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ORIGINAL ARTICLE

Towards long term monitoring of electrodermal activity in daily life

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Abstract Manic depression, also known as bipolar disorder, is a common and severe form of mental disorder. The European research project MONARCA aims at developing and validating mobile technologies for multiparametric, long term monitoring of physiological and behavioral information relevant to bipolar disorder. One aspect of MONARCA is to investigate the long term monitoring of Electrodermal activity (EDA) to support the diagnosis and treatment of bipolar disorder patients. EDA is known as an indicator of the emotional state and the stress level of a person. To realize a long-term monitoring of the EDA, the integration of the sensor system in the shoe or sock is a promising approach. This paper presents a first step towards such a sensor system. In a feasibility study including 8 subjects, we investigate the correlation between EDA measurements at the fingers, which is the most established sensing site, with measurements of the EDA at the feet. The results indicate that 88% of the evoked skin conductance responses (SCRs) occur at both sensing sites. When using an action movie as psychophysiologically activating stimulus, we have found weaker reactivity in the foot than in the hand EDA. The results also suggest that the influence of moderate physical activity on EDA measurements is low and has a similar effect for both recording sites. This suggests that the foot recording location is suitable for recordings in daily life even in the presence of moderate movement.

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1 Introduction

Mental disorders like depression affect around 25% of the human population during their life. These disorders are universal—affecting all countries and societies, and individuals at all ages. According to the World Health Organization, the negative direct and indirect impact on economy and on the quality of life of individuals and families is substantial [12].

Manic depression, also known as bipolar disorder, is a common and severe form of mental disorder characterized by repeated relapses of mania and depression. Therapists are interested in relevant physiological and behavioral measures recorded during daily routines of the patient. These measures would enable the therapist to assess early warning signs and to predict the occurrence of manic and depressive episodes in an objective and timely way. Currently, the therapist does not have any access to long-term objective measures of physiology and behavior from daily life.

The European research project MONARCA aims at developing and validating mobile technologies for multiparametric, long term monitoring of physiological and behavioral information relevant to bipolar disorder. The project will integrate those technologies into an innovative system for management, treatment, and self-treatment of the disease. This approach is in line with the goals of pervasive healthcare: making healthcare available anywhere, anytime and to anyone [1].

The MONARCA system will consist of four sensing components: a sensor enabled mobile phone, a wrist worn activity monitor, a stationary EEG system for intermittent

measurements and a novel "sock integrated" electrodermal activity (EDA) sensor. This paper presents a feasibility study towards developing the EDA sensor sock.

EDA is known as a relevant indicator of the emotional state and the stress level of a person [10, 11]. To ensure that users accept this kind of sensing in daily life, all sensors need to be comfortable, invisible and easy to apply. Therefore, we integrated the EDA measurement electrodes into normal socks. From a physiological point of view, the feet are known to serve as a feasible measurement location to measure EDA [2, 6]. In comparison to traditional sensing locations—such as the hand—sensor socks will completely hide the sensing unit while comfort and usage are similar to normal socks.

There are already several studies involving EDA measurements of persons with mental diseases [13]. However, these measurements are usually obtained from electrodes at the hand/fingers and under laboratory conditions. Considering the requirements mentioned above, we are investigating the feasibility of EDA measurements on the feet. Additionally, since our aim is to use the device in daily life of patients, we included moderate physical activity into the experiment design. As supplement to instructed deep breathing, we added an action movie as a naturalistic psychophysiologically activating stimulus.

Consequently, there are two questions we will investigate in this study:

1. To which extent are EDA measurements obtained with our EDA sock equivalent to conventional EDA measurements obtained from finger electrodes?
2. How does movement of limbs influence EDA measurements obtained with foot or finger electrodes?

In this feasibility study, we decided to investigate healthy subjects first, before addressing bipolar patients. If the result would be that EDA measurements at the feet are not comparable with EDA measurements at the hand for healthy subjects, we would not expect comparable measurements for patients. However, ethics approval for similar studies including bipolar patients is currently ongoing and will be considered in future work.

In the following sections we will introduce the physiological background and provide a short description of the developed prototype. Afterwards we explain the experimental design, present the evaluation methods and discuss the results.

2 Physiological background

The sweat glands are exclusively innervated by the sympathetic nervous system [2]. The number of active sweat glands thus increases with sympathetic activation. Since the skin conductivity is proportional to the sweat secretion [4], the measurement of the skin conductance is used to record Electrodermal Activity (EDA) to assess psychophysiological activation. EDA measurements are usually obtained from the palmar sites of the hands or the feet where the density of sweat glands is highest (>2,000/cm^2). The measured skin conductance signal consists of a slowly changing part which is overlaid by short, fast conductance changes (i.e. the phasic part). Different parameters can be extracted from the two parts:

Skin conductance level (SCL): The skin conductance level (SCL) denotes the slowly changing part (low-frequency part, baseline) of the EDA signal. It is a measure of the general psychophysiological activation [3] and can vary substantially between individuals.

Phasic parameters: Depending on the causality of the short-term conductance changes (also denoted as "peaks" in the following), two different types are distinguished:

(a) **Skin conductance response (SCR):** If the peak occurs in reaction to a single stimulus (e.g. a startle event) it is called (specific) skin conductance response. It appears between 1.5 and 6.5 s after the stimulus. Features used to describe the characteristics of a SCR include the amplitude of the SCR, the latency (between stimulus and SCR onset) and the recovery time. They are shown in Fig. 1.

(b) **Non-specific skin conductance response (NS.SCR):** In contrast to the specific SCRs, the non-specific fluctuations (NS.SCRs) occur "spontaneously" without any external stimulus. In addition to the SCL, the frequency and the mean amplitude of NS.SCRs are also considered as measures for psychophysiological activation [2].

3 Prototype of the EDA sock

For the prototype of the EDA sock, we adapted the Emotion Board presented by Schumm et al. [9].

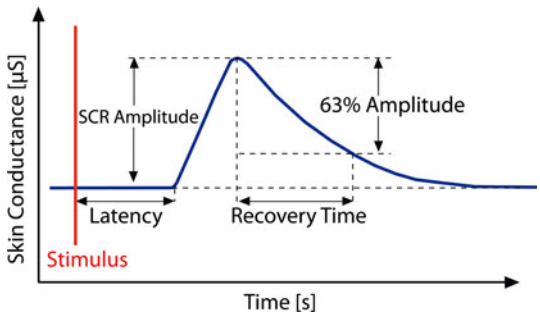

Fig. 1 Ideal skin conductance response (SCR) with typically computed features (© IEEE 2010 [10])

The measurement principle is referred to as an exosomatic quasi constant voltage method [7]. Hereby, a constant voltage (500 mV) is applied to one electrode leading to a current flowing through the skin to the other electrode, see Fig. 2. Measuring the voltage at the reference resistance allows us to directly determine the skin resistance. To eliminate high-frequency noise, a 2nd order low-pass filter with a cut-off frequency of fc = 5 Hz is applied before A/D conversion of the measured signal (referred to as "level" in the following). Applying an additional high-pass filter (2nd order, fc = 0.05 Hz) yields the phasic part of the EDA signal (referred to as "phase" in the following). For further noise reduction, this signal is once more low-pass filtered (2nd order, fc = 5 Hz), amplified and fed to the A/D converter. A Bluetooth wireless link is used to transfer the EDA data at 22.4 Hz [9]. Figure 4 displays an example of the EDA signals recorded by the Emotion Board.

4 Experiment

We investigated 8 subjects, 4 males and 4 females. As depicted in Fig. 3, we attached one Emotion Board to the non-dominant hand of a subject and another one to the corresponding foot. The signal recorded at the hand served as a reference measurement. Since all our subjects were right hander, the measurement site corresponds to the left hand and foot for all subjects. The electrodes were attached to the medial phalanxes of the index and middle finger and to the medial side of the foot adjacent to the plantar surface and midway between the first phalanx and a point beneath the ankle, as recommended by [5]. (see also Fig. 3 below and Fig. 28 of [2] for illustration).

The experiment consisted of 7 phases which lasted 3 min each. They were recorded during a single experiment session. During the first 5 phases, we investigated the effect of movement of different body parts on the measured EDA signals. While following the instructions showed on a screen, the subjects were simultaneously watching a relaxing documentary movie ("Alaska: Spirit of the Wild") in order to avoid boredom or distraction. During the last experiment phase, we used an action movie to induce psychophysiological activation. Table 1 shows the instructions of subject 1, as an example.

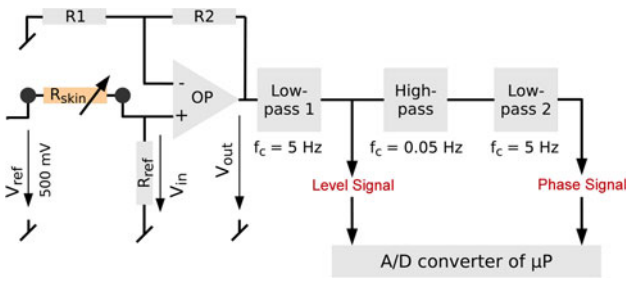

Fig. 2 Analog part of the Emotion Board with amplifiers and filters, adapted from [9]

Fig. 3 EDA signals were measured at the subject's hand and foot

4.1 Phases 1–5: effect of movement on EDA

To provoke specific SCRs in the EDA signal, the subjects took a deep breath from time to time, held his breath for 3 s before exhaling again. The experiment leader labeled the exact onset of each inhalation and the start of exhalation. The first relaxation phase and the four subsequent movement phases each contained 5 breathing events. During the relaxation phase, the subjects were sitting still. During the next four movement phases, they were instructed to move a single limb back and forth continuously. The four limbs were: the right hand, the left hand, the right foot and the left foot. In order to avoid time effects, the order of the four movement phases was counterbalanced among the 8 subjects. We deliberately chose a moderate movement strength that would not exhaust the subjects. They should mimic the type of "light" movements that occur often in daily life, e.g. during office work, in meetings, when holding presentations or when relaxing at home. Isolated movements of single limbs (instead of more complex daily life activities) were chosen to investigate whether the movement changes the EDA signal measured at a "moving limb" in another way than the EDA signal measured at a "resting limb". Furthermore, by choosing moderate movement intensity, we wanted to avoid artifacts which would occur due to changes in electrode contact pressure, e.g. when running (see also Fig. 11).

4.2 Phases 6–7: effect of emotional stimulus on EDA

The last two phases consisted of another 3 min relaxation phase (with the relaxing nature movie continuing) and a 3 min excerpt of an action movie ("Shoot Em Up", 2007). The excerpt was composed of the most thrilling episodes, in a way that the story line was clear to the spectator. The aim of the movie phase was to induce a state of general psychophysiological activation. Since the aim of the study was to *compare* EDA measured at the hand and at the foot, it was not important that the movie would induce a very specific type of emotion nor that the maximal possible arousal would be achieved for all subjects. Considering

Table 1 Experiment phases and instructions of subject 1

Nr.	Experiment phase	Movie genre	Instruction
1	Relaxation 1	Nature movie	Sit still, relax while watching the movie. Take a deep breath and hold for 3 s when instructed
2	Movement RH	Nature movie	Continuously move right hand, breathe and hold when instructed
3	Movement LH	Nature movie	Continuously move left hand, breathe and hold when instructed
4	Movement RL	Nature movie	Continuously move right leg, breathe and hold when instructed
5	Movement LL	Nature movie	Continuously move left leg, breathe and hold when instructed
6	Relaxation 2	Nature movie	Sit still, relax, no deep breathing
7	Movie	Action thriller	Watch movie, no deep breathing

this, we chose an action movie instead of a standardized video for specific emotion induction. No breathing events were included in these phases and the subjects were sitting still.

5 Evaluation methods

For the evaluation, we first compared the behavior of the slowly changing part of the EDA signal (the SCL) between the hand and the foot recording. In a second step we studied the "peaks", i.e. the fast EDA changes, and defined a consensus measure for comparing "hand" and "foot peaks". The analysis was performed separately for the stimulated breathing SCRs and for the NS.SCRs.

To investigate the effect of movement and the effect of the emotional stimulus, a statistical independence test (χ^2 test) was employed.

5.1 Comparison of skin conductance level (SCL)

After correcting errors caused by the Bluetooth communication, the signals were smoothed to reduce noise and transformed to SI values (μS). To compare the SCLs recorded at the hand and at the foot, the SI-transformed level signals of the two devices were synchronized and the Pearson linear correlation coefficient was calculated. The analysis was performed for each experiment phase and each subject separately.

5.2 Comparison of skin conductance responses (SCRs)

5.2.1 Peak detection and peak height calculation

Afterwards, the peaks in the high-pass filtered phase signal were detected by applying a threshold. Due to the characteristics of the high-pass filter, the peaks' heights cannot be derived directly from the phase signal. Instead, after locating the peaks in the phase signal, the level signal was considered for reading the actual peaks' heights and onsets. For finding an onset, the preceding area of the peak was searched until the gradient became negative. The peak height thus resulted in the difference between the level at the peak maximum and the level at the peak onset. The procedure is illustrated in Fig. 4.

The number of detected peaks depends on the choice of the threshold: The lower the threshold, the more peaks are detected. For our recordings, two kinds of thresholds were investigated:

1. **Fixed threshold using an amplitude criterion:** First, a small fixed threshold was applied to the phase signal to find all potential peaks. Then, after determining the peak height from the level signal, an amplitude criterion of 0.01 μS was applied (as mentioned in [2] for off-line computer analysis), i.e. peaks with amplitudes smaller than 0.01 μS were discarded.
2. **RMS threshold:** As an alternative, the Root Mean Square (RMS) of the phase signal (calculated over the whole recording) was chosen as threshold to detect the peaks. This results in a slightly different "absolute" threshold for each subject and each recording.

5.2.2 Consensus measure for hand and foot peaks and success of breathing SCR stimulation

To define consensus measures for the hand and the foot peaks, the signal measured at the hand was taken as reference signal. In a first step, all peaks found by the peak detection algorithm were used for the evaluation, regardless of their origin (induced by breathing, movement or spontaneous). Taking the "hand peaks" as reference, we searched for corresponding "foot peaks" in a 2-s window before and after the "hand peak", as shown on top of Fig. 5. In order to prevent two close peaks in the reference signal from being assigned to the same peak in the "foot signal", we decreased the window size, if the distance between two reference peaks was smaller than 4 s (Fig. 5, bottom left). On the other hand, if two peaks were found in the 4-s window of the foot signal, this was counted as wrong (Fig. 5, bottom right). To calculate an overall consensus measure between "hand peaks" and "foot peaks",

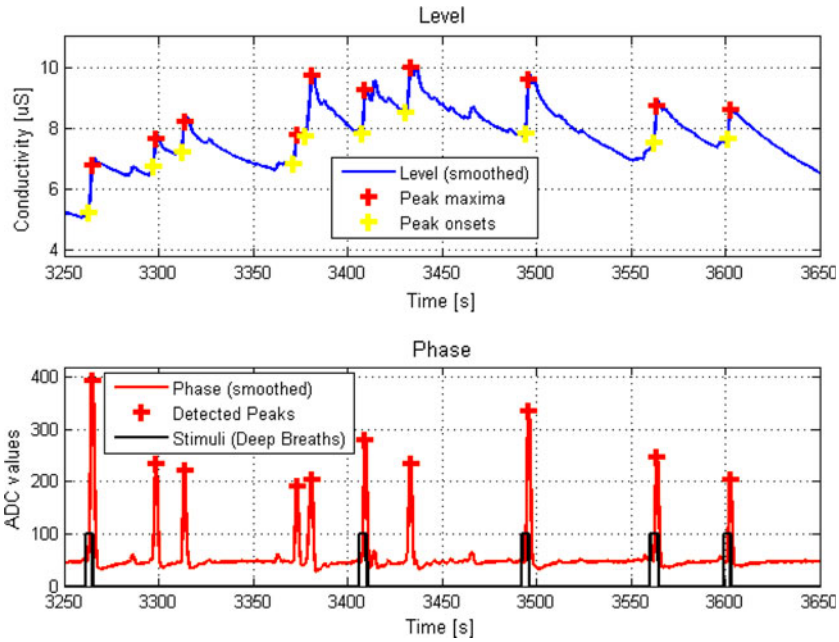

Fig. 4 Signal example recorded using the Emotion Board. Illustration of peak detection: Ten peaks are identified in the phase signal (*bottom*). To calculate the peak height, the level signal (*upper plot*) at the peak onset is subtracted from the level signal at the peak maximum. The *black* "step signal" indicates the inhalation and exhalation of 5 breathing events. The signal thus contains 5 SCRs and 5 NS.SCRs

we counted all "hand peaks" that could be assigned to a single "foot peak" and divided this number by the total number of "hand peaks".

To evaluate the success of breathing SCR stimulation, we distinguished between peaks induced by breathing and all others (i.e. the NS.SCRs). Using the labels of the breathing onsets, we searched for following "hand peaks" in a 5-s window to count the successfully induced breathing events. To determine the SCR stimulation success for the foot, the same procedure was followed for the "foot peaks". However, since peaks tend to occur later at the foot than at the hand, we allowed 7 s between the breathing onset label and the "foot peak".

To calculate the consensus for SCRs between hand and foot, we considered all the successfully induced SCRs at the hand and looked again for corresponding peaks in the EDA foot signals (2 s tolerance before and after the "hand peak"). Finally, all unlabeled peaks of the hand signal were taken as reference and used to look for corresponding "foot peaks" (again with a tolerance of 2 s before and after the reference peak) to calculate the consensus for NS.SCRs.

5.2.3 *Influence of movement*

In order to investigate the influence movement on the EDA measured at different sites in the presence of movement, several χ^2 tests were carried out. Using a contingency table of two discrete variables x and y, the null hypothesis is tested that the two variables have no association. In other words, the null hypothesis states that the distribution of the values of x is independent of the values of y. For our case, we tested whether there is an association between the measurement site (i.e. hand or foot) and the kind of detected peaks (i.e. SCRs or NS.SCRs). The test was performed separately for the first relaxation phase and for each of the 4 movement phases. If the test yields a significant result, e.g. for the movement of the left hand, this means, that the movement influences the EDA peaks measured at the hand *in another way* than the EDA peaks measured at the foot.

5.2.4 *Influence of emotional stimulus*

In order to test whether the emotional stimulus induced different effects at the hand than at the foot, we performed again a χ^2 test for the detected peaks. The first variable consisted in the recording site (hand, foot) and the second was the experiment phase (Relaxation 2, Movie).

6 Results

In this section, we will present the comparison of hand and foot SCLs, followed by the analysis of phasic EDA.

6.1 Comparison of skin conductance level

Figure 6 shows the linear correlation coefficient between the SCL measured at the hand and the SCL measured at the foot for the individual subjects. It was calculated for the first relaxation and the 4 movement conditions. The correlations are comparable for the experiment conditions. However, there are differences between the subjects. E.g. subject 1 shows low correlation for all the experiment

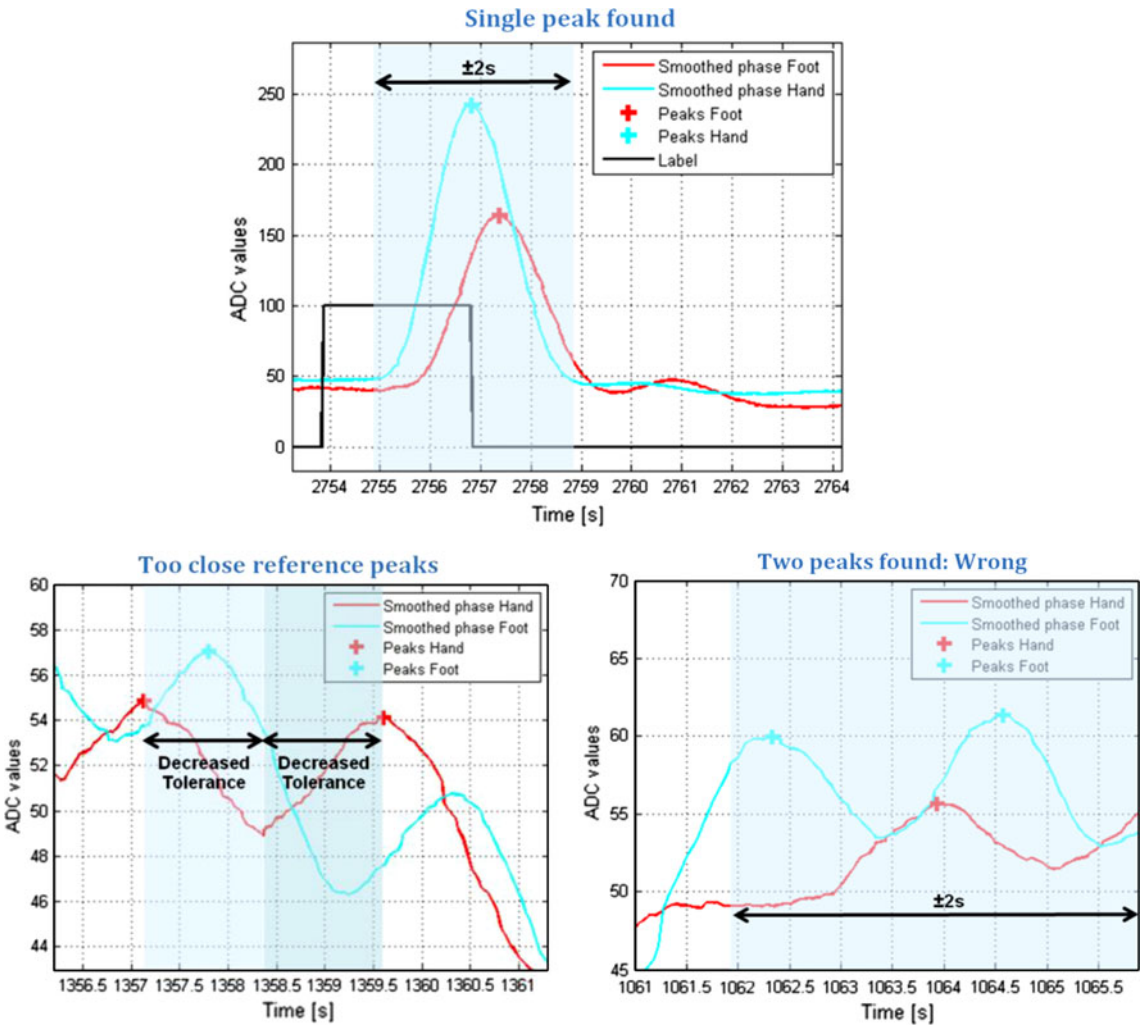

Fig. 5 Procedure to calculate consensus measure for hand and foot peaks. *Top* A single peak is found in a ±2 s window: Counted as correct. *Bottom left* One foot peak lies within the tolerance of ±2 s of two reference peaks: The tolerance after the first reference peak and the tolerance before the second reference peak are decreased such that the foot peak is only associated with the first reference peak. *Bottom right* Two foot peaks are found within the tolerance of a single reference peak: Counted as wrong

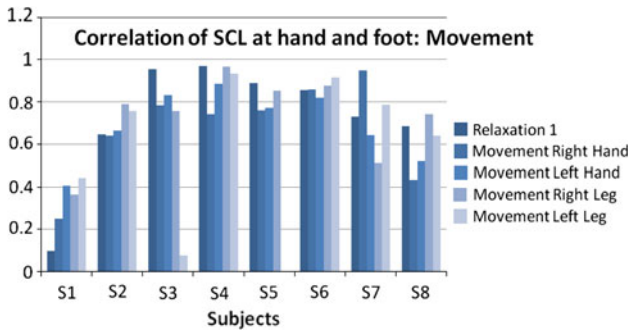

Fig. 6 Correlation of the level signals measured at the hand and at the foot during the first relaxation and the four movement conditions

phases. For this particular subject, the mean EDA level at the foot was 1.35 μS. This value is considerably lower than the value of all the other subjects and approaches the end of the measurement range of our hardware device. This recording might therefore be unreliable.

For subject 5 the movement of the left foot unfortunately let to a loose connection on the device attached to the foot. The zero correlation of the Left Leg condition for this subject is due to the missing data.

The linear correlation coefficients for the second relaxation phase and the action movie are shown in Fig. 7. The corresponding EDA level signals are depicted in Fig. 8. Since we expect a parallel signal trace for both EDA levels measured at the hand and at the foot, a positive correlation is expected. This is the case for all subjects during the relaxation phase. However, during the movie phase, the correlation coefficient is >0.6 for only 6 of the 8 subjects. For subjects 1 and 8, the EDA level at the hand increased (as expected) whereas the EDA level at the foot decreased

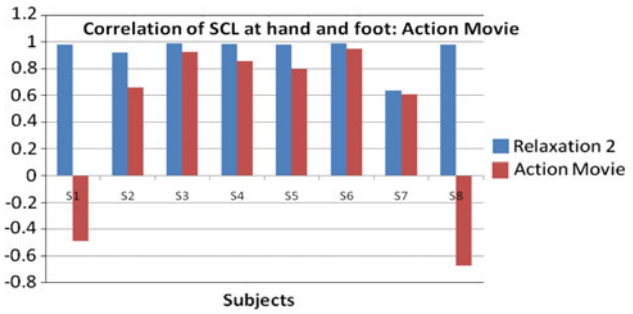

Fig. 7 Correlation of the level signals measured at the hand and at the foot during the second relaxation and the movie condition

which resulted in a negative correlation coefficient for the movie phase. The subjects were both women.

6.2 Comparison of skin conductance responses

In this section, we will first discuss the choice of the threshold for peak detection, before presenting the consensus results for the hand and foot SCRs as well as the success of SCR induction. Finally, we will investigate the influence of movement and of emotional psychophysiologically activating stimuli on phasic EDA.

6.2.1 *Choice of peak detection threshold*

As already mentioned, the number of detected peaks depends on the choice of the threshold: The lower the threshold, the more peaks are detected. On the other side, it has been found, that the peak heights can depend on the skin conductance level (SCL) [2]. If a higher SCL implies higher peaks, more peaks will exceed a fixed threshold for relatively "high" SCLs and less for relatively "low" SCLs.

To investigate this issue, we first used a fixed threshold of 0.01 μS and calculated the mean peak height and the mean value of the skin conductance at the peak onsets (yellow markers in Fig. 4) for each recording. Figure 9 depicts the mean peak height on the y-axis and the mean SCL at peak onset on the x-axis for the hand and the foot recording of each subject. The correlation of the two variables results in 0.6348 ($p = 0.0082$). This means that a

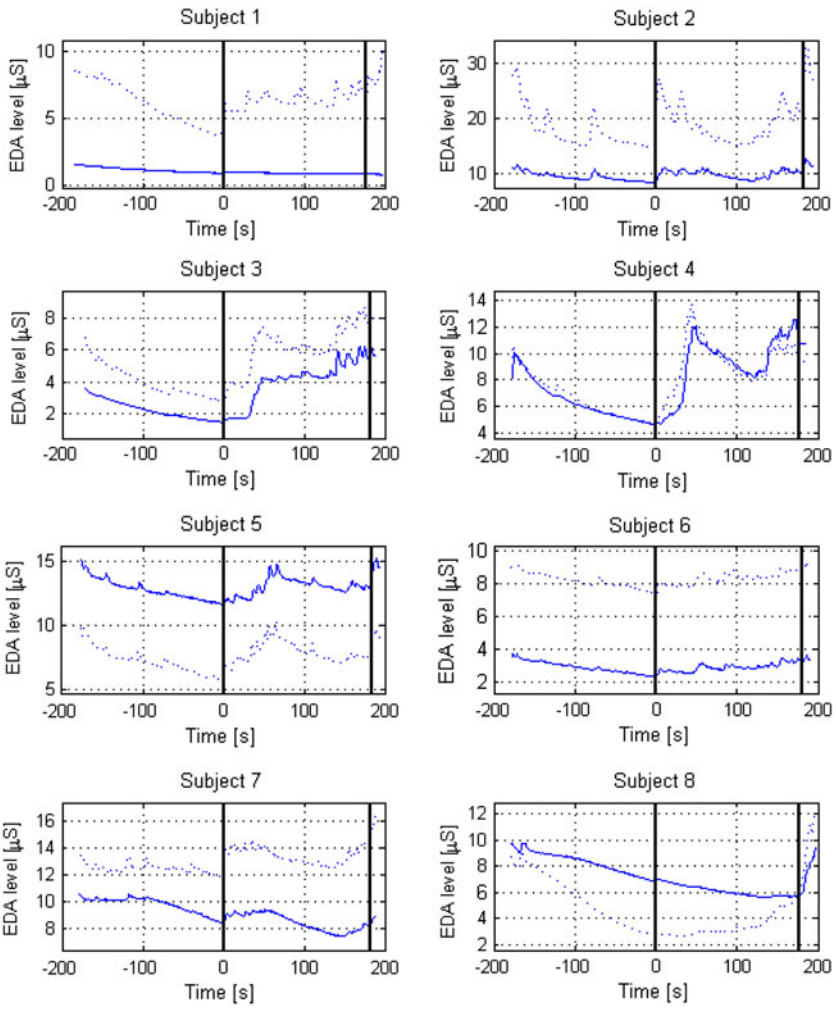

Fig. 8 Comparison of EDA levels measured at the foot (*solid line*) and the hand (*dotted line*) during the second relaxation phase and the action movie. The action movie starts at 0 s and ends at 180 s, as indicated by the *vertical lines*

higher SCL indeed implies higher peaks. For this reason, we decided to replace the fixed threshold by the Root Mean Square (RMS) of the phase signal (calculated over the whole recording) to detect the peaks. This results in a slightly different "absolute" threshold for each subject and each recording. For recordings with relatively "high" peaks, the threshold will be slightly larger than for recordings with "low" peaks.

Table 2 shows, how the choice of the threshold influences the number of detected peaks. Using a fixed threshold results in a considerable difference between the total number of peaks detected at the hand (746) and at the foot (500). For the RMS threshold, the difference between the numbers of detected hand and foot peaks decreases from 246 to only 52 and the consensus between hand and foot increases. The RMS threshold was therefore used for all the following analyses.

6.2.2 *Consensus measure for hand and foot peaks and success of breathing SCR stimulation*

After determining the peak heights, we compared the EDA reference peaks recorded at the hand with the peaks recorded at the foot, to obtain the hand-foot consensus. First, all SCRs were considered. In a second step, we distinguished between peaks stimulated by breathing and all the others (denoted as NS.SCRs). Table 3 shows the results summed up over all subjects and calculated for the entire recording (i.e. from the first relaxation phase to the movie).

One hundred sixty-four of the 199 breathing events successfully stimulated the hand EDA (82.4%). For the foot EDA, 155 peaks could be associated with one of the breathing stimuli respectively. As already mentioned, the movement of the left foot led to a loose connection on the device attached to the foot for subject 5. Taking this into account, the stimulation success for the foot results in 155/194 = 79.9%, i.e. comparable with the hand stimulation. The consensus between hand and foot EDA—when neglecting the corrupted phase—results in 65% for all peaks, 88% for the stimulated peaks and 50% for the NS.SCRs. As observed before, the consensus is higher for stimulated peaks than for NS.SCRs.

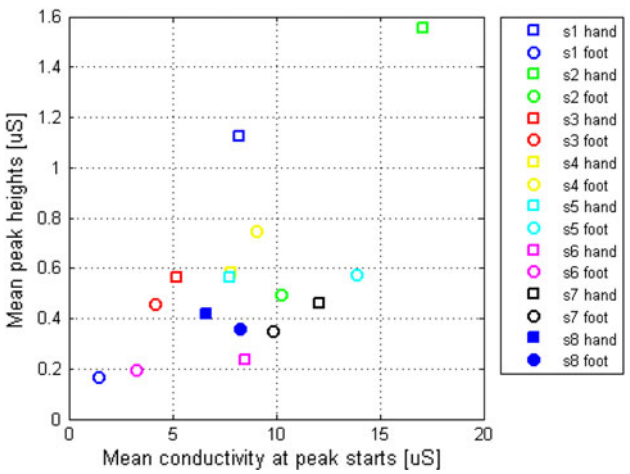

Fig. 9 Comparison of mean conductivity at the onset of the detected peaks and the mean peak height. Linear correlation coefficient: 0.6348 ($p = 0.0082$)

Figure 10 shows the consensus between "hand" and "foot peaks" of the entire recording for each test subject separately. The overall consensus varies between 49 and 77%. Each subject shows a higher consensus for stimulated peaks than for NS.SCRs.

6.2.3 *Effect of movement on phasic EDA*

For the analysis of the phasic EDA, we have so far looked at all the phases of the main experiment jointly, regardless of the presence of movement or the psychophysiologically activating stimulus. In this part, we will specifically investigate the effect of movement on the distributions of SCRs and the NS.SCRs measured at the hand and at the foot. The number of stimulated peaks and the number of NS.SCRs in the hand and the foot signals—summed over all subjects—were used to build contingency tables. A separate contingency table was created for each experiment phase, as shown in Table 4. To exclude potential transition times between successive experiment phases (e.g. when the subject switched from hand to foot movement), only 170 s of the 3 min movement phases were included in the analysis.

χ^2 tests were used to investigate, whether the measurement site, i.e. hand or foot, changes the distribution of the stimulated peaks and the NS.SCRs. Since the χ^2 tests yielded non-significant results for all experiment phases (see Table 4 for p-values), we can conclude, that moderate limb movement does either not change the EDA signals at all, or it changes the EDA at the hand and the foot in the same way. Consequently, the EDA can be measured either at the hand or at the foot.

We also checked whether the distribution of the stimulated peaks and NS.SCRs varied between the first relaxation phase and the different movement conditions. This test was performed separately for the peaks measured at the hand and at the foot. The only significant result was obtained for the hand peaks, when comparing the peaks of "Relaxation 1" with the peaks measured when moving the left hand ($p = 0.034$). The effect of moderate limb movement on the EDA is therefore considered to be small.

However, more severe movements which lead to changes in electrode contact pressure will result in artifacts. This was shown in a pre-study as shown in Fig. 11.

Table 2 Comparison of the number of detected peaks for a fixed threshold with amplitude criterion of 0.01 μS and for the RMS threshold

	Recording at hand	Recording at foot	Consensus of hand and foot
# Peaks for fixed threshold	746	500	408 (55%)
# Peaks for RMS threshold	440	388	276 (63%)

1st column: EDA peaks detected with the measurement at the hand. 2nd column: EDA peaks detected with the measurement at the foot. 3rd column: EDA peaks detected in both sensing sites

Table 3 Comparison of hand and foot recording using the RMS of the phase signal as threshold

	Recording at hand	Recording at foot	Consensus of hand and foot
Overall	440	388	276 (63%)
Stimulated	164	155	142 (87%)
NS.SCRs	276	233	134 (49%)

Sum over all experiment conditions and all subjects: 1st column: EDA peaks detected with the measurement at the fingers. 2nd column: EDA peaks detected with the measurement at the foot. 3rd column: EDA peaks detected in both sensing sites. The rows differentiate between all peaks, the stimulated peaks evoked by the deep inhalation and the NS.SCRs

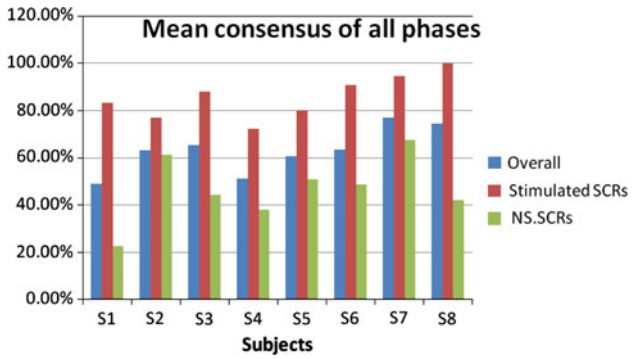

Fig. 10 Overall consensus of hand and foot peaks for each subject

6.2.4 Effect of emotional stimulus on phasic EDA

In the last step, we are interested, whether an emotional stimulus leads to similar reactions in the hand and the foot EDA signals. Another χ^2 test was performed to test the association between the emotional stimulus (Relaxation 2 phase versus Movie phase) and the peaks measured at the hand and at the foot. The corresponding contingency table is shown in Table 5. Again, the result was not significant, i.e. the effect of the emotional stimulus on the peak frequency is independent from the measurement site. As expected for an increase in arousal, more peaks were detected during the movie phase than during the relaxation phase for the hand and for the foot measurements.

Figure 12 shows the detected hand and foot peaks for each subject separately. As expected, all the subjects showed a large increase of the peak frequency in the hand EDA signal during the movie phase, compared to "Relaxation 2". The intended psychophysiological activation was thus successful despite the use of a non-standardized stimulus. Regarding the peak frequency of the foot signal, 6 of 8 subjects showed an increase of the peak frequency from the relaxation to the movie phase. This increase was equal or less than for the corresponding hand signal. The two subjects who showed no increase are the same that exhibited a negative correlation of the SCL. For those two subjects, the effect of the emotional stimulus is not visible in the foot EDA signals and inconsistent with the signals at the hand.

7 Discussion, conclusion and outlook

Even though SCR stimulation works slightly better on the hand than on the foot (82.4% vs. 79.9%), the presented results indicate that the hardware architecture of the Emotion Board is capable of measuring important EDA features at the feet in healthy subjects. The findings related to peak occurrences are consistent with [8] where "evoked non-palmar, non-plantar activity was found to be present irregularly, but was always accompanied by evoked palmar responses". A consensus measure was defined to compare the detected peaks at the hand and at the foot. The overall consensus of hand and foot peaks was 65%, where it varied between 49 and 77% for the different subjects. Consistently, all subjects showed higher consensus for stimulated SCRs (88%) than for the NS.SCRs (50%).

We found a positive inter-subject relationship between mean peak heights and mean SCLs at the peak onsets. We therefore recommend an adaptive threshold for peak detection instead of the commonly used fixed threshold of 0.01 μS. Using the RMS of the high-pass filtered EDA signal as an adaptive threshold, the difference between the numbers of detected hand and foot peaks was decreased from 246 to only 52. For daily life recordings, one might include a calibration procedure using breathing SCR stimulation to account for day-to-day variations or even to compensate for circadian fluctuations.

In [9] it was shown, that increasing walking speed from 0 to 6 km/h increases the number of peaks in the EDA signal measured at the hand. In our experiment, the subjects were sitting and performed movements of moderate strength using different limbs, mimicking "quiet" activities occurring often in daily life. The effect of movement on the peak frequency was found to be small. However, the

Table 4 Contingency tables used for χ^2 tests, calculated separately for each movement phase. For the missing data of subject 5 during the "Left Leg" movement condition, the mean values of the remaining subjects were added to the corresponding contingency table, which results in non-integer numbers. The χ^2 tests all yielded non-significant p-values indicating no different influence of movement on EDA measured at the hand or at the foot

Relax1 $p = 0.33$	SCR	NS.SCR
Hand	35	23
Foot	33	31

Movement right hand $p = 0.38$	SCR	NS.SCR
Hand	34	40
Foot	32	50

Movement left hand $p = 0.37$	SCR	NS.SCR
Hand	30	42
Foot	32	33

Movement right leg $p = 0.36$	SCR	NS.SCR
Hand	31	30
Foot	32	22

Movement left leg $p = 0.81$	SCR	NS.SCR
Hand	34	23
Foot	29.7	18.3

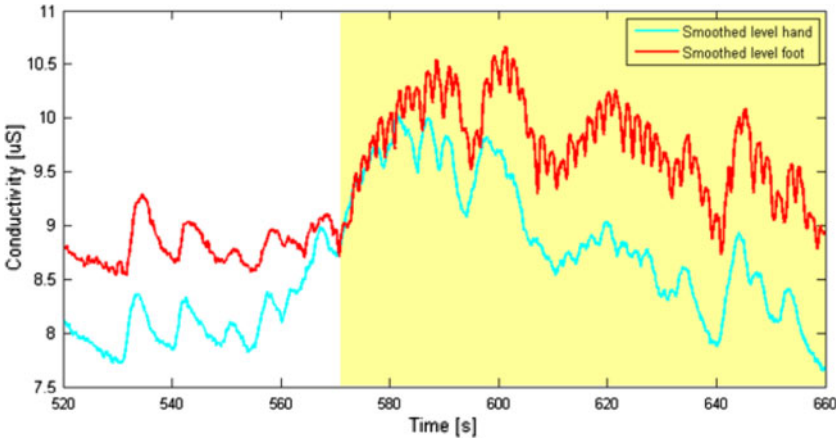

Fig. 11 Effect of walking on EDA signals measured at the hand (*blue*) and the foot (*red*). The subject was walking during the time marked *yellow*. Artifacts in the foot signal are due to changes in electrode contact pressure

Table 5 Contingency table for χ^2 test of movie data

Arousal $p = 0.81$	Hand	Foot
Relax 2	17	11
Movie	72	42

The test resulted in a non-significant p-value

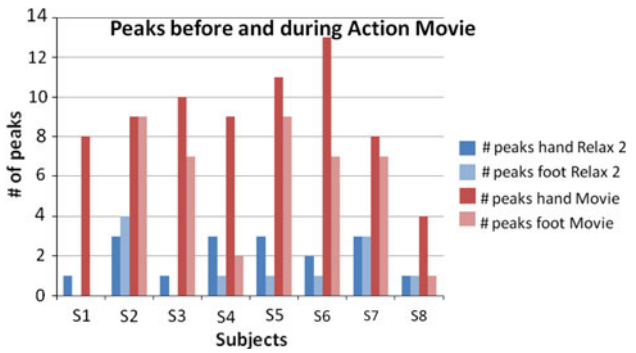

Fig. 12 Detected peaks during the second relaxation phase and the movie phase for each subject separately

question which is more important for us is: Does moderate physical activity influence the EDA measurements at the hand in a different way than the measurements at the foot? Since the χ^2 tests yielded non-significant results for all experiment phases, we can conclude, that moderate limb movement changes the EDA at the hand and the foot in the same way. Consequently, the foot is expected to represent a suitable location to measure SCR and NS.SCRs in relatively quiet conditions, e.g. in the office. However, this still needs to be confirmed in further experiments including "real" activities (e.g. typing). Regarding the correlation between hand and foot SCL, no differences were observed depending on the movement condition. However, there were subjects showing generally higher correlation than others.

As already mentioned, we deliberately chose moderate movement intensity to avoid artifacts which can occur due to mechanical impact/movements of the electrodes. An example of such artifacts is shown in Fig. 11 where walking induced periodic oscillations in the EDA signal measured at the foot. These changes are not due to psychophysiological activation but due to changes in electrode contact pressure. It is difficult to differentiate the walking-induced peaks from SCRs. For practical applications, such phases of strong activity will have to be excluded from the analyses, whereas phases of moderate activity (as they occur mostly in daily life e.g. for people working in an office) can be utilized. As supplement to breathing, we included an action movie as naturalistic emotional stimulus to induce psychophysiological activation, preceded by a relaxation phase. As expected, all subjects show decreasing EDA levels and positive correlation during Relaxation. During the movie, the correlation coefficient was >0.6 for 6 of 8 subjects, but 2 subjects showed a reversed SCL trend at the foot compared to the hand. They were the same subjects that did not show an increase of peak frequency at the foot during the movie phase. However, since both of them showed an increase in SCL and in peak frequency at the hand, we *cannot* conclude, that the emotional stimulus would have been ineffective. We would like to emphasize that we did not investigate the effect of specific emotions on the EDA signals. Doing that would have required the usage of validated videos which are proven to provide very specific emotional stimuli.

The subjects with unexpected results were all women. The chapter about gender differences of [2] mentions that women have shown a slower sweat secretion than men which might be related to this observation. E.g. for subject 8 (see Fig. 8), the EDA level at the hand continues increasing after the movie, and the EDA level at the foot follows later. However, the behavior of the level at the foot in the presence of an emotional stimulus deserves further evaluation. More subjects and longer time periods should be included and gender effects considered.

In a next step, we are planning to obtain EDA data from patients suffering from bipolar disorder. The corresponding ethics approval is currently ongoing. Future experiments will show, whether our findings generalize to patient groups for long-time measurements in daily life.

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