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ORIGINAL ARTICLE

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Bilateral comparison of traditional and alternate electrodermal measurement sites

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Abstract

Advances in mobile and wireless technology have expanded the scope of electrodermal research. Since traditional electrodermal measurement sites are not always suitable for laboratory research and are rarely appropriate for ambulatory measurements, there is a need to explore and contrast alternate measurement locations. We evaluated bilateral electrodermal activity (EDA) from five measurement sites (fingers, feet, wrists, shoulders, and calves). In a counterbalanced, randomized, within-subjects design study, participants (N = 115) engaged in a 4-min-long breathing exercise and were exposed to emotionally laden and neutral stimuli. High within-subject correlations were found between the EDA measured from fingers bilaterally (r = .89), between the left fingers and both feet (r = .72). Moderate correlations were found between EDA measured from the left fingers and wrists (r = .30 and r = .33), low correlations between the left fingers and the shoulders (r = −.03 and r = −.06) or calves (r = .05 and r = .14). Response latency was the shortest on the fingers while it was the longest on the lower body. Short response windows would miss some of the responses from the palmar surfaces and a substantial number from other evaluated locations. The fingers and the feet are the most reliable locations to measure from, followed by the wrists. We suggest setting site-specific response windows for different measurement locations. An investigation of repeatability showed that within-subject correlations, response frequencies, response amplitudes show a similar pattern from the first measurement time to a later one.

KEYWORDS

anatomical location, electrodermal, latency, SCR, skin conductance

1 | INTRODUCTION

The ecological validity and generalizability of acute laboratory measures of psychophysiological parameters have been challenged multiple times (Schwarz, 2012). These limitations drive the methodological and technical advances toward measurements in real-life settings and ambulatory monitoring. The rising popularity of wearable devices increases the feasibility of noninvasive data collection (Wilhelm, Grossman, & Müller, 2012). However, the measurement sites most

commonly used for recording psychophysiological parameters, such as electrodermal activity (EDA), are not viable for recording day-to-day activities or for laboratory research in some instances. Thus, there is a growing need to find new, valid electrode sites. In this project, we aimed to compare the usefulness of different anatomical sites for electrodermal measurement.

It has been widely agreed that the most responsive sites to measure EDA (in awake condition in a laboratory) are the palmar and plantar surfaces (Boucsein, 2012; Boucsein et al., 2012; Dawson, Schell, & Filion, 2007; Edelberg, 1967; Payne, Dawson, Schell, Singh, & Courtney, 2013; Payne, Schell, & Dawson, 2016; Rickles & Day, 1968). However, there are instances where measurement from those body parts is not feasible (e.g., Kasos, Kekecs, Kasos, Szekely, & Varga, 2018; Rickles & Day, 1968). Also, there are certain conditions, for example, during sleep measuring non-Rem sleep storm activity, when the strongest responses were found not on the fingers but on the wrists (Sano, Picard, & Stickgold, 2014). The palmar and plantar sites are suboptimal for ambulatory measurement, since these surfaces are often used during day-to-day activities, which would result in displacement of the electrodes or movement-related artifacts. Also, electrodes located at the traditional measurement sites (palmar and plantar surfaces) are not comfortable for long-term wear. Thus, recording EDA during experiments when traditional sites are not available and during everyday activities, or over a long period of time requires a new approach. New wearable devices are designed to measure from body sites that are comfortable for the wearer for extended periods and their appearance is inconspicuous. However, these measurement locations do not tend to correspond to traditional measurement locations. Comparing anatomical locations bilaterally might also be important, since recent reports highlight lateral differences in skin conductance level (SCL) and skin conductance response (SCR) (e.g., Banks, Bellerose, Douglas, & Jones-Gotman, 2012; Kasos, Zimonyi, et al., 2018; Picard, Fedor, & Ayzenberg, 2015).

The wrists are regarded as practical locations for long-term electrode placement. This alternate measurement site has been studied extensively in the past few years (Fletcher et al., 2010; Picard et al., 2015; Poh et al., 2012; Poh, Swenson, & Picard, 2010; Sano et al., 2014). However, results regarding this measurement site are contradictory. Some reported relatively high within-subject correlation with the palmar surfaces (e.g., Poh et al., 2010; van Dooren, de Vries, & Janssen, 2012), while others found lower within-subject correlation (Payne et al., 2016; Ranogajec & Geršak, 2014). These discrepancies might be explained by the varied hydration time used in studies evaluating this anatomical location. In a recent research that found only moderate correlation between the wrists and the fingers, the hydration time allowed was only 1 min before the start of the experiment (Payne et al., 2016). Some, however, suggest that a hydration time of 25 to 120 min would be necessary on the wrists (Payne et al., 2016). The shoulders, and the lower calves are also used in some studies as optimal electrode locations for longer or nonstationary measurements when the palmar sites are not available (Kasos, Kekecs, et al., 2018; van Dooren et al., 2012). However, evaluation of correspondence of these measurements with more conventional measurement sites are limited (van Dooren et al., 2012). For example, the lower calf was used in an experiment that involved children with ADHD. The experimenters found this particular location beneficial because it did not interfere with activities and movement-related artifacts were minimized (Hedman et al., 2012). Another experiment compared EDA measured from the back of the lower calves to the forearm and found high correlation (Fedor & Picard, 2014). They also reported that participants of the study rated the lower calf location more comfortable than the distal forearm location and concluded that the back of the lower calves could be used as longer-term placements for electrodes. We agree that both the shoulders and the calves are potential placement sites for electrodes, however they need to be compared to the palmar surfaces which have not been done bilaterally yet.

Amplitude is one of the most commonly analyzed characteristics of SCRs. Another important, but rarely reported attribute of SCRs is latency. The response window for the detection of SCRs is based on estimated response latency. This temporal window ranges typically from 0.8–1 s to 4–5 s after stimuli onset. This 4–5 s response detection window is based on measurements from the palmar sites only. It is unknown whether it is also appropriate when measuring from alternate sites (foot, wrists, shoulders, calves). For example, Payne and colleagues reported longer latencies from the nondominant foot compared to the nondominant fingers (Payne et al., 2013). In some studies, even shorter response windows have been proposed (Levinson, Edelberg, & Maricq, 1985; Steiner & Barry, 2011), but never evaluated on other than palmar sites. See Figure 1 for detailed description of skin conductance characteristics used in this article.

The initial aim of the present study was to assess the similarities and differences in EDA measured at alternate and traditional anatomical sites. Further goals included the assessment of measurement sites regarding response latency to psychologically significant stimuli.

2 | METHOD

2.1 | Participants

To counterbalance the five types of stimuli used in the experiment in a latin square design 120 Caucasian participants were

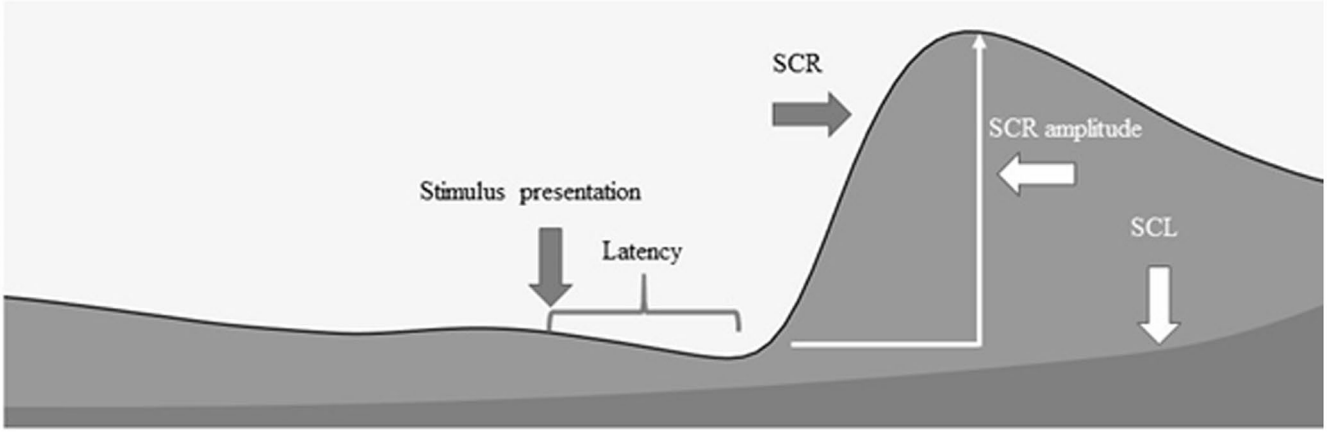

FIGURE 1 EDA characteristics explored in the present article

recruited. Data of five subjects were lost due to failed equipment or human error, thus 115 right-handed participants' electrodermal responses were analyzed in our study (mean age = 20.72, *SD* = 2.19; Male (*N* = 26), mean age = 20.69, *SD* = 1.71; Female (*N* = 89), mean age = 20.73, *SD* = 2.31). Exclusion criteria were left-handedness, self-reported use of psychiatric drugs, use of sedatives, any psychiatric illness, and auditory impairments.

2.2 | Procedure

The study protocol was approved by the Institutional Ethical Board of the University. After signing informed consent, participants filled out two questionnaires: the State and Trait Anxiety Inventory (Spielberger, Gorsuch, & Lushene, 1970), and the Barratt Impulsiveness Scale (Patton, Stanford, & Barratt, 1995). Data obtained from the questionnaires were not analyzed in the present study. After filling out the questionnaires, participants were led into a sound attenuated chamber. The EDA sensors were attached on the medial phalanges of the index and middle fingers on both hands, both wrists, both shoulders, both lower calves, and both feet (Figure 2). The experiment was designed to measure one participant at a time. The ambient temperature ranged between 21 and 26°C.

The outline of the experiment is presented in Figure 3. Rest period measures were taken while the participants were listening to a 4-min-long audio recording, which also helped participants to get used to the experimental conditions. The recording contained a breathing exercise, including instructions for deep breathing (with eyes open and closed) with silent periods in between instructions (Kasos et al., 2019). All participants listened to the same recording. Following the breathing exercise, participants were exposed to four 7 s long musical segment (conveying emotions of fear, sadness, happiness, and peacefulness) and one 7 s long, emotionally neutral computer-generated tone with a frequency randomized between-subjects (between 650 and 1,300 Hertz using 50 Hertz increments). The order of the stimuli was counterbalanced and randomized. After each musical segment, a 60-s-long inter-stimulus interval was used to let the SCL return to baseline. Participants rated the segments they had just heard during this break: identified what type of emotion they had heard (fear, sadness, happiness, peacefulness, or neutral). Likert scales ranging from 1 to 10 were also administered to rate clarity of the emotion experienced, to report level of induced arousal (from calming to stimulating), and valence of the experienced stimuli (from pleasant to unpleasant). The experimental sessions lasted for approximately 15 min. When finished, the devices were removed, and the participants were debriefed.

2.3 | Sources and justification of stimuli used in the experiment

Breathing instructions are commonly used in psychophysiological research to elicit electrodermal responses (Blain, Mihailidis, & Chau, 2008; Edelberg, 1967; Hygge & Hugdahl, 1985; Rickles & Day, 1968; Rittweger, Lambertz, & Langhorst, 1997). The musical segments used in this study have been extensively evaluated and widely used to elicit emotions in laboratory studies (Kasos, Zimonyi, et al., 2018; Khalfa, Isabelle, Jean-Pierre, & Manon, 2002; Peretz, Gagnon, & Bouchard, 1998; Vieillard et al., 2008). Neutral tones of differing length, pitch, and intensity are also commonly used to study skin conductance orientation responses (Kasos, Zimonyi, et al., 2018; Kekecs, Szekely, & Varga, 2016; Mueller-pfeiffer et al., 2014; Weger, Meier, Robinson, & Inhoff, 2007; Zuckerman & Neary, 1976). The music used in experiment 2 (Online Appendix 2) was meticulously validated for the emotions induced and the persistence of the induced emotions (Ribeiro, Santos, Albuquerque, & Oliveira-Silva, 2019).

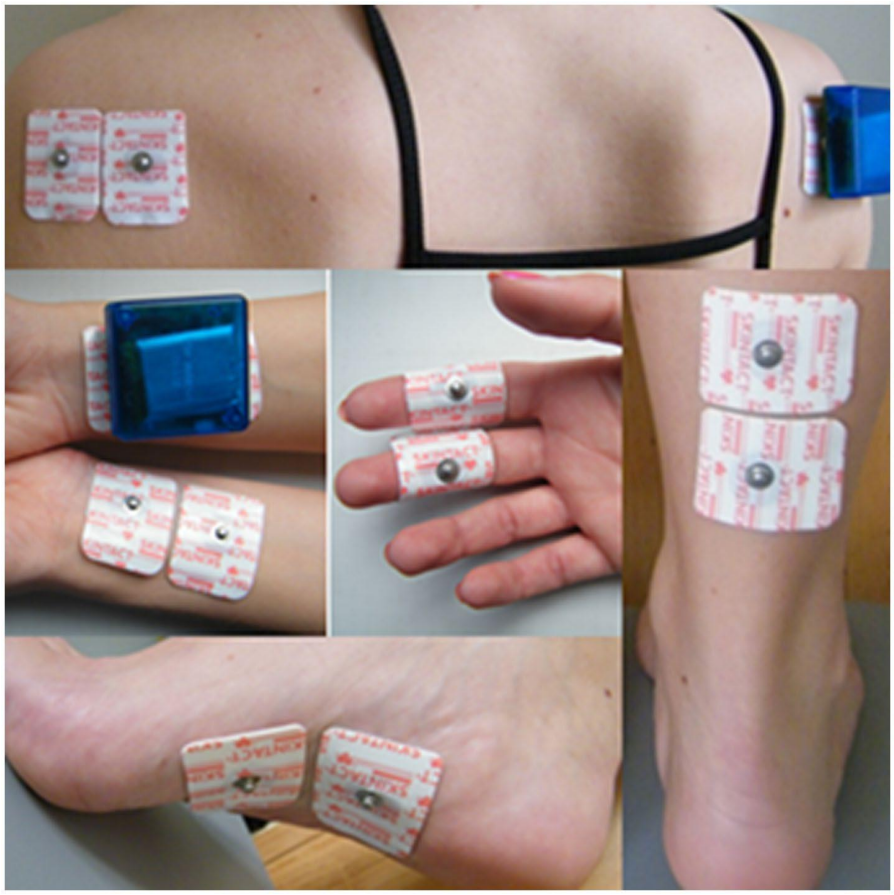

FIGURE 2 Electrode placement sites for bilateral measurements during the experiment

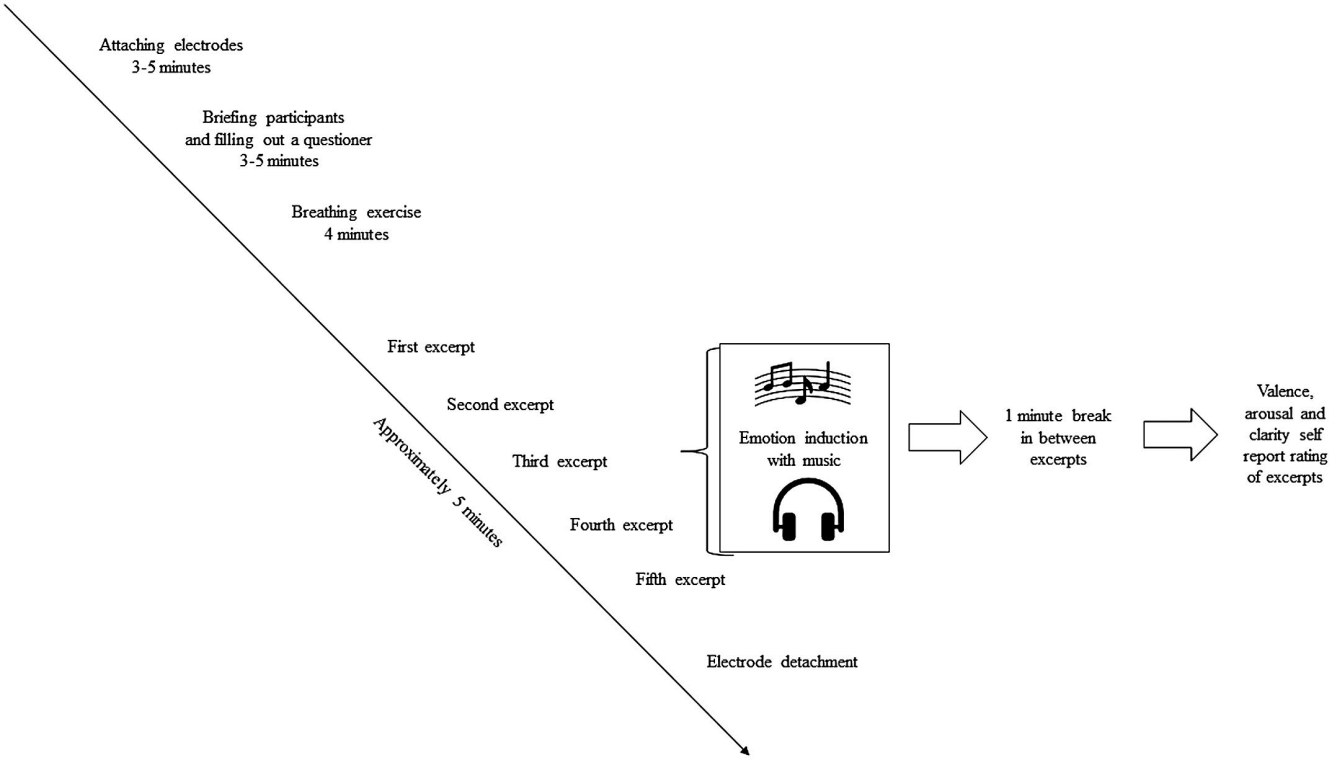

FIGURE 3 Schematics of the experimental proceedings

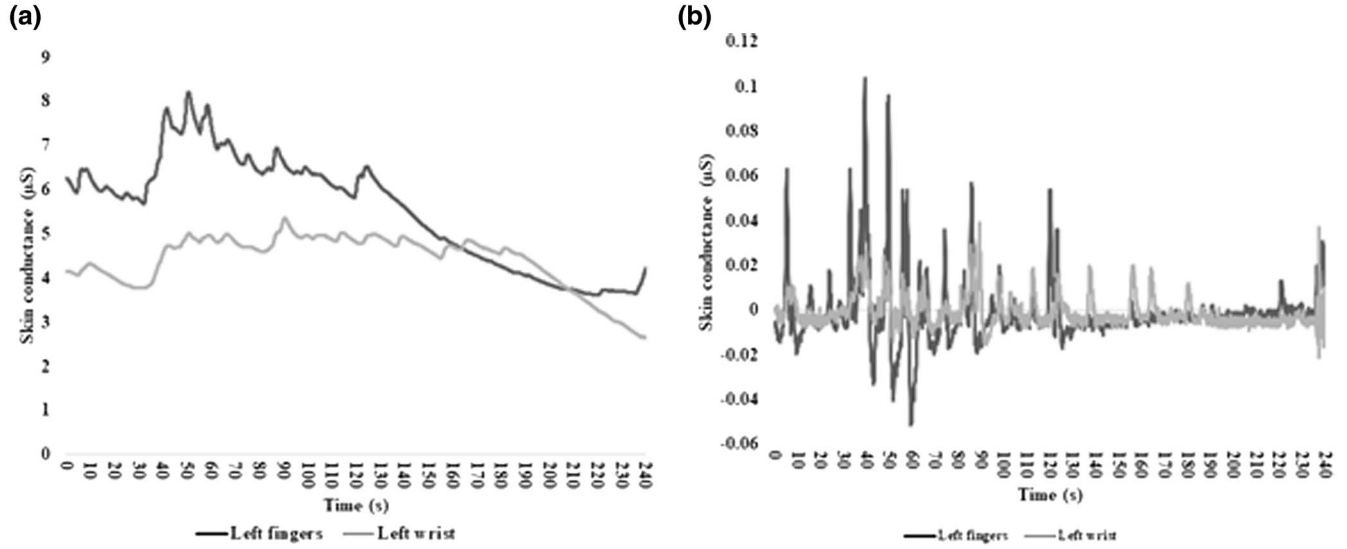

FIGURE 4 (a) Raw EDA data for a single subject (1,920 data points) measured from the left fingers and the left wrist. (b) Detrended EDA data for a single subject (1,919 data points): difference between two consecutive values ($X_{t+1} - X_t$) measured from the left fingers or the left wrist

2.4 | Equipment and data processing

For the measurement of skin conductance, the Open-Source Bio monitor (obimon.com) was used with an 8 Hz sampling frequency (see Kasos et al., 2019 for further details and validation). Skin conductance was recorded with pair of disposable Ag/AgC1 electrodes (32 × 41 mm in size, Skintact FS-RG1; Leonhard Lang GmbH. Innsbruck, Austria). A detailed description of the electrode used is available in Online Appendix 3. Electroconductive gel of the pre-prepared electrodes ensured proper contact between the electrode and surface of the skin. Raw data were inspected for artifacts based on guidelines provided by Kocielnik, Sidorova, Maggi, Ouwerkerk, and Westerink (2013). Artifact detection was done using a hybrid method of automated detection and visual confirmation. A more than 20% second-by-second rise or a more than 10% second-by-second drop in EDA measured on the raw data were flagged as a potential artifact and was later visually inspected to confirm the presence of artifacts. Segments that contained artifacts were excluded from the analysis. EDA was analyzed with Ledalab 3.4.8 (Benedek & Kaernbach, 2010a, 2010b). After Gaussian smoothing to decrease error noise, SCL and SCR were obtained by optimized Continuous Decomposition Analyses (Benedek & Kaernbach, 2010a, 2010b) (refer to Figure 1). A 4-s window was used for extracting electrodermal responses starting 1 s after stimulus onset to 5 s after stimulus onset. A threshold of 0.01 microSiemens was used for SCR extraction.

SCR data obtained from the breathing exercise and in response to musical and neutral stimuli were positively skewed, therefore, we used square root transformation to normalize the data (Barry, 1990, 2004; Barry & Sokolov, 1993; Dawson et al., 2007; Payne et al., 2016).

Response latency to stimuli was extracted with Ledalab version 3.4.8. Latency was defined as the time passed between stimulus onset and SCR onset (Figure 1).

2.5 | Statistical analysis

2.5.1 | Raw and detrended EDA data

Pearson correlation is often reported in studies that compare anatomical measurement sites (Payne et al., 2016). However, when the data are nonstationary, such as skin conductance data, the correlation coefficient partially reflects the inherent trend in the data set. The overall trend provides valuable information of skin conductance. When comparing two measurement sites for example, it describes how the overall activity of the measurement locations relate to each other (see an example of such trends in Figure 4a). However, correlation of these trends in some instances may overestimate (or underestimate) the relationship between measurement sites. For example, the Pearson correlation value for the raw EDA data displayed in Figure 4a is $r\,(1918) = .63$, which suggests quite a strong association between measurements from the fingers and the wrist.

If we would like to focus on the variation in the data (how the variation in measurement from one location relates to the variation measured from another location) we propose to report the correlation between data sets without trend. A method to remove the trend from a set of nonstationary data are to take the difference between two consecutive values ($X_{t+1} - X_t$). The new values will only represent changes that take place between sampling times (see the detrended raw data of the previous example in Figure 4b).

This method is referred to as the first differences method and it was recommended for nonstationary data (Granger & Newbold, 1974). The Pearson correlation obtained from the detrended data are r (1917) = .46 between the left fingers and the left wrist and it is free of the influence of the trend native to the data set. This is in contrast to the correlation obtained when the trend was not removed in Figure 4a. Another method to remove the trend is using linear regression and take the calculated slope out of every data point. This method is less sensitive to noise then the first differences method and will also be included in this article.

2.5.2 | Calculation of within-subject Pearson correlations

Within-subject Pearson correlations were computed between the left fingers and all other measurement sites using the raw and detrended EDA data measured during the 4-min rest period (eight measurements per second resulted in a total of 1,920 data points).

Within-subject Pearson correlations were also computed for each of the five types of stimuli between the left fingers and all other sites (each of the 7 s segments resulted in 56 raw data points). The five Pearson correlations obtained for the five types of stimuli were then averaged within each subject to obtain one average within-subject correlation score to characterize relationship of each recording site with the left fingers. As a next step, within-subject correlations were averaged between subjects to simplify presentation of data. The same calculations were performed for the detrended data sets as well.

One sample t tests were used with correlations measured at different measurement locations as the dependent variable to examine whether correlations differed significantly from 0 and to obtain a p value for the significance.

2.5.3 | Regression model descriptions

We chose to use mixed linear models in our study because they can easily handle clustering of data across multiple variables (sides, sites, stimulus type, time), and can treat data series with missing data better than repeated measures ANOVA. This approach allows us to study the effect of each level of multilevel categorical predictors individually (such as each measurement site). At the same time, it also helps to assess the effect of the multilevel categorical predictor as a whole (Field, Miles, & Field, 2012).

To assess the effect of recording side and the different recording locations, we built linear mixed-effects regression models with the magnitude/latency of the raw SCRs or the average raw SCLs as outcome variables. The reference level was the left fingers location in all our models.

In our first model, the main effects and interaction of recording side (left or right) and recording location (finger, wrist, shoulder, calf, or foot) were fixed effect predictors, with the random intercept over participants as a random effect (we will refer to this as the "***interaction model***") (Field, Miles, & Field, 2012). The reference level was the left finger in the model. Additionally, we built a simpler model including only the main effects of side and location, but not their interaction (we will refer to this as the "***main effects model***") (Field, Miles, & Field, 2012). We contrasted the model fit of the interaction model and the main effects model to assess whether the interaction between side and location overall has any predictive value of the observed electrodermal indices. As customary in the literature, we used an absolute difference of 2 or greater in **conditional Akaike information criterion** (cAIC) as a threshold for concluding that the models are significantly different in their model fit (Greven & Kneib, 2010). If the cAIC of the model containing the interaction was lower than the cAIC of the model without the interaction by at least 2, we concluded that there is a significant benefit in considering the interaction of side and location (in addition to the main effects) when predicting that particular outcome.

Furthermore, to assess whether it is worthwhile to take location of recordings into consideration when assessing SCR amplitudes/magnitudes, we built a third model with only the main effect of side as a fixed effect predictor (we will refer to this as the "***side only model***"). The model fit of this model was compared to one of the above-mentioned models, the one with the lower cAIC. Again, if the cAIC of the model containing the effect of location was lower by at least 2 than the cAIC of the side only model, we concluded that there is a significant effect of location overall in this context, that is, that knowing the recording site gives useful information for predicting the EDA index in question.

When reporting our results and as a reference level in all our regression models we used the left finger location (nondominant finger in this case for our participants) as the reference site to compare other locations to. The left fingers have been thought of as the "gold standard" location to measure EDA from. It is recommended and costumery to compare other sites to this location (Fowles, 1981).

We only report statistics of the models we selected based on the criteria mentioned above. The statistics of the models that were discarded are available in Online Appendix 1.

In all models, "CI" stands for confidence interval, "b" stands for the beta coefficient of the regression model or the slope in a linear regression, "standard beta" is the

standardized beta coefficient with a mean of zero and a standard deviation of one.

3 | RESULTS

3.1 | Data processing results

Segments that contained artifacts were excluded from analysis. After excluding segments that contained artifacts and loss of data due to failed equipment, 909 valid measurements were analyzed in the baseline SCL analysis out of the 1,150 possible measurements (10 measurement sites × 115 participants). A total of 3,636 responses to the breathing instructions were analyzed out of the possible 4,600 responses (4 breathing instructions × 10 measurement sites × 115 participants). A total of 5,257 valid responses were analyzed out of the 5,750 possible responses to musical and neutral stimuli (5 responses × 10 measurement sites × 115 participants).

3.2 | Rest period results

3.2.1 | Rest period SCL

The average SCL for each subject within the 4-min resting period was calculated for all 10 measurement sites separately (the left and right shoulders, wrists, fingers, lower calves, and feet).

When analyzing the rest period SCL, we found that the main effects model (cAIC = 2,156.34) had significantly better model fit than the interaction model (cAIC = 2,164.35) and the side only model (cAIC = 2,808.13), indicating that location of the electrodes (on the fingers, the foot, the wrist, the calf, or the shoulder) holds important information about resting SCL. In contrast, interaction of side (left or right) and location was not prominent. Results of the main effects model ($R^2 = .427$, CI = 0.386–0.471) is displayed in Table 1. SCL during the rest period was significantly lower at the shoulders, wrists, and calves compared to the reference site (the left fingers), while the SCL recorded at the feet did not differ significantly from the SCL recorded at the fingers. Side of the recordings did not have a significant effect.

3.2.2 | Rest period SCR magnitudes

Average response magnitude in response to the breathing instructions during rest period was calculated by averaging the SCR values following all four breathing instructions within-subjects. This includes 0 μS responses as well (Dawson et al., 2007; Payne et al., 2016).

When comparing the model fit of the three mixed-effects models regarding the resting period SCR magnitude, we found again that the main effects model had the best model fit, showing that measurement location, but not side-location interaction is important in determining SCRs (main effects model cAIC = 205.27; interaction model cAIC = 212.50; side-only model cAIC = 836.77). Specifically, the main effects model ($R^2 = .53$, CI = 0.491–0.576) indicated that SCRs recorded at the shoulders, wrists and calves were significantly lower than the SRCs recorded at the left fingers, while SCRs at the feet were significantly higher (see Table 2). Similarly to SCL results recording side was not a significant predictor.

3.2.3 | Rest period response frequency

During the rest period, EDA response indicated whether a "breathing in" instruction elicited a response or not (an SCR amplitude threshold of 0.01 μS was used). Response frequency was calculated for all 10 measurement locations separately (see results in Table 3). Absolute frequency was calculated by dividing all observed (non-zero) responses (summed up across participants) by all possible responses (summed up across participants) and multiplied by 100.

As shown in Table 3, the highest response frequency for the "breathing in instruction" was measured from the classical sites; the fingers and the foot. Response frequency was considerably lower on the wrists and the calves and the shoulders produced the lowest response frequencies.

3.2.4 | Rest period correlations

The results of the within-subject correlations measured during the rest period are shown in Table 4. Strong relationships

TABLE 1 Rest period SCL. Details of the linear mixed model with two main effects (side and location) without the interaction effect. Intercept is the left finger in the model

	b	95% CI lower bound	95% CI upper bound	Standard beta	*p* value
Intercept	2.72	2.58	2.86	.00	<.001
Side	0.02	−0.06	0.11	.01	.620
Foot	0.01	−0.14	0.15	.00	.902
Wrist	−1.21	−1.33	−1.08	−.46	<.001
Calf	−1.20	−1.33	−1.07	−.45	<.001
Shoulder	−1.54	−1.68	−1.41	−.57	<.001

	b	95% CI lower bound	95% CI upper bound	Standard beta	*p* value
Intercept	0.90	0.85	0.95	.00	<.001
Side	0.01	−0.02	0.05	.01	.529
Foot	0.08	0.03	0.14	.07	.005
Wrist	−0.55	−0.60	−0.50	−.54	<.001
Calf	−0.60	−0.65	−0.53	−.54	<.001
Shoulder	−0.65	−0.71	−0.58	−.49	<.001

TABLE 2 Rest period SCR magnitudes. Details of the linear mixed model with two main effects (side and location) without interaction effect. Intercept is the left finger in the model

TABLE 3 Absolute and relative response frequencies on the different locations for the "breathing in" instructions during rest period. Relative frequency was calculated with reference to the response frequency measured on the left finger

Location	Absolute frequency %	Relative frequency %
Left finger	94.09	100
Right finger	95.09	97.80
Left foot	96.11	96.97
Right foot	91.87	93.46
Left wrist	62.26	64.75
Right wrist	59.23	61.94
Left shoulder	27.55	28.86
Right shoulder	29.95	31.30
Left calf	48.84	50.38
Right calf	45.51	46.99

were found between the left finger and right finger and the left finger and both feet. EDA measured from the wrists show a moderate relationship with the activity measured from the left finger. Shoulder and calf locations show only a very weak or no correlation with the left finger. When the trend is removed from the data set the correlation between the left and right fingers remain virtually unchanged. However, association is weak between the left finger and other body parts in this case.

3.3 | Results of the musical stimuli

3.3.1 | SCR magnitudes

During the musical and emotionally neutral stimuli, we calculated the magnitude of SCRs. Within-subjects' responses to the five types of stimuli (fear, happy, peaceful, sad, and emotionally neutral) were averaged, including 0 responses.

When assessing the SCR magnitudes during the emotional and neutral stimuli segments, we found that the main effects model (R^2 = .497, CI = 0.541–0.456) had the best model fit according to the comparison with the interaction model and the side-only model (main effects model cAIC = 289.75; interaction model cAIC = 297.06; side-only model cAIC = 909.92). As shown in Table 5, results were similar to findings reported for the resting period. Wrists, calves, and shoulders produced lower SCRs. SCRs at the feet did not differ significantly from those at the fingers. Again, side was not a significant predictor in this model.

3.3.2 | Musical stimuli response frequency

We calculated response frequency for all 10 measurement locations separately (see results in Table 1) in response to the musical stimuli. Absolute frequency was calculated by dividing all observed (non-zero) responses (summed up across participants) by all possible responses (summed up across participants) and multiplied by 100.

Results for the absolute and relative frequency of responding to psychologically significant stimuli are detailed in Table 6. Our results show that the most responsive measurement sites are the palmar and plantar surfaces followed by the wrists. The shoulders and calves show lower responding rate than all other evaluated body parts.

3.3.3 | Correlations of measurement locations during the presentation of psychologically significant stimuli

The results of the within-subject correlations measured during the presentation of musical segments and neutral stimuli are detailed in Table 7. There are high correlations between the left and right fingers. Moderate correlations between the left fingers and both feet. EDA measured from the wrists shows a weak to moderate relationship with the activity measured from the left finger. Alternative electrodermal measurement locations show only a weak correlation with the left fingers.

TABLE 4 Average of within-subject correlations with reference to the left finger during the 4 min breathing exercise

	Raw-data		Detrended data (method: first differences)		Detrended data (method: linear regression)	
Location with reference to the left finger	**Average Pearson *r***	***SD* of Pearson *r***	**Average Pearson *r***	***SD* of Pearson *r***	**Average Pearson *r***	***SD* of Pearson *r***
Right finger	.89***	.16	.87***	.15	.93***	.12
Left foot	.72***	.30	.54***	.27	.77***	.17
Right foot	.72***	.33	.58***	.23	.80***	.16
Left wrist	.33***	.49	.26***	.20	.27***	.34
Right wrist	.30***	.50	.26***	.19	.26***	.35
Left shoulder	−.06	.60	.07***	.13	.15***	.37
Right shoulder	−.03	.60	.09***	.15	.15***	.38
Left calf	.05	.57	.15***	.20	.24***	.35
Right Calf	.14*	.55	.12***	.16	.22***	.33

Note: Significant correlations marked with asterisk,

*$p < .05$, ***$p < .001$.

TABLE 5 SCR magnitudes during stimuli presentation. Details of the linear mixed model with two main effects (side and location) without interaction effect. Intercept is the left fingers in the model

	b	95% CI lower bound	95%CI upper bound	Standard beta	*p* value
Intercept	0.90	0.84	0.95	.00	<.001
Side	0.03	−0.01	0.06	.04	.420
Foot	0.01	−0.05	0.06	.01	.774
Wrist	−0.53	−0.59	−0.48	−.53	<.001
Calf	−0.62	−0.68	−0.59	−.54	<.001
Shoulder	−0.60	−0.67	−0.54	−.51	<.001

TABLE 6 Absolute and relative respond frequency during stimuli presentation

Location	Absolute frequency %	Relative frequency %
Left finger	95.26	100.00
Right finger	96.59	98.67
Left foot	91.56	94.26
Right foot	89.06	92.50
Left wrist	55.58	57.12
Right wrist	58.56	60.19
Left shoulder	31.27	32.15
Right shoulder	34.21	34.65
Left calf	38.30	39.40
Right calf	37.61	37.74

3.3.4 | Average latency results

Latency was defined as the start of the initial response (greater than 0.01 μS in amplitude) in the predefined response window (1 s after stimulus onset to 5 s after stimulus onset). Average latency was calculated for the four musical and one neutral stimulus for each of the subjects at each of the measurement locations. Latencies were first averaged within-subject for the five types of stimuli and then, averaged between subjects.

Once again, the comparison of the linear mixed-effects models with the SCR latency observed as an outcome variable yielded main effects model ($R^2 = .084$, CI = 0.055–0.127, see details in Table 8) as the best model fit (main effects model cAIC = 1,538.68; interaction model cAIC = 1,544.72; side-only model cAIC = 1,623.66). As shown in Table 8, results were similar to findings reported for the resting period. Calves and feet showed slower responses as compared to the fingers, shoulders or wrists. Side was not a significant predictor in this model either.

3.3.5 | Cumulative frequencies

Cumulative frequencies were calculated for all 10 measurement locations by summing detected response frequencies at 0.5 s intervals starting at 1 s after stimuli onset to

TABLE 7 Average of within-subject correlation with reference to the left finger during the seven seconds stimuli presentation. Correlations in Table 7 are all significant at the $p < .001$ level

	Raw data		Detrended data (method: first differences)		Detrended data (method: linear regression)	
Location with reference to the left finger	**Average Pearson *r***	***SD* of Pearson *r***	**Average Pearson *r***	***SD* of Pearson *r***	**Average Pearson *r***	***SD* of Pearson *r***
Right finger	.89	.14	.86	.17	.86	.20
Left foot	.56	.23	.40	.22	.45	.29
Right foot	.51	.31	.40	.30	.38	.26
Left wrist	.27	.30	.27	.21	.33	.24
Right wrist	.28	.30	.26	.21	.34	.24
Left shoulder	.16	.25	.10	.15	.10	.21
Right shoulder	.18	.27	.10	.19	.12	.24
Left calf	.13	.28	.10	.21	.10	.28
Right Calf	.14	.26	.06	.17	.07	.22

TABLE 8 Latency of SCRs during stimuli presentation. Details of the linear mixed model with two main effects (side and location) without interaction effect. Intercept is the left finger in the model

	b	**95% CI lower bound**	**95% CI upper bound**	**Standard beta**	***p* value**
Intercept	2.36	2.25	2.46	.00	<.001
Side	0.03	−0.05	0.11	.02	.428
Foot	0.36	0.24	0.47	.21	<.001
Wrist	0.26	0.15	0.38	.16	<.001
Calf	0.54	0.41	0.66	.30	<.001
Shoulder	0.15	0.02	0.28	.08	.027

5 s after stimuli onset (Figure 5 shows traditional measurement locations and Figure 6. describes alternate sites). For example, Cumulative response frequency at 3 s after stimuli onset for the left finger is close to 80% (majority of the detected responses at this measurement location was within a 3 s interval after stimuli onset). In contrast, this response frequency ratio characterized the left foot only by 3.5 s. Latencies measured at alternate locations show that cumulative frequencies are highest for the left shoulders at 2 s and remain highest up to 3.5 s after stimuli onset.

3.4 | Reproducibility of the results

We conducted an experiment with 20 participants to explore whether the obtained correlations, response frequencies and SCR magnitudes can be reproduced within an individual 3 days later. The detailed description and results of that experiment can be found in Online Appendix 2. The results show the same patterns for all the examined EDA characteristics the first day and second day of the experiment as the main study.

4 | DISCUSSION

This is the first large scale study to compare traditional and alternative electrodermal measurement locations bilaterally, providing information on how SCL, SCR, and latency measured at different locations relate to the nondominant fingers. We measured EDA from five anatomical sites bilaterally, during breathing exercise and psychologically significant stimuli in the first experiment. In the second experiment, we measured from five sites bilaterally during a 3 min long musical stimulus and during the presentation of computer-generated tones. Traditional measurement sites (fingers and feet) were more responsive and showed higher correlation than alternate measurement sites. We found that latency of SCRs was different across anatomical sites. We measured longer latencies from the lower body compared with the upper body. We found that all measured EDA characteristics remain stable within individuals from 1 day to another.

We found a high rate of responding (both to breathing instructions and to psychologically significant stimuli) from the fingers (96%) and the feet (90%), lower responding from the wrists (57%), and the lowest rates of responding from the shoulders and the calves. The response rates

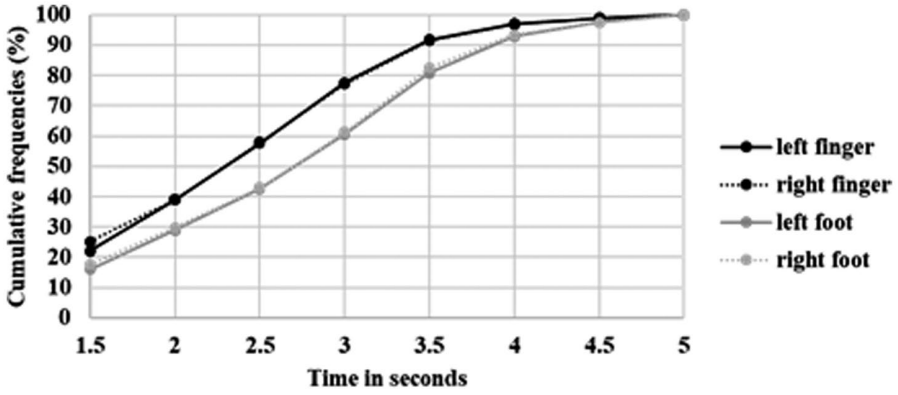

FIGURE 5 Cumulative percentage of detected responses in a 4 s response window (measured from the traditional measurement locations)

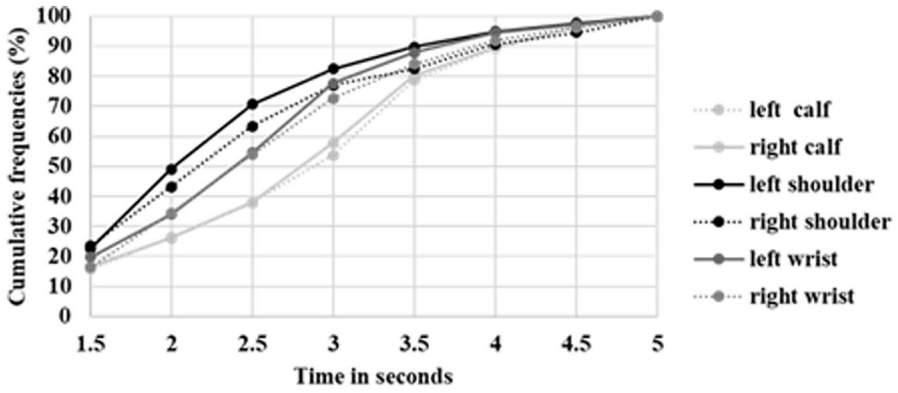

FIGURE 6 Cumulative percentage of detected responses in a 4 s response window (measured from alternate sites)

identified in our study were higher than those reported by Payne and colleagues (2016), who found a low 14% of absolute rate responding rate at the wrists and also lower absolute responding rate at the fingers (30%) and (25%) of the feet. In their study, participants looked at 19 images that may be enough to reach habituation and could explain the lower rate of responding. In our study, only four short musical segments and one neutral tone was presented to participants in order to avoid habituation. Nevertheless, when measuring from alternate locations, the incidence of non-detectible SCRs was higher than when measuring from the palmar and plantar sites. These findings are in line with the results of earlier studies as well (Edelberg, 1967; Rickles & Day, 1968).

It has been suggested, that alternate measurement locations are less active after electrode placement, but become more electrodermally active over time, as the skin at these locations takes longer to get hydrated (Payne et al., 2016). To see if response frequency improved during the short time interval between the first breathing instruction and the last stimulus (approximately 9 min passed between the breathing instructions and the stimuli presentation), we performed a post hoc comparison of the response rates of those two stimuli measured from the left fingers and left wrist. We found no improvement in response frequency of the wrist between the first breath in instruction (77%) and to the last stimuli that was presented (55%). This implies that such relatively short duration is not enough for the wrist to improve in response frequency.

Trying to provide an answer on whether extra hydration time improves response frequency at alternate sites, we reanalyzed data from a previous experiment (Kasos, Kekecs, et al., 2018). We found that after pedaling on a stationary ergometer for approximately 20 min using medium to heavy load, absolute response frequency of the left shoulder was 96%. This suggests that alternate measurement locations do get more electrodermally active with time and physical activity. In some instances, the experimental setting closely corresponds to this long hydration time combined with physical activity, as was the case in the experiment conducted by our lab (Kasos, Kekecs, et al., 2018). The question remains however, whether such long hydration time combined with physical activity is feasible in laboratory experiments.

In the second experiment (Online Appendix 2) the hydration time was 20 min before taking EDA measurements. We found a similar rate of responding at traditional measurement sites compared to the first experiment and these numbers remained stable from one measurement day to the other. At alternate measurement sites the wrist showed a similar rate of response frequency to the first experiment. Response rate of the calves seemed to improve compared to the first experiment. Furthermore, correlation between the left finger and the calves also improved and became comparable to the correlation between the left fingers and

the wrists. Extra hydration time did not seem to affect the response rate of the shoulders and the correlation between the shoulders and the left fingers.

Response rate of measurement sites remains stable from 1 day to the other. Correlations between measurement sites also remain similar across time. The strength of the response to repeated stimuli (measured as the magnitude of SCRs) shows the expected habituation across time. Although participants show similar response rate on the second day to the first day, SCR amplitudes tend to be smaller on the second day compared to the first day (Table 13 in Online Appendix 2).

Our findings suggest that alternate locations do not perform as well as the traditional locations regarding response frequency. However, the additional analyses reported above also indicate that with adequate hydration time some of the alternate locations may improve in EDA. The shoulders improved in response rate after physical activity but not after leaving the electrodes on for the 20 min wait period. The lower calves became comparable to the wrists after the 20 min wait period (Online Appendix 2).

We found higher SCL during the rest period at the fingers and at the feet than at all other evaluated locations, similarly to previous reports (Payne et al., 2016). This is likely due to higher density of eccrine sweat glands present at traditional sites. According to our results, the fingers did not differ from the feet in terms of SCL during rest period measurements. Both the calves and the wrists showed higher baseline SCL than the shoulders.

Our results show significant and high within-subject correlation between the left and the right fingers regarding SCL during rest (in both raw and detrended EDA). Pearson correlation between the left fingers and the feet calculated from raw data shows high correlation, yet lower than the correlation between the left and right fingers. Nevertheless, correlation of the detrended EDA shows only a moderate association. Thus, the feet present a similar overall trend as the fingers but may not present the same pattern of changes as the fingers. The moderate to low correlations calculated from both raw and detrended data between the left fingers and the wrists, shoulders, and calves suggest that neither the trend nor the changes between sampling times are very similar to the left fingers. The standard deviation of the Pearson *r* between the left fingers and alternate measurement sites are greater than between the left and right fingers. This implies greater individual variability of EDA measured from alternate sites compared to the fingers. Some individuals have alternate measurement sites that show a high association with the traditional sites. Moreover, many show no association or negative association with EDA measured from the traditional sites. Furthermore, detrending EDA before performing correlation adds valuable information on how much of the association lies in the overall trend and how much of the association lies in the changes that take place from sampling time to sampling time.

As expected, response magnitudes of SCRs to breathing instructions, music segments and neutral tones were higher at the finger and feet locations compared to the other three measurement locations. This is most likely due to the density of eccrine sweat glands being highest at the palmar and plantar surfaces. Eccrine sweat gland density is linearly correlated with SCR amplitudes (Levy, Reid, Rowley, & Abraham, 1992). The only other location that rivals the traditional sites in terms of sweat gland density is the forehead. However, according to previous studies SCRs recorded at the forehead were found to display a very low correlation with the fingers (Payne et al., 2016).

Previous reports indicated laterality differences in SCRs to emotionally laden stimuli (Banks et al., 2012; Kasos, Zimonyi, et al., 2018). We did not find laterality effects in either tonic or phasic EDA, or response latency. It was not the purpose of the present article to assess emotion-specific responses. Future studies interested in laterality differences may need to evaluate EDA changes with respect to different emotional triggers.

Fingers had the shortest, while calves the longest response latency. The lower extremities are generally slower than the upper body in reacting to stimuli. This is probably due to the difference in distance from the central nervous system. Interestingly, the average latency at the wrists was significantly longer than the latency at the fingers. There are reports of differences in the number of sweat glands and even their size and shape at different parts of the body (Kennedy, Wendelschafer-Crabb, & Brelje, 1994), which might explain this curious finding. There are fewer eccrine sweat glands located on the wrists than on the fingers. The number of sweat glands affect SCR amplitudes, but there are no reports of association between sweat gland density and response latency. Other characteristics (shape and size) of the sweat glands have not been investigated with regard to their effect on response latency. There may be qualitative differences in the sudomotor nerves that innervate eccrine sweat glands across body locations. Further evaluation and replication of this finding are needed to elucidate the reason behind latency differences across anatomical sites.

According to our second experiment, response latencies remain similar from one measurement day to the other within individuals. The short latencies measured from the fingers were confirmed in the second experiment. Furthermore, we found longer latencies measured on the lower body and the wrists again in line with the first experiment. These findings are similar to the results of the first experiment; however we have to be mindful of the low sample size in the second experiment.

Shorter response windows are promoted by researchers to avoid contamination of the response window with nonspecific

responses. It is recommended to shorten the response window from the traditional 1–5 s after stimuli onset to a 1–3 s window (Levinson et al., 1985; Steiner & Barry, 2011). These recommendations were based on measurements taken from the fingers. Our results reconfirm that most response to stimuli on the fingers start in this shorter window. A shorter temporal window would most probably fail to capture some of the responses on the feet as well as on the calves for example. Moreover, short response windows might not capture maximum amplitude of SCRs, if the SCR starts close to the end of the response window. This is especially true for the lower body. Our data indicates for instance that a 1–3 s window would have missed 43% of responses from the left foot and 59% of responses from the left calf, compared to 24% from the fingers. The 4 s window used in our study was sufficient to capture most responses from the traditional measurement sites. Detectable responses from alternate sites also started within this response window. We suggest setting site-specific response windows for different measurement locations.

Based on our results when looking to measure from alternate sites (planning only to measure from one site) one should consider sites that have a high absolute response frequency. Response frequency is important if we are looking to evaluate responses to different stimuli or emotional triggers. Those sites are located on the palmar and plantar surfaces and have a high correlation with the nondominant fingers with comparable response magnitudes. The other evaluated alternate sites in our study yielded low response frequencies and lower correlations with the nondominant fingers, also lower response amplitudes. Therefore, results from alternate sites would not be comparable to results obtained from traditional sites.

Comparing alternate measurement sites to the nondominant fingers has a long tradition nested in the idea that there is one true arousal which can be measured best at the palmar surfaces. Differences in measured arousal between the fingers and other measurement sites are usually explained by differences in the number of eccrine sweat glands or the function of sweat glands (alternate sites may be more involved in thermo regulation) and sometimes with more time needed for those sites to become active (hydration time). Multiple Arousal Theory (Picard et al., 2015) explains these differences with the notion that different electrodermal arousal could be present at the same time in different parts of the body. Depending on the underlying neural activation (whether a person is nervous or excited for example) different dermatomes will be activated with different intensity. Our experiment, although not designed to specifically test this theory, yielded results that may support it. Correlations between the nondominant fingers and alternate sites range from positive to negative depending on the person. This shows that it is possible to have (in one part of the body) falling arousal and in the same time rising arousal at another part of the body. Response latencies vary at sites which may imply that different dermatomes are influenced by different underlying generators. A future experiment that manipulates the psychological state of participants and measures from multiple sites could test the theory and provide more definitive answers.

4.1 | Limitations

Limitations of the present study include loss of data due to movement artifacts, and equipment failure. Furthermore, we assessed a sample that is relatively homogeneous in age and gender, which may limit the generalizability of our findings. Hydration time in our study might be shorter than needed for the alternate sites to become electrodermally active. The range of ambient temperature in the experiment was wide, which may have affected our results. We conducted our study in a laboratory setting; thus, our results are generalizable to laboratory circumstances. Results from ambulatory measurements may differ since emotional changes could be different in "real life." The electrode gel salt content, which can affect electrodermal measurements, is unknown.

4.2 | Conclusion

In the present study, we contrasted EDA measured at five different anatomical sites bilaterally in a relatively large university student sample. Our results confirm previous findings that the fingers and the feet are the most responsive to stimuli, and the feet may be used instead of the fingers if one is interested in measuring SCR magnitudes and amplitudes. The wrists are less responsive and show smaller SCR amplitudes compared to the fingers. We recommend this site if neither the fingers nor the feet are available. With adequate hydration time (20 min) the calves also become comparable to the wrists in response frequency, magnitude and correlation. The shoulders present small SCR amplitudes and response frequency and should only be used if there is no other option. Future studies assessing hydration time of alternate measurement sites could be interesting. We also found that response latencies significantly differ among measurement sites. Thus, we suggest that measurement site should be taken into consideration when setting response windows for analysis; longer windows are necessary when measuring EDA from the lower body.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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