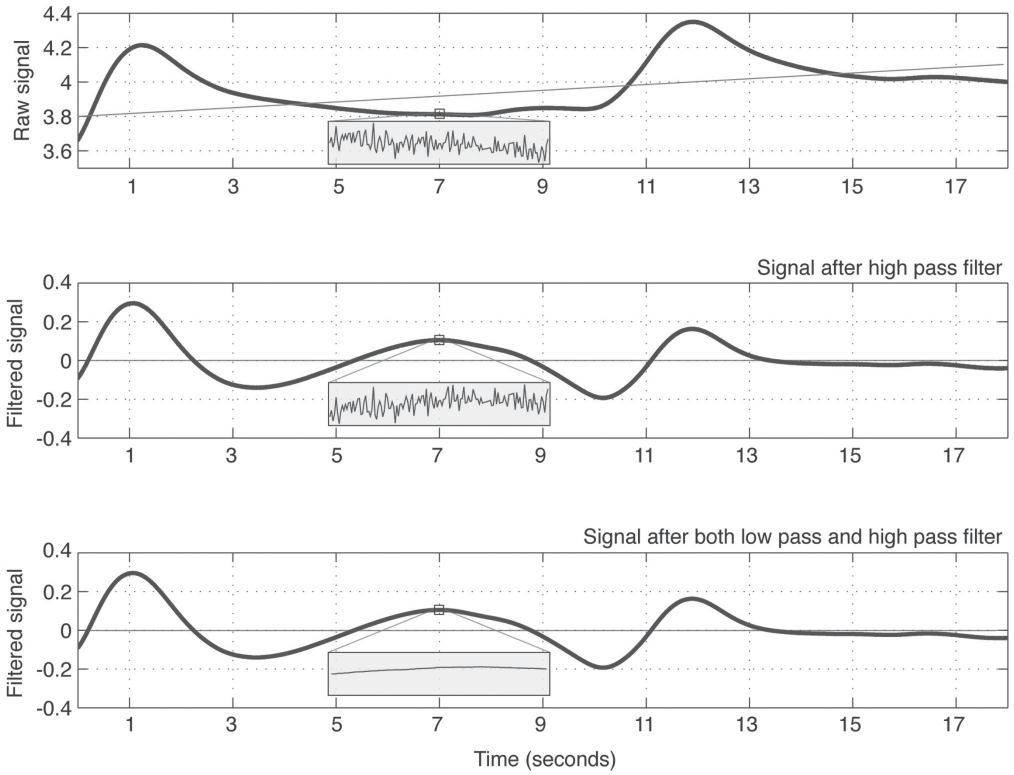

FIGURE 11.5 The effects of filters on signal data. Top panel, raw skin conductance signal, reflecting both SCL and SCR (equivalent to channel B in Figure 11.3). Middle panel, filtered signal after application of a 0.5 Hz high-pass filter (equivalent to channel E in Figure 11.3). The slow drift in the signal (representing the SCL) has been removed such that the filtered signal reflects only phasic changes, i.e., SCRs (note the difference in the slope of the straight gray line in the top panel compared to the middle and bottom panels). Bottom panel, signal after application of 2 Hz low-pass filter to remove high-frequency noise present in the data (see insets zooming in on a small time window of about 200 msec), the general shape of the signal remains unchanged by the third step but eliminates unwanted noise in the data. The last step is done after data collection, during data preprocessing, by applying a moving average smoothing function.

A more recent indicator, which lends itself more readily to automated analysis, is the *area bounded by the SCR curve*. Here, instead of an onset latency window, a window of interest is defined (the *measurement window*; see Figure 11.6). The measurement window has to be long enough to capture most of the SCR-related fluctuations, but short enough to avoid catching variance related to non-specific SCRs or SCRs to following stimuli. In general, longer ISIs allow longer measurement windows. Assuming sufficiently long ISIs, a common window of interest might start 1 sec after stimulus onset and end 6 sec after stimulus onset, making sure that most of the SCR-related activity will be captured in the 5 sec of interest. In the next step, the SCR-related variance in the data is quantified within this measurement window.

There are different approaches for this quantification. Naqvi and Bechara (2006), for example, use the area defined by the SCR curve and a sloped line delineated by the intersection of the measurement window and the SCR curve. We use the area bounded between the SCR curve and the abscissa within the window of interest (see Figure 11.6). As our filtering of the raw skin conductance signal has the effect that the resulting SCR data are centered around 0, the area bounded by the curve can be simply calculated by summing up the absolute values that lie within the time window.[21] Usually, the area bounded by the curve measure is standardized per time unit (typically per second) by dividing it by the length of the time window of interest in seconds such that the resulting measurement is in μS/sec.

The determination of the size of the measurement window is obviously somewhat arbitrary, specifically the endpoint. Conversely, the starting point cannot vary so much because it has to be between the stimulus onset and the SCR onset. We find it useful to plot the SCRs in relation to

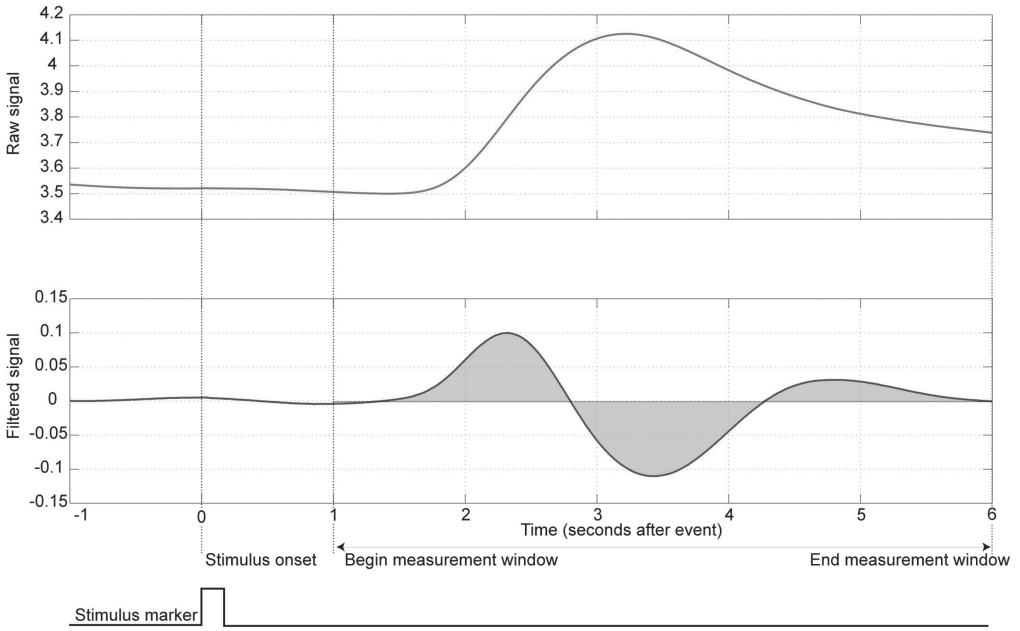

FIGURE 11.6 Raw (top) and filtered skin conductance signal (bottom), showing quantification of SCR within a time of interest window (measurement window) as the area bounded by the filtered SCR signal and the abscissa.

the stimulus onset: One plot represents each SCR by an individual curve in the same graph and one plot shows only one curve, representing the average of all SCRs. These graphs are very helpful in defining a sensible measurement window. Obviously, the time window of interest has to be the same for all participants and conditions within an experiment for this type of analysis, as results might otherwise be difficult to interpret. One caveat is regarding the selection of window size (as with any arbitrary parameter). Some researchers may be tempted to analyze their data using a wide range of different windows and then "cherry pick" results that correspond to a particular window size, reporting only those results and not disclosing their data-dredging activities. This is a kind of *p*-hacking as it capitalizes on error variance to yield particular results. Researchers are strongly discouraged from this practice as data-dredging is a kind of scientific misconduct and it undermines the accumulation of knowledge. Thus, the decision about the window of interest is ideally independent of the data of interest. For example, one solution would be to first conduct a pilot study and use these data to determine the window of interest.

Data Transformations: Normalizations and Standardizations

Normalization and standardization of skin conductance data do not refer to the same thing. In normalization, data transformations are conducted to make sure the relevant requirements for the used statistical method (such as regression, ANOVA, etc.) are met. For example, regression approaches (including ANOVA) require approximately normal distribution of the residuals. Accordingly, data transformation methods traditionally have been used to reduce, for example, skew or kurtosis so that the data are amenable to parametric statistical analysis (to avoid confusion, the typical statistical models require that the *residuals* follow a normal distribution, not the dependent variable; however, the transformation is applied to the dependent variable when the residuals violate the model assumptions). It is worth checking distributions of SCR magnitudes because they are typically positively skewed and leptokurtotic (Boucsein et al., 2012; Dawson et al., 2007). The most common normalization of SCR magnitudes is a logarithmic transformation. A log transformation should be applied after SCR magnitudes have been determined; a log should not be applied to the raw scores. If zero responses are included, it is often recommended that the log of (SCR + 1.0) should be used because the log of zero is undefined. Square root transformation can also be used to normalize SCR magnitudes, which unlike logarithmic transformation does not necessarily require the addition of a constant (Edelberg, 1972). Logarithmic or square-root transformation can also be used to normalize SCL data.

The transformations should be evaluated in terms of their capacity to reduce and mitigate skew, kurtosis of the residuals, and, if relevant for the used statistical model, heterogeneity of variance across groups (Ferguson & Takane, 1989). Log and square-root transformations tend to generate similar results. If distributional problems are not initially evident, then it is likely not necessary to apply these data transformations. A recommended alternative to transformations (and also an option if transformations are insufficient to mitigate distributional problems) is the use of robust or non-parametric statistical techniques.

Normalization does not address the considerable individual differences that characterize skin conductance data, which complicates inter-individual comparisons. An SCR of 1.0 μS may be relatively high for one participant and relatively low for another, depending on their idiosyncratic SCR ranges. EDA ranges can vary widely due to physiological variables (e.g., thickness of the corneum) that are unrelated to the psychological processes of interest. Standardization procedures can be used to correct for such individual differences so that SCRs or SCLs of different participants can be meaningfully compared (Boucsein, 2012; Dawson et al., 2007). This

means that the skin conductance data is standardized *within each participant* prior to conducting between-group analyses.

Lykken, Rose, Luther, and Maley (1966) proposed the standardization method of EDA data known as *range correction*. A participant's maximum SCR is measured in response to an arousing and startling stimulus (e.g., the participant blows up a balloon until it bursts). Each SCR is then standardized by calculating the proportion of maximal response (i.e., dividing it by the participant's maximum SCR). To standardize SCL data, a participant's potential SCL range is first calculated, and individual SCLs are then transformed in terms of this range. The minimum value is typically measured during a rest period, and the maximum SCL during the most aroused period. SCL during any particular time period is than calculated as a proportion of his/her particular range according to the formula: (SCL – SCLmin)/(SCLmax – SCLmin).

The advantages of range correction are the reduction of error variance, and thus increased statistical power in analyses involving group comparisons. However, range correction should not be used if groups have quite different skin conductance ranges (Ben-Shakhar, 1985; Dawson et al., 2007). Further, it can be difficult to establish a participant's range (maximum and minimum responses) with adequate reliability. To address these limitations, Ben-Shakhar (1985) proposed using within-subject standardized (z-) scores to correct for individual differences because such scores are based on the mean, a more robust statistic than the maximum or minimum value. There is evidence that standard scores provide greater statistical power, e.g., compared to range correction or no standardization (Boucsein et al., 2012; Bach, 2014), and for example might mitigate the effect of SCR habituation within blocks of stimuli, thereby better highlighting relevant effects (Ben-Shakhar & Dolev, 1996).

Conclusions

There are several advantages and disadvantages to be taken into account when considering using EDA measures in JDM research. Some advantages are that skin conductance is a comparatively robust physiological measure that can be measured relatively cheaply, easily, and unobtrusively. It yields a continuous measure that is related to activity in the sympathetic branch of the ANS. Accordingly, it does not reflect one single psychological process, which can be seen either as an advantage or a disadvantage. Irrespective of this, skin conductance measurement requires that the setup of the experiment and/or additional measures such as self-reports constrain the possible interpretations of the changes in skin conductance by constraining the psychological processes that such changes reflect. A clear disadvantage of skin conductance is the slowness and time-lag of its signal, typically requiring long ISIs. Newer analysis approaches, however, mitigate this issue, while at the same time increasing sensitivity and statistical power.

Notes

1 Particularly in older literature—and sometimes on hardware used to measure skin conductance—the outdated unit micromho (μ℧) can still be found. Mho is derived from spelling ohm backwards. This unit should not be used anymore as it has been replaced by the unit siemens (S) in the International System of Units.

2 The CCT is a dynamic risky decision-making task that assesses levels of risk taking and information use. Two different versions of CCT exist—a relatively affect-charged *hot* version and a more deliberative *cold* version (Figner et al., 2009; Figner & Weber, 2011). In both versions, participants turn over cards from a deck, which consists of a known number of gain and loss cards. Gain and loss amounts and probability to win or lose vary between trials to assess their influence on participants' risk taking.

3 The older term galvanic skin reaction or galvanic skin reflex (GSR) can still be found in the literature. It should be avoided as it is technically incorrect and it is not always clear to what aspect of EDA it refers (Boucsein, 2012).

4 More simply, a measure of the central tendency, e.g., the mean or median, over the whole time interval of interest could be taken. However, this is likely to lead to an overestimation of the true SCL, as such a measure includes the data points forming the SCRs.

5 This measure has been suggested to index *quantity of affect* by Traxel (1957; see also Boucsein, 2012; Naqvi & Bechara, 2006). Sometimes it is also referred to as *area under the curve*, which can be misleading as the measure includes areas both *under* and *above* the SCR curve.

6 *Volar* refers to the underside of hands and feet, i.e., the palm of the hand and the sole of the foot (including the underside of fingers and toes).

7 For our studies, we set up the EDA acquisition parameters as follows: On the Biopac hardware, amplification is set to 5 μSiemens/V, the low-pass filter is set to 1 Hz, and no hardware high-pass filters are activated (i.e., the switches are set to DC).

8 While lower sampling rates are still sometimes used in the literature and are often sufficient for many types of analysis, the computing speed of regular computers today and the relatively low cost of data storage media allow use of much higher sampling rates than was common several years ago.

9 In the more recent JDM literature, sampling rates most commonly are in the range between 100 Hz and 2 kHz.

10 We found it useful to additionally secure the electrodes by applying a short piece of scotch tape to connect the ends of the electrodes to make sure that they do not fall off.

11 We also have used placement of skin conductance electrodes on the middle and third finger in a study in which we used a transducer for cardiovascular activity on the index finger. We did not observe any systematic changes; again, it seems to be more important to be consistent within an experiment.

12 Participants are typically curious about what we are recording with the electrodes. Therefore, we show them the AcqKnowledge monitor at this time. Afterwards, we make sure that the participant cannot see the monitor since it might distract them. The experimenter also avoids watching the monitor as this might make participants feel overly scrutinized.

13 In general, we and others (e.g., Venables & Christie, 1980) have found that higher room temperatures work better than low room temperatures.

14 About 5 to 10% or even up to 25% of the population have been found to be non-responders (Dawson et al., 2007), with some clinical groups exhibiting even higher rates of non-responders (e.g., in schizophrenia; Boucsein, 2012).

15 For work on the linearity of overlapping SCRs see Bach, Flandin, Friston, and Dolan, 2009, 2010; Freedman et al., 1994; Lim et al., 1997; Lykken and Venables, 1971.

16 If the dependent variable is the area bounded by the SCR curve, Bach, Friston, and Dolan (2010) proposed a solution for obtaining area measures from overlapping SCRs based on a convolution model of the SCL-corrected time integral.

17 For an introduction and methods comparison, see Bach (2014). For work related to the PsPM toolbox and its foundations, see Bach et al. (2009, 2010); Bach and Friston (2013). For work related to the ledalab toolbox and its foundations, see Benedek and Kaernbach (2010a, 2010b). For decision-making papers using these approaches, see, e.g., Nicolle, Fleming, Bach, Driver, and Dolan (2011); Talmi, Dayan, Kiebel, Frith, and Dolan (2009).

18 There are also free MATLAB functions that allow the direct import of.acq files, available at MATLAB Central.

19 Alternatively, a low-pass filter with a cutoff of 2 Hz can be applied, leading to the identical result of removing high-frequency noise without altering the shape of the curve. As sympathetic neural activity operates at low frequencies (below 0.15 Hz; Nagai et al., 2004), even relatively low-frequency low-pass filters do not remove substantial information.

20 SCRs with an onset time outside this onset latency window would be counted as non-specific. Only the onset of the SCR has to lie within this window, usually there is no criterion when the SCR has to be finished as SCR recovery time can be very long.

21 Usually, the two methods will lead to very similar results. However, it appears that our method provides a more consistent index of the SCR compared to the previous approach, as it is less sensitive to variations in the defined location of the time window: If either the start or the end of the measurement window falls onto an SCR, our approach leads to a more reliable SCR quantification due to not relying on a sloped bounding line but using the abscissa instead.

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Recommended Reading

- Boucsein (2012), Dawson et al. (2007) and Venables and Christie (1980) provide excellent and thorough overviews on measuring EDA.
- Critchley, Dolan and colleagues (an overview can be found in Critchley, 2010) focus on the neural substrates involved in EDA.
- See Alexander et al., 2005; Bach, 2014; Bach et al., 2009, 2010; Bach and Friston, 2013; Benedek and Kaernbach, 2010a, 2010b; de Clercq, Verschuere, de Vlieger, & Crombez, 2006; Lim et al., 1997 for more novel analysis approaches using short ISIs.
- For model-based analysis approaches, we recommend the PsPM toolbox, which also includes a very helpful manual (http://pspm.sourceforge.net/).

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