Using skin conductance in judgment and decision making research

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Introduction

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. 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 and reliably.

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 research, serving as indicators of such processes as 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—and perhaps even influences (Bechara, Damasio, Tranel, & Damasio, 2005; but see Dunn, Dalgleish, &

Lawrence, 2006)—otherwise hidden 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 choice and judgment. 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 use it successfully. Accordingly, the main goal of this chapter is to give an introduction to the use of skin conductance in JDM research with a strong focus on providing concrete and hands-on advice for the researchers who are unfamiliar with this physiological medium but are interested in using it.

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 tangible 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 more concrete issues. 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 the skin conductance data. We will give most attention to more traditional and standard ways of study design and data analysis. However, we want also to briefly outline more recent ideas for novel experimental design and data analysis approaches that are being developed in our own and other laboratories. More detailed information about virtually *all* aspects of EDA and its physiological background can be found in the excellent volume by Boucsein (1992; see further recommended literature at the end of this chapter).

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, and therefore some clarification is in order. In 1967, the Society of Psychophysiological Research (Brown, 1967; see also Boucsein, 1992) 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 alternative 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*.[2]

As previously mentioned, *skin conductance* is the most commonly used measure in JDM and thus we focus on it. Skin conductance can be divided into *tonic* and *phasic* phenomena. The main

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[1] Particularly in older literature —and sometimes on hardware used to measure skin conductance—, the outdated unit micromho ($\mu \mho$) 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 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, 1992).

differences between these phenomena are related to their time scale and their relationship to the evoking stimuli.

Figure 1 shows a raw skin conductance signal from one participant in a risky decision making experiment using the "hot" Columbia Card Task (CCT; Figner, Mackinlay, Wilkening, & Weber, 2009).[3] 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 1), the participant made risky choices in the computer-based hot CCT which gives 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 short (i.e., over the span of a few seconds) modulations in skin conductance (seen as sharp peaks in Figure 1).
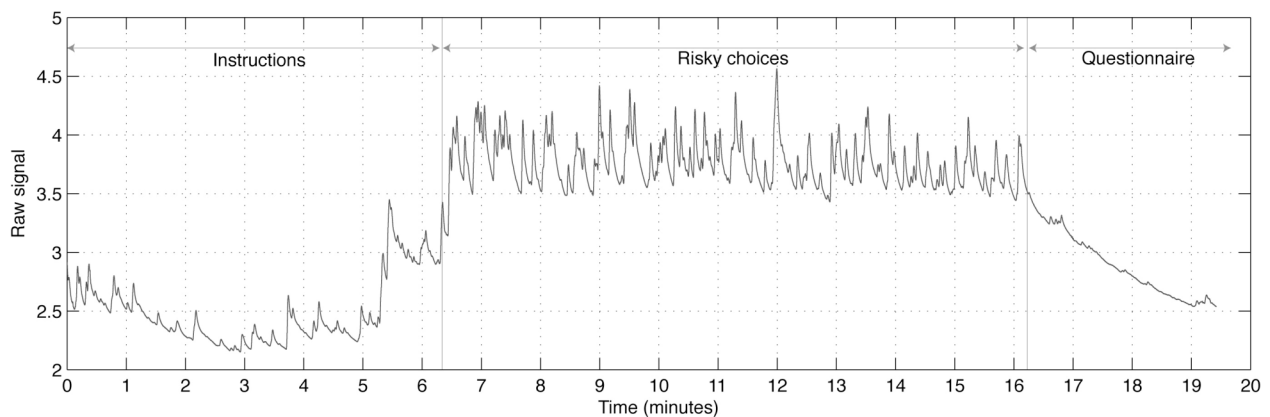

Figure 1. Raw skin conductance signal from one participant over the course of an experiment using the hot version of the Columbia Card Task (see Figner et al., 2009).

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[3] 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). 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.

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). 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 2). SCRs reflect the higher-frequency variability of the signal that is modulated on top of the slower changes in SCL.
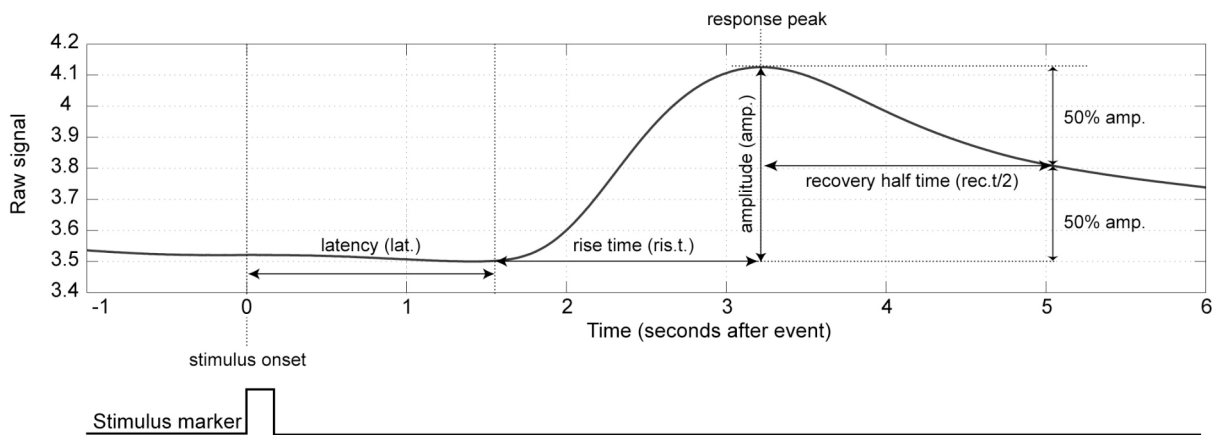

Figure 2. Raw unfiltered skin conductance signal, showing components of an SCR that can be used to quantitatively characterize SCRs. A stimulus marker corresponding to the participant turning over a loss card is also shown as part of the time course.

SCL is typically operationalized by taking the average of several discrete measurement points distributed across the time window of interest (Boucsein, 1992). 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 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 so-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 an SCR is specific (i.e., related to a stimulus) or non-specific, Boucsein (1992) suggests that SCRs that start more than 5 sec after the end of a stimulus should be categorized as non-specific. However, in many studies, the distinction between specific and non-specific SCRs can be problematic, as can be seen, for example, in the anticipatory SCRs that are crucial for the somatic marker hypothesis (SMH, Bechara et al., 2005; see more details further below). Anticipatory SCRs are assumed to reflect affective evaluation processes of different choice options. However, they cannot necessarily be attributed to a concrete stimulus, as they appear *before* the choice and are related to internal rather than externally observable stimuli.

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 and because it can be operationalized across shorter time intervals than SCL

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[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.

(for a recent study using both SCL and SCR, see Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004). SCRs have been quantified using various characteristics and measures (see Figure 2 and Boucsein, 1992, p. 135). The onset latency (lat.) is the time between the onset of the stimulus and the start of an SCR, typically 1 to 3 seconds. The rise time (ris.t.) is the time between the onset of the SCR and its peak amplitude, typically also 1 to 3 seconds. 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 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 6 and explanations further below), which is better suited for automated data analysis and captures both the amplitude and 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, thus skin conductance reflects the arousal of the sympathetic ANS which accompanies various psychological processes. The mechanisms and pathways involved in the central nervous

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[5] This measure has been suggested to index *quantity of affect* by Traxel (1957; see also Boucsein, 1992; 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.

control of eccrine sweating are relatively complex (Boucsein, 1992; Critchley, 2002) and a recent fMRI study suggested that SCL and SCR are related to activity in different brain areas (Nagai et al., 2004).[6]

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[7] 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

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[6] This study investigated neural activity during biofeedback and relaxation tasks. They found that neural activity within the ventromedial prefrontal cortex and the orbitofrontal cortex was related to SCL while activity in the lateral prefrontal cortex, thalamus, hypothalamus, insular cortex, and visual cortex was related to SCR.

[7] *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).

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, 1992), 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; Grings & Dawson, 1973), 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*. 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 vs. anger vs. joy vs. 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 would be 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 less unobtrusive—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 choice (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 SMH (Bechara et al., 2005), these anticipatory SCRs develop *before* participants have an explicit knowledge of the advantageousness of the different choice options and thus have been suggested to guide and influence the participants' choice behavior. The SMH is the object of a lively debate and, together with the IGT, keeps inspiring research in healthy normals as well as developmental and clinical populations, typically measuring anticipatory and outcome-related SCRs (e.g. Jenkinson, Baker, Edelstyn, & Ellis, 2008; Luman, Oosterlaan, Knol, & Sergeant, 2008; Crone, Somsen, van Beek, & van der Molen, 2004; Crone & van der Molen, 2007; Hinson, Whitney,

Holben, & Wirick, 2006; Wagar & Dixon, 2006; for a recent review see Dunn et al., 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.

Recently, Reid and Gonzalez-Vallejo (2009) used SCR in an innovative way as an indicator of affective processes, improving the predictive validity of choice models and showing how symbolic and affective information can be combined in such models. In two of their experiments, they used the magnitude of SCRs during the presentation of choice-relevant information to derive for each participant the weight of the influence of symbolic versus affective information on their preferences. They found that adding such physiologically derived emotional weights improved the predictive power of their models, giving evidence that symbolic-cognitive and emotional information can be combined using a weighted proportional difference rule. In a different experiment reported in the same paper, they assessed amplitude of SCRs during the sequential presentation of risky choice options of equal expected value.[8] They found that the emotional weight derived from the relative magnitude of SCRs was predictive of participants' preferences.

In our own research, we use measures of skin conductance in combination with the CCT (e.g., Figner et al., 2009) as well as with a task involving morally challenging and dilemma-like decisions (Krosch, Figner, & Weber, submitted). 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

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[8] As SCR indexes only the magnitude but not the valence of affective arousal, they assessed the affective *valence* with a self-report measure, the self-assessment manikin (Bradley & Lang, 1994).

choices predicted participants' reported decision difficulty as well as their projected future worry about their decision.

Hands On

In this part of the chapter, we intend to describe the steps necessary to do research with skin conductance. We will provide descriptions of equipment, laboratory setup, task structure, and data analyses techniques and discuss considerations important when planning and doing research with skin conductance measures.

Equipment

There are several commercially available systems to measure skin conductance. In our laboratory, we use a Biopac system, consisting of the base module (MP150) in combination with the modules for skin conductance (GSR100C) and cardiovascular activity (PPG100C). 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

In our laboratory, we set up the 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*). Figure 3 shows a screenshot of the

AcqKnowledge software processing 6 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. 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 megabytes is not a problem, we suggest that the *sampling rate* should be no lower than 100-200 Hz.[9] 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. Since sampling rates can easily be set as high as 1 or 2 kHz without running into problems of

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[9] While lower sampling rates are still sometimes used in the literature (e.g., 20 Hz in Fung et al., 2005) 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.

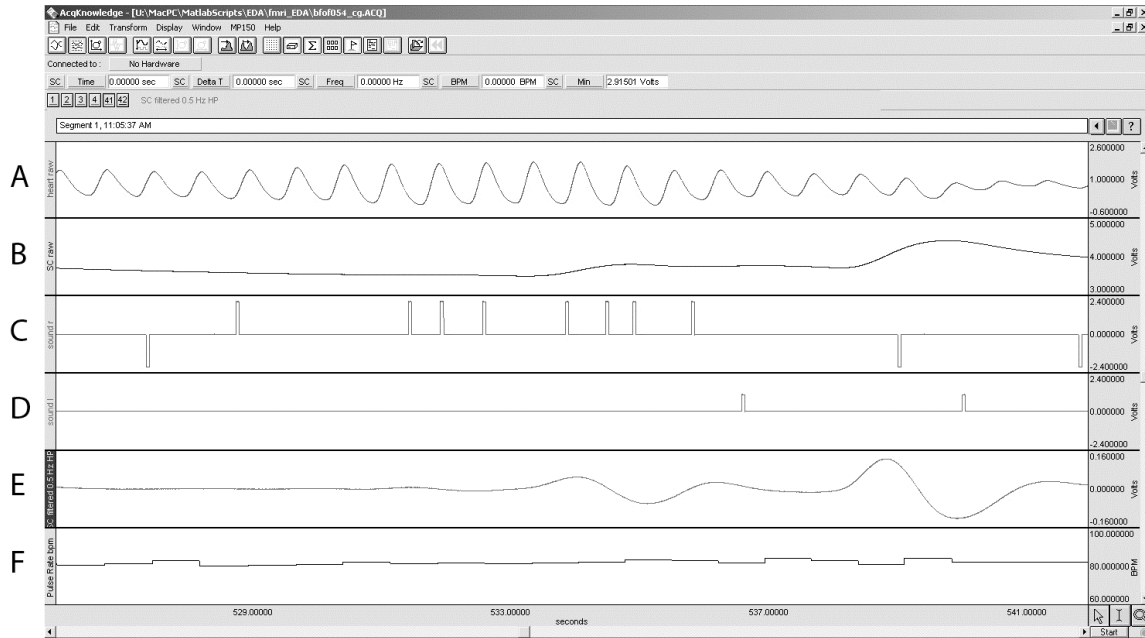computing resources or data recording speeds in modern computers, we usually sample at 1

kHz.[10]

Figure 3. Screen shot of the AcqKnowledge software. Six channels of data are recorded and displayed here (see explanations in the main text).

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. The use of *disposable electrodes* is becoming more common, as they 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).

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[10] In the more recent JDM literature, sampling rates appear to be most commonly in the range between 100 Hz and 2 kHz.

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[11] 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, such as no pretreatment at all, only water, water and soap, or alcohol (e.g., Naqvi & Bechara, 2006; Venables & Christie, 1980; Walschburger, 1976, as cited in Boucsein, 1992). Independent of which pretreatment is chosen, it is important to use the same procedure within an experiment.

After briefly letting the alcohol dry, we put the electrodes on the distal (first) phalanges of the index and middle finger (see Figure 4).[12] 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, &

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[11] 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.

[12] 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.

Venables, 1992; as cited in Boucsein, 1992). 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, 1992), we record the temperature and

humidity at the start and end of each participant's session (to potentially use as covariates in later

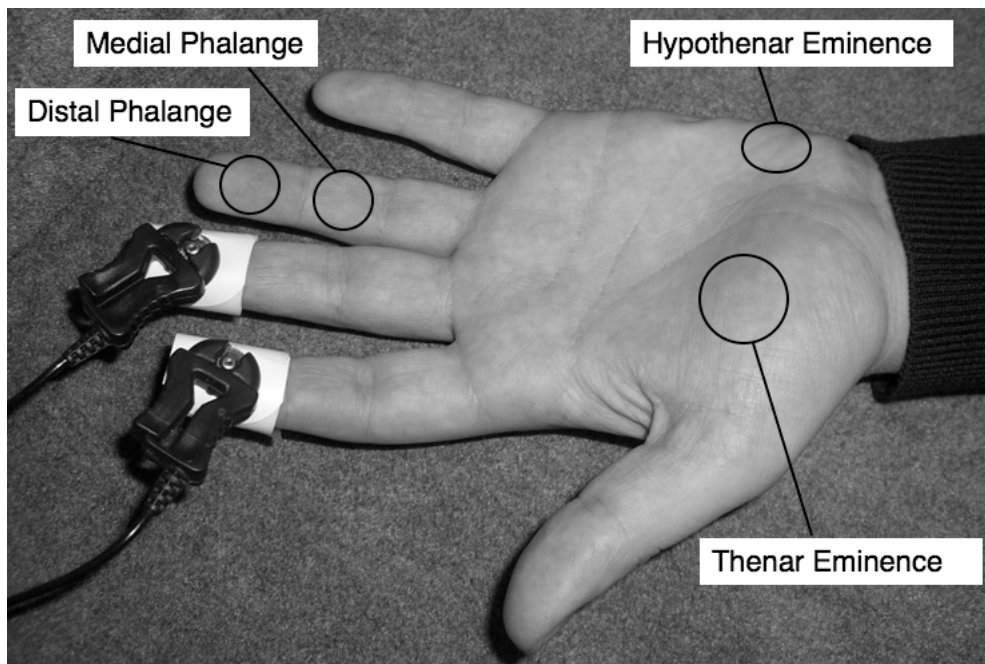analyses) using an inexpensive combined hygrometer/thermometer.

Figure 4. Electrode setup and terminology for common electrode placement locations

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 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, our CCT is 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 3 as channels C and D.[13]

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.[14] 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

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[13] Additional information is available upon request.
[14] 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.

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 covariates 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. Usually by this point in the procedure, data is being properly recorded. If not, 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, 1992).[15] If the second try fails again, it is likely that this participant is a non-responder[16] 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 abort participation.

Experimental Design and Task Structure

As described above, 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 seconds (most often, the latency of SCRs is between 1 and 2 seconds; Boucsein, 1992). This makes the signal similar to the blood oxygenation level dependent (BOLD) response in fMRI research, which is also slow and time-

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

[16] 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, 1992).

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 lead to any significant 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 seconds 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; Reid & Gonzalez-Vallejo, 2009). While this is a clean design practice that leads to data that are simple to analyze, such a design can have disadvantages, depending on one's goals for the study.

For example, if one wants to distinguish between the processes *before*, *during*, and *after* a decision (i.e., anticipated, decision, and experienced utility), such a long ISI would have to be inserted between each of these phases. In combination with the need for repeated measurements and perhaps a factorial within-subject design, this can result in very long experiments. Because the resulting task would consist mainly of waiting periods, the experiment might be excessively boring for participants. More importantly, even in shorter tasks, such long and repeated ISIs can change the very decision processes that one plans to study.

Researchers in fMRI studies came up with different ways to optimize their task designs, in response to such 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 our manipulation check purpose (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., with the blocks forming the conditions of interest administered

repeatedly, within-subject, and in random or counterbalanced order with blocks of rest between

them.[17]

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** are most interesting for our purpose. This chapter

allows us to outline only briefly ideas on how such analysis can be applied to SCR data (see

Alexander et al., 2005; Lim et al., 1997 for related approaches). Importantly, such designs are

based on the assumption that repeated and overlapping physiological responses add up in linear

fashion (in our case several SCRs; in fMRI, several BOLD responses).[18] If this assumption holds,

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[17] This might be a viable design, for example, to investigate emotional arousal during different forms of information acquisition in a decision-making task.

[18] For BOLD in fMRI this is well investigated and it has been shown that linearity holds reasonably well for responses that are spread apart by more than 50 ms (Burock, Buckner, Woldorff, Rosen, & Dale, 1998). To the best

separate events of interest do not have to be divided by long ISIs. Instead, responses can be allowed to overlap, as they can be deconvoluted statistically with regression approaches. 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 the 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 a value 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. 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.

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 (for use in fMRI, see Maccotta, Zacks, & Buckner, 2001; Moritz, Carew, McMillan, & Meyerand, 2005), an approach that we adopted in our CCT studies. We are currently working on such an analysis approach to be used with skin conductance data (see also Alexander et al., 2005; Lim et al., 1997). Such an approach has the potential to be very useful and statistically powerful in more natural task designs that cannot be realized pragmatically with long ISIs. Naturally, this might be particularly interesting

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of our knowledge, linearity for overlapping SCRs has not been systematically investigated yet. However, there is evidence supporting the additivity of multiple SCRs (see Freedman et al., 1994; Lim et al., 1997; Lykken & Venables, 1971).

for process-tracing studies. However, 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.[19] We use MATLAB for the analysis, as it is 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.[20]

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 1. Examining the plots of each channel can reveal serious problems with a dataset that would invalidate later results from the experimental session, e.g., if an electrode fell off a person's finger during the

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[19] Depending on the sampling rate and the duration of the experiment, the data files can be quite large (usually between 50 MB and 100 MB per participant).
[20] There are also free MATLAB functions that allow the direct import of .acq files, available at MATLAB Central.

experiment. For the remainder of the analysis, we focus on the high-pass filtered SCR data channel (Channel E in Figure 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 our laboratory the Biopac picks up electromagnetic disturbances (from sources such as the overhead florescent lights) and hence records 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 ms). 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.[21] 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 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 tell us 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 below).

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[21] 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.
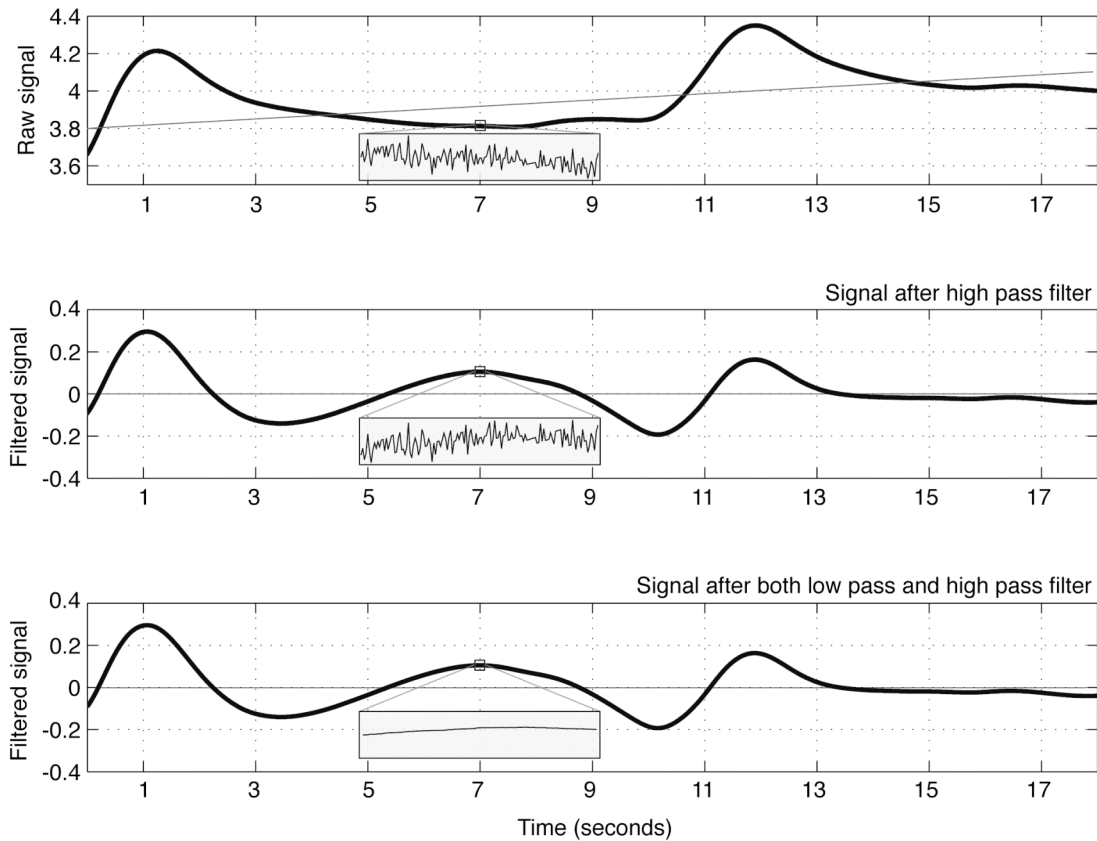
Figure 5. The effects of filters on signal data: Top panel, raw skin conductance signal, reflecting both SCL and SCR (equivalent to channel B in Figure 3). Middle panel, filtered signal after application of a 0.5 Hz high-pass filter (equivalent to channel E in Figure 3). The slow drift in the signal (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 milliseconds), 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.

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.[22] In order to quantify these, 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 seconds after stimulus onset.[23] 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, 1992).

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 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 second after stimulus onset and end 6 seconds after stimulus onset, making sure that most of the SCR-related activity will be captured in the 5 seconds of interest. In the next step, the SCR-related variance in the data is quantified within this measurement window.

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[22] Sometimes magnitude and amplitude measures are distinguished, with the former measure including SCRs with 0 amplitude and the latter counting only cases in which an actual SCR was observed (i.e., excluding instances where no discernable SCR occurred in the time window).

[23] 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.
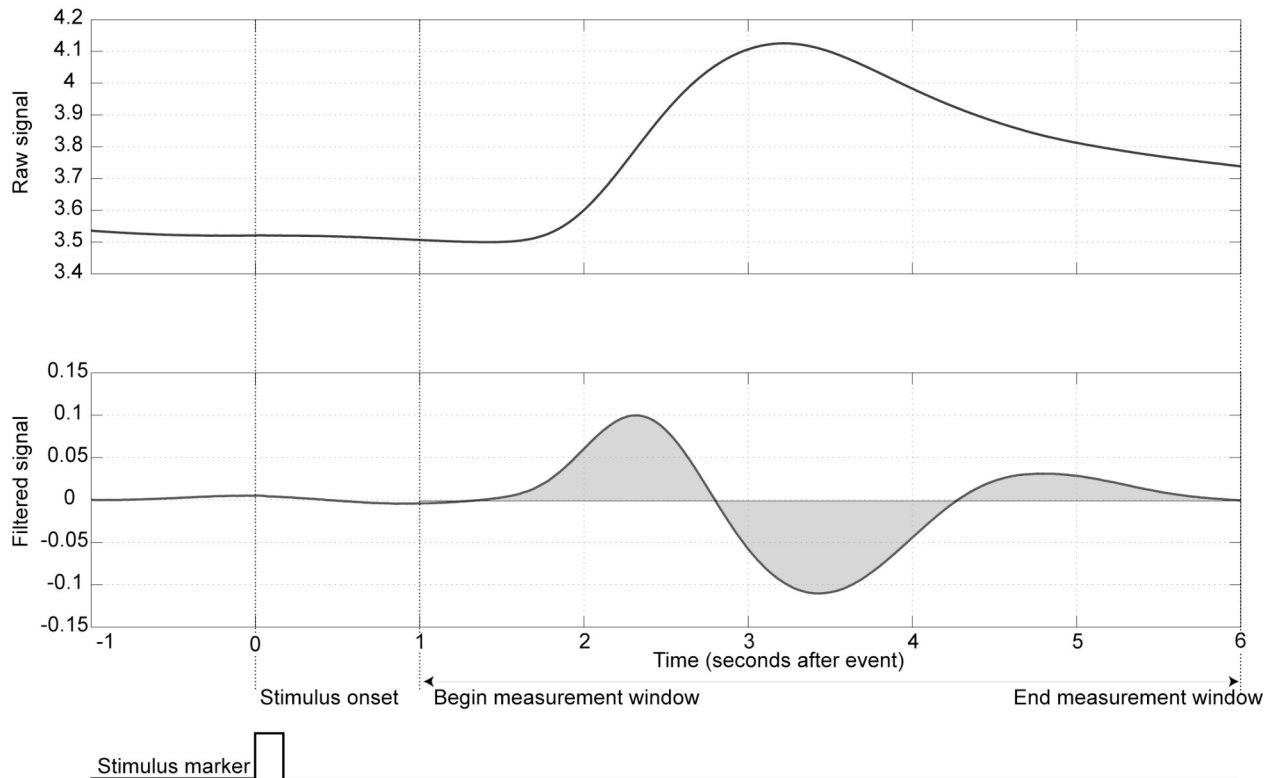
Figure 6. Raw (top) and filtered skin conductance signal (bottom), showing quantification of SCR within a time of interest window (measurement window) as the area bounded by the filtered SCR signal and the abscissa.

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 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.[24] Usually, the area bounded by the curve measure is standardized per time unit

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[24] 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

(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 regarding the endpoint (the starting point cannot vary that 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 the stimulus onset: One plot represents each SCR by an individual curve in the same graph and one plots shows only one curve, representing the average of all SCRs. These graphs are 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.

Data transformations. It is worth checking the distribution of the data. Particularly, SCR magnitude has been found to be skewed, which may be addressed with either a log or square root transformation. Also, it may be useful to standardize the SCR data within each participant because the magnitude of skin conductance data can vary between participants not only due to psychological but also due to physiological causes, such as the thickness of the corneum, and standardization can eliminate or reduce the influence of the latter source of variance (Boucsein, 1992; Dawson et al., 2007). Dawson et al. (2007) discuss advantages and disadvantages of different standardization approaches. Many researchers, however, do not use participant-wise standardization, instead choosing to use the unstandardized measures in their ensuing statistical analysis.

Conclusions and Recommended Reading

approach leads to a more reliable SCR quantification due to not relying on a sloped bounding line but using the abscissa instead.

There are several advantages and disadvantages to be taken into account when considering using EDA measures in JDM research. The 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 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 it is reflecting. A clear disadvantage of skin conductance is the slowness and time lag of its signal, typically requiring long ISIs. Newer analysis approaches, however, promise to help mitigate this issue.

We have provided only a very brief overview of the physiological background and the various ways to measure different components of EDA besides SCRs. This information and much else about EDA can be found in the excellent and thorough volume by Boucsein (1992). Other recommended chapters have been written by Dawson, Schell, and Filion (2007) and Venables and Christie (1980). Naqvi and Bechara (2006) published a chapter on EDA related to the IGT and the SMH. If the reader is specifically interested in the neural substrates involved in EDA, we recommend the work by Critchley, Dolan and colleagues (an overview can be found in Critchley, 2002) and the work by the Iowa group, e.g., on the role of ventromedial cortex (e.g., Bechara et al., 1996 and Bechara, Damasio, Tranel, & Damasio, 1997). For more novel analysis approaches using short ISIs, we suggest consulting the most recent literature (also in fMRI) as this is an area of rapid development (Alexander et al., 2005; De Clercq, Verschuere, De Vlieger, & Crombez, 2006; Lim et al., 1997).

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