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Methodological Considerations in Ambulatory Skin Conductance Monitoring

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Abstract

Little is known how much skin conductance (SC) recordings from the fingers are affected by factors such as electrode site deterioration, ambient temperature (TMP), or physical activity (ACT), or by age, sex, race, or body mass index.

We recorded SC, TMP, and ACT in 48 healthy control subjects for a 24-hour period, and calculated SC level (SCL), its standard deviation, the coefficient of SC variation, and frequency and amplitude of non-specific SC fluctuations. One method of assessing electrode site deterioration showed an average decline of 20 %, while a second method found no significant change. All SC measures were higher during waking than sleep. Other factors influenced different measures in different ways. Thus, 24-hour SC recording outside the laboratory is feasible, but some measures need to be corrected for the influence of confounding variables.

Keywords

skin conductance; non-specific fluctuations; ambulatory recording; arousal

Introduction

With the exception of measuring hot flashes (for example, Thurston et al., 2005), which are more related to thermoregulation than to emotional activation, long-term electrodermal recording has rarely been reported in the literature. Theoretically such recording in a natural setting could contribute to our understanding of emotions and stress in people with and without mental disorders (see also, Turpin, 1990). Fowles (1980) linked electrodermal activity to Gray's Behavioral Inhibition System, neural pathways related to anxiety, citing numerous papers that show increases in electrodermal activity in response to conditioned stimuli for punishment. Indeed, anxious arousal indicated by increased electrodermal activity and reactivity has been observed in a variety of anxiety disorders, such as panic disorder (Braune et al., 1994; Hoehn et al., 1997; Lader and Wing, 1964) and posttraumatic stress disorder (Blechert et al., 2007). In depression, on the other hand, electrodermal activity is often reduced (Argyle, 1991; Ward et al., 1983).

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Ambulatory monitoring can test whether findings recorded for limited time periods or in special settings also are present in daily life. In panic disorder and generalized anxiety disorder, for example, normal skin conductance levels but reduced variance were observed in time limited ambulatory recordings (Hoehn-Saric et al., 2004), while a more recent 24-hour ambulatory study found chronically elevated skin conductance levels in panic disorder patients (Doberenz et al., 2010). But ambulatory studies are rare. Although technically feasible, investigators may have been discouraged by the possibility that long-term recordings in daily life might be subject to uncontrollable confounding influences of electrode site deterioration, ambient temperature, physical activity, and incidental environmental stimuli.

To our knowledge, only two studies have been published on the problems of long-term ambulatory electrodermal recording. Turpin et al. (1983) tested 12 subjects for a maximum of 7 hours. Epidermal hydration, produced by aqueous electrode solutions with a salt concentration lower than interstitial fluid or sweat or with high percentages of water in the gel base, had been suspected of negatively affecting long-term skin conductance (SC) measurement by causing swelling of the epidermis and closure of sweat gland pores (Fowles and Venables, 1970). Recording of electrical activity of the heart or brain may benefit by skin changes towards lower resistance under electrodes over time, but for SC such changes lead to inaccuracy. Thus, Turpin et al. (1983) compared hydrating (high water content in base solution) vs. non-hydrating (minimal water content in base solution but similar salt content) electrolyte mediums. Contrary to their prediction of a continuous decrease over three hours in SC level (SCL) and in the number and amplitude of SC responses (SCRs) to a reaction time task, no main effect for duration of recording could be found, indicating no differences in these measures between old and freshly applied electrodes. The hydrating medium, however, resulted in significantly fewer and smaller SCRs after three and six hours compared to the non-hydrating gel.

Boucsein et al. (2001) obtained reliability estimates of electrodermal responses in different auditory habituation sequences after 24-hour monitoring from 12 female students. They compared freshly applied electrodes to old electrodes that had been worn 24 hours. The correlation of SCR amplitudes between a reference set of freshly applied electrodes measured by a laboratory device and *freshly* applied electrodes at a different site recorded simultaneously by an ambulatory device was 0.96 (n=12), between the reference set and the *old* electrodes at a different site measured with the ambulatory device was 0.85 (n=3), and between the reference set and a set of *freshly* applied electrodes at the site of the *old* electrodes measured with the ambulatory device was 0.90 (n = 5). Despite the low subject numbers and missing statistical comparisons between these different correlations, the authors concluded that the ambulatory recordings lacked both reliability and validity after 24 hours, although these correlations seem reasonably high.

Turpin et al. (1983) were also aware of *circadian* influences on SC although they did not look at the effects of sleep. In part these may be related to changes in body temperature (Hot et al., 1999; Turpin et al., 1983), with SCL minima in the morning (5 am to 7 am) and maxima during the evening (7 pm to 9 pm) (Miró et al., 2002; Venables and Mitchell, 1996). Electrodermal levels and fluctuations have been observed to drop during sleep except during “electrodermal storms” (Lester et al., 1967) and transitorily during certain sleep stages (Broughton et al., 1965; Freixa i Baque et al., 1983; Johns et al., 1969; Johnson and Lubin, 1966; Koumans et al., 1968; Lester et al., 1967; McDonald et al., 1976).

Recording outside of a temperature-controlled laboratory also poses potential problems. Although the hands are not the principal areas of thermoregulatory sweating, Turpin et al. (1983) found that *ambient temperature* was positively correlated with the frequency of

SCRs, but only between subjects. Temperature did not correlate with SCL. In the laboratory, higher electrodermal activity was seen when exposing male subjects to hot compared to cold air (Lobstein and Cort, 1978; Scholander, 1963). Venables and Mitchell (1996) on the other hand, who examined tonic and phasic SC measures in children and young adults in a laboratory on the island of Mauritius during the hot and cold seasons, did not find seasonal differences in males. In females differences were limited to higher orienting response magnitudes during the hot season.

Physical activity, which is highly correlated with heart rate under ambulatory conditions, might also change SC through its effects on thermoregulation and sweating or through emotional arousal associated with the activity. Turpin et al. (1983) examined the effects of somatic activity on ambulatorily acquired SCL and SCR frequency and amplitude, but found no significant correlations. However, the wrist activity sensors they used could register only imperfectly the metabolic demands of gross body activity. Szpiller and Epstein (1976) found that motor activity (tapping rate) was unrelated to the number of non-specific SC fluctuations (NSFs; $r = .05$) during anticipation of shock in 60 undergraduate male volunteers, while correlations with magnitude of SCRs and SCL were small ($r = .23$ and $r = .27$, respectively). The relevance of this to motor activity in daily life is tenuous. In an aversive classical conditioning paradigm in 10 male rats, Roberts and Young (1971) examined the relationship between gross body movement, electrodermal activity recorded from the soles of the animals and heart rate (HR) and heart rate variability (HRV). They found that HR positively correlated with movement while SC increased after the conditioned stimulus regardless whether movement increased or decreased. Seventy-seven percent of the SC variability was attributable to habituation but none to movement, leading them to conclude that there was no electrodermal-somatic coupling.

Electrodermal measures may also vary with individual differences in age, sex, race, and body mass index (BMI). If aged skin is drier than young skin, electrodermal activity should diminish with *age*, which is supported by several studies (Barontini et al., 1997; Eisdorfer et al., 1980; Gavazzeni et al., 2008; Kronholm et al., 1993) although testing younger populations has yielded mixed results (Greene, 1976; Shibagaki et al., 1994; Venables and Mitchell, 1996). *Sex* may play a confounding role in EDA measurement because of monthly hormonal variations in women (Goldstein et al., 2005). Laboratory studies have been inconclusive, some finding no sex differences in electrodermal levels and responding (Carrillo et al., 2001; Furedy et al., 1999; Gavazzeni et al., 2008), and others finding that men have higher SCL (Eisdorfer et al., 1980; Kelly et al., 2006; Kronholm et al., 1993), and that women have higher SCR amplitudes to a stressful task (Carrillo et al., 2001; Eisdorfer et al., 1980). Some of these differences disappear with age (Eisdorfer et al., 1980) while others show no sex-age interactions (Gavazzeni et al., 2008). *Racial* effects on electrodermal measures may be due to a decreasing number of active sweat glands with increasing skin darkness (Boucsein, 1992). African versus Indian descent had no effect on SC measures of children and young adults from Mauritius (Venables and Mitchell, 1996), while some studies indicate that Caucasians show higher electrodermal activity levels than Blacks (for a review of the literature, see Boucsein, 1992). Little data exist on the effect of Asian versus Caucasian race on electrodermal measures. Wesley and Maibach (2003) cited data from unpublished conference abstracts suggesting lower electrodermal activity in Asians compared to Caucasians. *Body mass index* (BMI) did not correlate significantly with a sympathetic activity index (SCL, SCR amplitude, habituation of SCR) (Kronholm et al., 1993), although Peterson et al. (1988) reported a decrease in several non-electrodermal indicators of sympathetic and parasympathetic nervous system activity with increasing percentage of body fat and higher BMI.

Other influences on electrodermal variables that may be independent of emotional arousal in 24-hour recording include medications with anticholinergic effects (Schlenker et al., 1995), caffeine intake (Barry et al., 2005), and smoking (Furedy et al., 1999; Knott, 1984). Diseases such as hyper- or hypothyroidism (Dolu et al., 1999) or individual differences in the physical properties of the skin such as sweat gland density (Allen et al., 1973) also affect SC.

The first goal of the present study was to repeat the observations of Turpin et al. (1983) with a larger number of normal subjects, longer recording times, and a wider variety of SC variability measures. The most frequently obtained SC variability measure in laboratory experiments is non-specific SC fluctuations (number and amplitude), but their detection depends on arbitrary amplitude and rise-time thresholds based on visual impressions rather than on theory (Bach et al., 2010). Whether these thresholds are valid in an ambulatory setting is unknown. A measure with fewer assumptions is skin conductance variance, which was used by Hoehn-Saric et al. (2004) in an ambulatory study of panic disorder and generalized anxiety disorder. They found skin conductance variance to be reduced in their sample compared to healthy volunteers, which they interpreted as diminished autonomic flexibility in these patients. SC variance is affected by both number and amplitude of SC fluctuations. Here we report the more familiar SC standard deviation. As this variability measure depends on SCL, we also computed the coefficient of SC variation. Area under curve (AUC) of SC has also been proposed (Bach et al., 2010) but was not tested here.

From our review of the literature, we predicted that (a) SCL would decline over the course of 24 hours due to epidermal hydration-induced electrode site deterioration, (b) all measures of electrodermal activity would decrease during sleep, (c) ambient temperature would be positively related to the number and amplitude of NSF, (d) physical activity would show no effects on any of the electrodermal measures, (e) age would be negatively related to SCL and NSF number and amplitude, and (f) men would show higher SCL and smaller NSF amplitudes. We were uncertain about the effects of race and BMI.

The second goal of this study was to determine the relationship between electrodermal measures and self-reported arousal and sleep quality after the effects of the confounding variables are removed.

Materials and Methods

1.1. Participants

Forty-eight healthy volunteers (37.3 ± 11.8 years, age range 19 – 64 years, 67% women) were recruited from the local community by advertisement for three separate but methodologically similar studies. Their mean BMI was 23.1 ± 3.2 kg/m² and the majority of participants were self-identified as Caucasian (48%) or Asian (44%), while four identified themselves as of other races (8%, 2 American Indian/Alaska Native, 1 Black, 1 more than one race). There were no significant correlations among age, sex, BMI, or race. Exclusion criteria for all participants were substance abuse or dependence in the past year and a history of, or current, DSM-IV axis I disorders as diagnosed by the Structured Clinical Interview for DSM-IV-TR Axis I Disorders (First et al., 2001). Also excluded were participants who reported a history of severe cardiovascular, lung, or neurological disease, uncontrolled thyroid problems, or who showed signs of cognitive impairment during the phone screening and direct interactions with the interviewers. Eligible participants were allowed to continue on stable doses of medicines prescribed by physicians, but were excluded if they were taking psychoactive drugs or drugs with substantial anticholinergic effects, which have direct effects on SC. Participants received monetary compensation for being tested.

1.2. Procedure

This investigation was carried out in accordance with the latest version of the Declaration of Helsinki. The study design was reviewed and approved by the Stanford Institutional Review Board. Individuals who passed the phone screening were invited to an appointment where they gave written informed consent for further assessment. This began with a Structured Clinical Interview for DSM-IV-TR Axis I Disorders (First et al., 2001) conducted by graduate students in psychology who were trained and supervised by a clinical psychologist. If no grounds for exclusion were found, they were asked to wash their hands with soap in preparation for the application of skin conductance electrodes (Dawson et al., 1990; Venables and Christie, 1980). Next, they underwent testing in a laboratory room where numerous autonomic and respiratory measures were recorded while they were trying to relax and to change their breathing according to several different instructions. The procedure and results of this testing have been reported elsewhere (Conrad et al., 2007; Roth et al., 2008; Wollburg et al., 2008). After the laboratory session, the ambulatory monitoring device was connected at 1:17 pm on average. Participants wore it continuously until they returned the next day. Length of recording ranged between 18:42 and 28:51 with a mean of 24:02 (hr:min) during which the SC electrodes were applied to their non-dominant hand, secured with medical tape for the duration of the recording. All participants were supplied with additional tape to secure the electrodes if they seemed to be coming unattached. As soon as the participants returned to the laboratory, a set of fresh SC electrodes was attached to the same hand. After 20 min, an SCL reading was first obtained from the old SC electrodes and immediately afterward (within 20 sec) from the freshly applied electrodes using the same digital recorder.

During the 24-hour monitoring, subjects were asked to fill out a short questionnaire at 4 pm and 8 pm the first day, as well as at 8 am the second day. This questionnaire assessed their emotional state over the last four hours (4 pm and 8 pm) or since they woke up in the morning (8 am) on a subjective units of distress scale from 0, “not at all”, to 10, “extremely” for such items as “excited” and “sleepy”. Self-reported measures of sleep including the number of awakenings during sleep, sleep duration, and whether the sleeper felt rested after sleep were obtained on the morning of the second day of recording. In addition, participants were given a packet of questionnaires to return completed the next day, which included the Beck Anxiety Inventory (BAI; Beck et al., 1988) to be answered for the past week and the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) to be answered for the past month. The Beck Depression Inventory (BDI; Beck et al., 1961) was given to all but 19 participants who instead received the short version of the Beck Depression Inventory (Abdel-Khalek, 2001).

1.3. Physiological Assessment

Physiological data were recorded with a 3-channel ambulatory digital recorder (3991x/3 BioLog, UFI, Moro Bay, CA, USA) worn in a handbag or waist pack. The device measures $3.3 \times 7.1 \times 12.7$ cm and weighs 230 g with its battery. Channels were (1) skin conductance measured by applying 0.5 V DC to electrodes on the middle or lower phalanges of digits 2 and 3 (digits 4 and 5 for the freshly applied electrodes if there was not enough space on digits 2 and 3) of the non-dominant hand. Skin conductance in the range 0.01–39.95 μS (iemens) was sampled with ± 0.01 μS resolution at 10 Hz and digitally low-pass filtered at 0.5 Hz. Commercial disposable electrodes with a circular contact area of 1 cm diameter were used (EL507, Biopac Systems, Inc., Goleta, CA, USA). They were pre-filled with isotonic wet gel (by weight 0.5% saline and 75% water), which was supplemented by additional gel of the same kind applied to the center of the electrode. Gel of such high water content is likely to hydrate the skin under it. (2) Bodily activity was sampled at 1 Hz from a UFI 1110 Jitterbug Actigraph accelerometer attached to the participant’s ankle on the non-

dominant side. This device responds to motion in all directional axes. The absolute deviation of its voltage oscillations is a measure of leg activity in arbitrary units, which is representative of general body movement. (3) Ambient temperature was sampled with an accuracy of 0.1 degrees Celsius at 0.1 Hz from a sensor in the handbag or waist pack where it was exposed to ambient air but insulated from body heat and direct sun exposure. The recorder had an event-marker button, with which participants could indicate time of getting into bed and turning out the lights, and of getting up in the morning. The nature of the event was written on a paper log along with the time the button was pressed.

1.4. Data Reduction

Physiological recordings were analyzed offline with customized software written by the second author in Matlab® (MathWorks, Natick, MA, USA). First, following a standardized set of rules, data were examined visually for artifacts which were excluded from further analysis. Manual editing excluded time periods when electrodes were detached or that contained spikes in skin conductance (SC) greater than 0.5 μ Siemens, which represented movement artifacts or loose electrodes. Automatic editing excluded SC values below 0.5 μ Siemens. After editing, the SC data were filtered using a zero-phase order 10 low-frequency Butterworth filter with a cutoff frequency of 0.05 Hz. The data were then segmented into waking and sleeping by locating two times: getting into bed and turning out the lights, and getting up, both based on self-report, event markers, and an examination of the activity channel for cessation and resumption of activity.

The edited data were then analyzed in 1-min epochs during each of three periods (waking on day 1, sleeping, waking on day 2) resulting in, for example, 360 epochs (i.e., 6 hours) for one person's sleep recording. Skin conductance (SC) for each 1-min epoch was measured as: (1) SC level (SCL) from the *mean* of filtered SC; (2) SCL standard deviation (SCLstd) from the *standard deviation* of filtered SC; (3) Coefficient of SC variation from SCLstd divided by SCL; (4) Number of non-specific skin conductance fluctuations (NSFs). NSFs were detected as rises greater than 0.01 μ S (iemens) between consecutive samples of the first derivative of filtered SC. The detection program skipped forward 5 seconds before looking for the next rise; (5) Amplitude of these NSFs, calculated as the difference between the minimum SCL within 3 seconds before a rise and the maximum SCL within 3 seconds after a rise. Physical activity and ambient temperature were averaged over each 1-min epoch.

Psychological measures included retrospective ratings of recent emotional states (the adjectives "excited" and "sleepy") taken at three prescribed times during the 24-hour measurement period. The ratings at 4 pm and at 8 pm on the first day were used as an approximation for the emotional state on day 1, whereas the ratings of how subjects felt since waking up the morning of day 2 (taken approximately at 8 am) were used to estimate mood on the second day. To measure sleep quality, an ad hoc composite score was calculated as sleep duration - the number of awakenings during sleep + 1 if the individual felt rested after sleep. This score was scaled by multiplication by 1/3. Thus, a higher score indicates a better sleep quality.

1.5. Statistical analysis

Within-subject analyses were based on individual 1-min epochs as described above (continuous data), while for *between-subject* analyses these epochs were averaged for each of the three time periods (waking on day 1, sleeping, waking on day 2), resulting, for example, in one SCL value for sleeping.

Between-subject analyses—Psychophysiological data were analyzed using linear mixed models as suggested by Baggiella et al. (2000), following a top-down strategy (see

West et al., 2007). Marginal models (without any random effects specified) were fitted by maximum likelihood with an unstructured covariance matrix for the residuals using SPSS 17.0 (SPSS Inc., Chicago, IL).

- (1) The extent of electrode site deterioration was determined in two ways: First, SCL was compared from the old and the freshly applied electrodes (electrode effect: old vs. fresh), while controlling for *between-subject* effects of the categorical variables sex (male, female) and race (Asian, Caucasian, Other), and for the covariates age, body mass index, mean temperature (averaged over the whole 24-hr period), mean activity (averaged over the whole 24-hr period), and length of recording using two-sided t-tests (contrasts). Second, a 15 min period at the beginning of the 24-hr monitoring was averaged and compared to an averaged 15 min period at around the same time 24 hours later. Ambulatory SC variables from these two 15-min time periods (time effect: beginning of recording, 24 hours later) were compared while controlling for *between-subject* effects of the categorical variables sex (male, female) and race (Asian, Caucasian, other), and the covariates age, body mass index, mean temperature during each 15 min period, and mean activity during each 15 min period using two-sided t-tests (contrasts). Data with a time difference of exactly 24 hours between those two time periods were available from 29 subjects and data with at least a 23 hour difference from another 4 subjects. Comparable time periods from the remaining 15 subjects were not available because of equipment failure shortly before the monitoring ended (1 subject), detachment of the activity sensor rendering the data invalid (1 subject), and stopping the recording for scheduling convenience earlier than the full 24 hours (13 subjects). For both methods, a percentage change index was calculated as $((\text{old electrode} - \text{fresh electrode})/\text{fresh electrode} * 100)$.
- (2) All ambulatory SC variables averaged over time of day periods were tested for the effects of time of day (Waking on day 1, Sleeping, Waking on day 2), sex (male, female), race (Asian, Caucasian, Other), and the covariates age, body mass index, temperature (averaged over time of day period), and activity (averaged over time of day period). Effect size for each variable was calculated as Cohen's d using t values and degrees of freedom [$d = 2t/\sqrt{df}$]. Variables with p-values greater than 0.1 were omitted from the models unless the model fit changed significantly.
- (3) Daytime residuals (day 1 and day 2, without sleeping) of the models described in (2) were subsequently entered as dependent variables into new models with several subjective self-report variables as covariates (e.g., excitement on day 1 and day 2, and sleep quality) to test their effect on the electrodermal variables after time of day and other variables had been accounted for.
- (4) To determine the relationships among the various SC measures, *between-subject* Spearman correlation coefficients (on averaged data) were calculated for all ambulatory SC variables for each time period separately (day 1, sleeping, day 2). To test whether they are differentially related to each other, these correlation coefficients were then converted into Pearson correlation coefficients based on formula (4) in Rupinski and Dunlap (1996), so they could be statistically compared while taking their dependence into account. The method employed here is based on Cohen and Cohen (1983), p. 57, whose formula yields a t-statistic with $n - 3$ degrees of freedom that tests for a significant difference in the correlation between variables X & Y and V & Y, e.g., SCL & SCLstd and number of NSFs and SCLstd. We did not adjust these analyses for Type I errors from multiple testing, so these results need to be interpreted with caution.

Within-subject analyses

- (5) The *within-subject* effects of continuously recorded physical activity and ambient temperature on the electrodermal indices (1-min epochs) were calculated by correlating the measures with each other for each subject, t-testing the Fisher's z-transformed correlation coefficients of the whole sample, and calculating Cohen's d effect sizes as described above.
- (6) To determine the relationships among the various SC measures, *within-subject* correlations as described above (see section 5) were calculated for all ambulatory SC variables for each time period separately (day 1, sleeping, day 2).

Results

- a. *Electrode site deterioration.* Comparing manual SCL readings from the old and freshly applied electrodes at the end of the 24-hr monitoring (first method), electrode sensitivity declined significantly by an average of 20% ($n=46$) over 24 hours ($F(1,46)=9.0$, $p<0.01$) with the old electrodes registering a mean SCL of 9.4 μS just before they were replaced, compared to 11.8 μS for the freshly applied electrodes. The difference between old and fresh could not be accounted for by age, sex, BMI, race, total 24-hour ambient temperature, total 24-hour physical activity, or the length of recording. The second method compared 15-min SC measurements from the same electrodes taken 24 hours apart. Electrode sensitivities did not change significantly (average change = 0%, $n=33$) with the electrodes registering a mean SCL of 6.6 μS both during first 15-min period (freshly applied) and 24 hours later (old). The differences in SCLstd, the coefficient of SC variation, amplitude or number of NSF's were not significant, indicating no significant change in electrode sensitivity.
- b. *Time of day* showed consistently lower electrodermal activity in all measures during sleep than during waking. SCL declined significantly from day 1 to day 2 whereas the coefficient of SC variation showed the opposite effect (see Figure 1).
- c. *Ambient temperature.* As shown in Table 1, ambient temperature significantly increased the number of NSF's but did not affect other electrodermal indices between-subjects. Within-subjects, however, significant positive relationships for all electrodermal indices were observed on both days, with effect sizes ranging from 1.0 for SCL to 1.5 for SCLstd on the first day and 0.7 for SCL and 0.8 for all others on the second day (see Table 2). The only exception was the coefficient of SC variation, which was not significantly related to temperature on the second day ($d=0.5$). During sleeping, on the other hand, none of the electrodermal measures showed significant within-subject relationships with ambient temperature (d 's ranging from 0.0 for NSF amplitude to 0.5 for the number of NSF's).
- d. *Physical activity* also increased the number of NSF's between-subjects, although its effect was smaller than for ambient temperature and did not reach significance. As shown in Table 2, within-subject physical activity was positively related to all electrodermal indices (effect sizes between 1.6 and 2.4 on both days) except for the amplitude of NSF's, which actually decreased with higher levels of activity (effect size -1.0 on day 1 and -0.3 on day 2). During sleeping, however, only positive correlations were observed, which were large for SCL standard deviation ($d=1.7$), the coefficient of SC variation ($d=2.6$), and the number of NSF's ($d=1.5$), and somewhat smaller for SCL and the NSF amplitudes (0.7).

- e. With the exception of the coefficient of SC variation (SCLstd/SCL), *age* was consistently negatively related to all electrodermal indices. This relationship was significant for the number of NSFs, whereas SCL and SCL standard deviation only tended to decrease with age.

Sex significantly affected NSF amplitudes and the coefficient of SC variation such that men had lower values than women.

Asians and Caucasians were the only two *racial* groups in our sample large enough for comparison. Asians had lower SCL and fewer NSFs than Caucasians, but higher coefficients of SC variation. No other differences were observed. Body mass index (*BMI*) significantly lowered the number of NSFs and was negatively but not significantly related to SCL and SCL standard deviation with small to medium effect sizes.

Intercorrelations of electrodermal measures

During both the first and the second waking period, all electrodermal measures were highly intercorrelated *between subjects* with correlation coefficients ranging from 0.6 to 0.9, and NSF amplitudes accounting for the lower values (see Table 3). The only exceptions were the correlations between SCL and the coefficient of SC variation which were lower than 0.6 and became non-significant on the second day. Statistically testing the relative strength of these correlations using t-tests confirmed that during waking, SCL was more closely related to SCLstd and the number of NSFs than to their amplitude. It was least related to the coefficient of SC variation, as were SCLstd and the number of NSFs. The most closely related to the coefficient was NSF amplitude. During both waking periods and sleeping, the number of NSFs was least related to the amplitude of NSFs. During sleeping, correlations between SCL, SCL standard deviation and the number of NSFs still ranged from 0.8 to 0.9, while all correlations with NSF amplitude and between the coefficient of SC variation and SCL standard deviation became non-significant. The coefficient of SC variation correlated negatively with SCL and the number of NSFs. Statistical comparisons of these correlations showed that NSF amplitude was unrelated to the other measures. SCL, SCLstd, and the number of NSFs showed equally strong correlations with each other. The coefficient of variation was more closely related to SCL than to the other measures. *Within subject*, all Fisher's z-transformed inter-correlations were significantly positive at all times.

Electrodermal residuals and self-report

Subjects reported normal values on trait measures of depression (BDI: 1.9 ± 3.5 , $n=48$) and anxiety (BAI: 2.5 ± 3.0 , $n=33$), and low levels of excitement ("feeling excited": 0.9 ± 1.0 , $n=47$) and daytime sleepiness ("feeling sleepy": 2.6 ± 1.6 , $n=47$) on the days of testing. In this group of healthy subjects, there were no significant relationships between the self-report measures above and any of the electrodermal daytime residuals. Information on subjective sleep characteristics is limited due to missing data. On the nights of testing, subjects reported waking up 1.8 ± 1.8 times ($n=25$), sleeping for 7.6 ± 1.0 hours ($n=26$), and feeling rested in 72% of cases ($n=25$). Their calculated score on the composite sleep quality measure was 2.1 ± 0.7 ($n=23$), and their habitual sleep quality was normal (PSQI: 3.8 ± 1.8 , $n=23$). Measures of subjective sleep quality (PSQI total score, calculated measure of sleep quality on night of testing) did not co-vary with any of the residuals at night.

Discussion

The results for *electrode site deterioration* were contradictory. The first method that involved comparing single SCL values from old and freshly applied electrodes at the end of the monitoring resulted in a significant SCL decrease over 24 hours and suggests electrode site deterioration. The second method, however, which compared 15-min periods at the

beginning of the recording with 15-min periods about 24 hours later from the same pair of electrodes, could not detect significant differences in any of the SC measures. The first method raises the question whether individual differences in emotional activation induced by the experimenter switching from the old to the new electrodes might have caused higher SCL values from the freshly applied electrodes. That SCL on the second day was lower than on the first day appears most likely to be a circadian *time of day* effect. Electrodermal activity has been reported to be lowest in the morning (Miró et al., 2002; Venables and Mitchell, 1996), which in our study was on the second day. Measures of electrodermal variability, however, were not lower on the second day. Coefficient of skin conductance (SC) variation was actually higher, probably because the drop in SCL on the second day increased the ratio of standard deviation to level. This is in contrast to Turpin et al.'s findings (1983) of both fewer and smaller SC responses in hydrating electrodes, but again, they only measured SC for up to 6 hours. Considering the methodological problems of the first method, we think that the results of the second are more accurate, and that electrode site deterioration has only a minimal effect on 24-hour SC measurements.

As predicted, both tonic and phasic electrodermal activity were much higher during *waking* than *sleeping*. This fits with regarding sleep as a low point on a SC arousal continuum (Koumans et al., 1968). We did not find evidence of greater night-time compared to waking rates of non-specific electrodermal fluctuations that had been previously reported (e.g., Broughton et al., 1965; Johnson and Lubin, 1966). Such "storms" (Lester et al., 1967) were usually seen with skin potential rather than skin conductance.

Ambient temperature had little impact on any of the between-subject measures except number of NSFs. This finding is similar to that of Turpin et al. (1983) who found no temperature effects on SCL but increased frequencies of NSFs with rising temperature. In the laboratory, increased palmar SCLs at hotter air temperatures have been observed (Scholander, 1963) which could be expected even though thermoregulatory sweating on the palms and soles is less prominent than on other skin areas. We observed, however, strong within-subject effects in all SC measures during the first day (and all but the coefficient of SC variation on the second day). Turpin et al. (1983) did not find the positive within-subject effects of temperature that we observed, possibly because their data pool was limited to mean values from 12 hourly intervals of a few minutes each. Non-significant temperature relationships at night might have been confounded by inconsistency in the location of the sensor. In bed, subjects removed the waist pack with the sensor in it, some putting the pack under the covers and some outside the covers. Thus, the effects of temperature on SC data cannot be generalized to entire 24-hour periods, but at the least waking and sleeping periods need to be considered separately. Averaging over longer time periods might obscure or remove the effects of possible relationships between ambient temperature and SC data.

Previous research had indicated that *physical activity* does not affect electrodermal activity (Roberts and Young, 1971; Turpin et al., 1983). In the current study, none of the electrodermal measures were significantly affected between subjects by the level of physical activity, although activity tended to increase the number of NSFs. Within subjects, however, physical activity increased electrodermal activity both during day and night, with the exception of NSF amplitude, which was negatively related to physical activity during the day. Activity may raise SCL and increase fluctuations because of associated emotional activation, or in the case of sustained or strenuous activity, because of increases in body temperature. Like for ambient temperature, shorter data segments might be necessary to show relationships between activity and SC most clearly.

Age was negatively related to the number of NSFs and also its relationships with SCL and SCL standard deviation were in the expected direction (e.g., Eisdorfer et al., 1980;

Gavazzeni et al., 2008) and of medium size. Coefficient of SC variation has less dependence on mean levels, and it did not show an age effect, recommending this measure for populations of diverse ages.

As predicted, *men* showed smaller NSF amplitudes and overall smaller coefficients of variation than *women* but their SCL was only slightly higher and did not reach significance. This is contrary to previous reports of significantly higher SCL in men (Eisdorfer et al., 1980; Kelly et al., 2006; Kronholm et al., 1993), but consistent with Furedy et al. (1999). Significant findings were obtained in large samples ($N > 95$) in which quite small differences became significant. In the current study, the other SC variability indices, SCL standard deviation and the number of NSFs, also showed small to medium albeit non-significant effect sizes in the direction of SC variability being higher in women.

Asians exhibited lower SCL and a trend to fewer NSFs than *Caucasians*. To the authors' knowledge, this is the first time these effects have been looked at ambulatorily in these two ethnicities. However, the coefficient of SC variation was higher in Asians compared to Caucasians indicating that once the effect of mean levels is reduced, Asians have higher SC variability. This variability is different from the kind indexed by the number of fluctuations.

Body mass index (BMI) decreased the number of NSFs without having a significant influence on other measures. These findings confirm the results from Kronholm et al.'s (1993) sample of 199 subjects, which did not show a relationship between BMI and a sympathetic index including SCL and SCR amplitudes (but not the number of NSFs). Effect sizes for SCL and SCL standard deviation in our study were of medium size and in the direction of higher BMI being associated with less electrodermal activity, and might have been significant in a sample as large as Kronholm et al.'s (1993). Peterson et al. (1988) also found a decrease in other sympathetic measures with increasing BMI. These findings indicate a negative relationship between BMI and some indicators of electrodermal activity. Coefficient of SC variation and NSF amplitudes on the other hand, do not seem to be influenced by BMI.

Overall, our results show that the various electrodermal indices we measured are not equally affected by the confounding variables. Two clusters of measures emerge. One comprises SCL, SC standard deviation, and the number of NSFs, which showed similar susceptibility to confounding variables and were correlated more closely with each other than with two other measures. The other cluster was NSF amplitude and coefficient of SC variation, which were less correlated with other measures. The coefficient of SC variation was the only measure that was greater in Asians than in Caucasians. These differences imply that not all electrodermal measures index a unitary activation dimension. A recent functional magnetic resonance imaging study found that different brain structures regulate tonic and phasic SC activation (Nagai et al., 2004). SCL, a tonic measure, had a closer relationship with brain regions associated with anticipatory anxiety (for a discussion, see Parente et al., 2005) than did SC variability. A recent 24-hour monitoring study in panic disorder patients found SCL to be chronically elevated in these anxious patients compared to normal controls (Doberenz et al., 2010) while measures of phasic SC activation were not.

Note that our between-subject results are based on averaging data over several hours, and thus are relatively insensitive to common variance that may be present in shorter epochs. Only with shorter epochs did relationships with ambient temperature and physical activity emerge. Similarly, longer analysis epochs may have obscured more transient relationships between mood and physiology. After the effects of the confounding variables were removed, none of the residuals of the averaged between-subject electrodermal measures showed significant relationships with self-reports of daytime arousal or subjective sleep quality.

Relatively small variations and floor effects in emotional activation in our sample of healthy volunteers may also have contributed to a lack of relationships.

Our study is limited in several ways. First, the relatively small sample size did not allow us to test for interactions between the different confounding factors. We tested quite a few measures in a relatively small subject sample. Second, we could have said more about the relationship of our measures to emotional activation if we had measured additional physiological channels such as heart rate and heart rate variability. Technological advances make multichannel recording less and less cumbersome and intrusive. Third, electrode deterioration using the first method could have been measured more accurately if fresh electrodes had been applied near the old electrodes and measurements made *simultaneously* for the two sets rather than sequentially, avoiding the possibility that emotional activation changed between measurements. We did not use a standardized challenge to assess skin conductance reactivity after 24-hours as other studies have done, which would have allowed us to compare the differences between old and fresh electrodes in electrodermal reactivity for the other SC measures as well.

We hope that our results will encourage greater use of ambulatory electrodermal monitoring in the study of emotional activation during waking activities and sleep. Corrections for the effects of confounding variables are quite feasible, for example, by including them as covariates in statistical analyses. While this might not be necessary for ambient temperature and physical activity at the between-subject level, it is advisable at the within-subject level. In clinical studies using electrodermal measures, additional factors such as the effects of psychotherapeutic medication must also be taken into account as we discovered in our 24-hour panic disorder study (Doberenz et al., 2010). Even relatively healthy populations in developed countries are frequent users of over-the-counter and prescription medications with autonomic or central nervous system effects.

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Figure 1. Electrodermal activity by measure for each 1-min epoch synchronized by onset of sleeping period. At least 25 valid observations were required for included time epochs. (SCL, skin conductance level; SCLstd, SCL standard deviation; NSF, non-specific fluctuations)

Table 1

Effect sizes and significance levels of between-subject relationships of confounding variables and electrodermal activity measures.

<i>Confounding variables</i>	<i>SCL</i>	<i>SCLstd</i>	<i>SCLstd/SCL (coefficient of SC variation)</i>	<i>NSF (number)</i>	<i>NSF (amplitude)</i>
<i>Temperature</i>	(0.4)	(0.2)	(0.0)	positive (0.6 [†])	(0.1)
<i>Activity</i>	(0.0)	(0.0)	(0.0)	positive (0.3 [†])	(0.1)
<i>Age</i>	negative (−0.6 [†])	negative (−0.5 [†])	(0.1)	negative (−0.6 [*])	(−0.3)
<i>Body mass index</i>	(−0.4)	(−0.4)	(0.0)	negative (−0.6 [*])	(0.0)
<i>Categorical Time</i>	W1>W2>S (W1>W2: 0.8 ^{**}) (W1>S: 1.7 ^{***}) (W2>S: 1.4 ^{***})	W1=W2>S (W1=W2: 0.1) (W1>S: 1.8 ^{***}) (W2>S: 1.4 ^{***})	W2>W1>S (W1<W2: −1.4 ^{***}) (W1>S: 1.6 ^{***}) (W2>S: 1.5 ^{***})	W1=W2>S (W1=W2: −0.1) (W1>S: 1.8 ^{***}) (W2>S: 1.8 ^{***})	W1=W2>S (W1=W2: 0.3) (W1>S: 1.1 ^{***}) (W2>S: 0.8 ^{**})
<i>Sex</i>	(0.2)	(−0.3)	Men < Women (−0.8 ^{**})	(−0.4)	Men < Women (−0.7 [*])
<i>Race</i>	Asian<Caucasian (−0.6 [*])	(−0.4)	Asian>Caucasian (0.8 ^{**})	Asian<Caucasian (−0.6 [*])	(0.2)

Note. Values given in brackets represent Cohen's d effect sizes (based on t statistics and degrees of freedom from contrast comparisons);

[†] p-value <0.1 (trend),

^{*} p-value<0.05,

^{**} p-value<0.01,

^{***} p-value <0.005; Abbreviations. SCL, skin conductance level; SCLstd, SCL standard deviation; NSF, non-specific fluctuations; W1, Waking on day 1; W2, Waking on day 2; S, Sleeping.

Table 2

Within-subject correlations between physical activity, ambient temperature, and electrodermal measures.

<i>Confounding variables</i>	<i>SCL</i>	<i>SCLstd</i>	<i>SCLstd/SCL (coefficient of SC variation)</i>	<i>NSF (number)</i>	<i>NSF (amplitude)</i>
<i>Physical activity</i>	W1: 2.1***	W1: 1.9***	W1: 1.6***	W1: 2.4***	W1: -1.0**
	S: 0.7*	S: 1.7***	S: 2.6***	S: 1.5***	S: 0.7*
	W2: 2.2***	W2: 1.9***	W2: 1.6***	W2: 2.4***	W2: -0.3
<i>Ambient temperature</i>	W1: 1.0**	W1: 1.5***	W1: 1.3***	W1: 1.3***	W1: 1.2***
	S: 0.3	S: 0.5	S: 0.2	S: 0.5	S: 0.0
	W2: 0.7*	W2: 0.8**	W2: 0.4	W2: 0.8**	W2: 0.8**

Note. Values represent Cohen's d effect sizes (based on t statistics and degrees of freedom from testing Fisher's z-transformed correlation coefficients);

* p-value<0.05,

** p-value<0.01,

*** p-value <0.005;

Abbreviations. SCL, skin conductance level; SCLstd, SCL standard deviation; NSF, non-specific fluctuations; W1, Waking on day 1; W2, Waking on day 2; S, Sleeping.

Table 3

Intercorrelations of electrodermal measures.

<i>Electrodermal measures</i>		SCL	SCLstd	NSF (number)	NSF (amplitude)	SCLstd/SCL (coefficient of SC variation)
<i>SCL</i>	<i>Between-S</i>		W1: 0.9** S: 0.8**	W1: 0.9** S: 0.8**	W1: 0.7** S: 0.1	W1: 0.3* S: -0.7**
	<i>Within-S</i>		W2: 0.9**	W2: 0.8**	W2: 0.6**	W2: 0.2
<i>SCLstd</i>	<i>Between-S</i>	W1: 11.1*** S: 3.7***		W1: 0.9** S: 0.9**	W1: 0.9** S: 0.2	W1: 0.7** S: -0.2
	<i>Within-S</i>	W2: 12.0***		W2: 0.9**	W2: 0.8**	W2: 0.6**
<i>NSF (number)</i>	<i>Between-S</i>	W1: 8.1*** S: 4.0***	W1: 8.7*** S: 4.7***		W1: 0.7** S: 0.2	W1: 0.6** S: -0.3*
	<i>Within-S</i>	W2: 8.0***	W2: 8.9***		W2: 0.6**	W2: 0.5**
<i>NSF (amplitude)</i>	<i>Between-S</i>	W1: 3.3*** S: 2.3***	W1: 12.6*** S: 4.2***	W1: 1.9*** S: 1.3***		W1: 0.8** S: -0.0
	<i>Within-S</i>	W2: 2.6***	W2: 8.0***	W2: 1.7***		W2: 0.7**
<i>SCLstd/SCL (coefficient of SC variation)</i>	<i>Between-S</i>	W1: 4.9*** S: 0.8**	W1: 9.3*** S: 6.0***	W1: 9.3*** S: 3.2***	W1: 12.8*** S: 4.0***	<i>Between-S</i>
	<i>Within-S</i>	W2: 5.1***	W2: 9.2***	W2: 7.5***	W2: 6.7***	<i>Within-S</i>

Note. Between-subjects correlations represent Spearman's rho correlation coefficients, within-subject values represent Cohen's d effect sizes (based on t statistics and degrees of freedom from testing Fisher's z-transformed correlation coefficients);

* p-value<0.05,
** p-value<0.01,
*** p-value <0.005;

Abbreviations. SCL, skin conductance level; SCLstd, SCL standard deviation; NSF, non-specific fluctuations; Within-S, within-subject correlations; Between-S, between-subjects correlations; W1, Waking on day 1; W2, Waking on day 2; S, Sleeping.