DOCTORAL (PhD) DISSERTATION

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Electrodermal activity as a valuable measure of emotional arousal

2020

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Electrodermal activity as a valuable measure of emotional arousal

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Budapest, 2020

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EÖTVÖS LORÁND TUDOMÁNYEGYETEM

ADATLAP a doktori értekezés nyilvánosságra hozatalához

I. **A doktori értekezés adatai**

A szerző neve: Kasos Krisztian

A doktori értekezés címe és alcíme:

Electrodermal activity as a valuable measure of emotional arousal

A doktori iskola neve: Pszichológiai Doktori Iskola

A doktori iskolán belüli doktori program neve: Magatartás-pszichológia Program

A témavezető neve és tudományos fokozata: Dr Veres-Székely Anna, DSc

A témavezető munkahelye: ELTE PPK Pszichológiai Intézet

MTMT Adatbázis-azonosító: 10057883

Nyilatkozatok

1. A doktori értekezés szerzőjeként[1]

a) hozzájárulok, hogy a doktori fokozat megszerzését követően a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az ELTE Digitális Intézményi Tudástárban.

b) kérem, hogy a mellékelt kérelemben részletezett szabadalmi, illetőleg oltalmi bejelentés közzétételéig a doktori értekezést ne bocsássák nyilvánosságra az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban;[2]

c) kérem, hogy a nemzetbiztonsági okból minősített adatot tartalmazó doktori értekezést a minősítés (*dátum*)-ig tartó időtartama alatt ne bocsássák nyilvánosságra az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban;[3]

d) kérem, hogy a mű kiadására vonatkozó mellékelt kiadó szerződésre tekintettel a doktori értekezést a könyv megjelenéséig ne bocsássák nyilvánosságra az Egyetemi Könyvtárban, és az ELTE Digitális Intézményi Tudástárban csak a könyv bibliográfiai adatait tegyék közzé. Ha a könyv a fokozatszerzést követőn egy évig nem jelenik meg, hozzájárulok, hogy a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban.[4]

2. A doktori értekezés szerzőjeként kijelentem, hogy

a) a ELTE Digitális Intézményi Tudástárba feltöltendő doktori értekezés és a tézisek saját eredeti, önálló szellemi munkám és legjobb tudomásom szerint nem sértem vele senki szerzői jogait;

b) a doktori értekezés és a tézisek nyomtatott változatai és az elektronikus adathordozón benyújtott tartalmak (szöveg és ábrák) mindenben megegyeznek.

3. A doktori értekezés szerzőjeként hozzájárulok a doktori értekezés és a tézisek szövegének plágiumkereső adatbázisba helyezéséhez és plágiumellenőrző vizsgálatok lefuttatásához.

Kelt: Budapest, 2020.04.20.

a doktori értekezés szerzőjének aláírása

[1] A megfelelő szöveg aláhúzandó.

[2] A doktori értekezés benyújtásával egyidejűleg be kell adni a tudományági doktori tanácshoz a szabadalmi, illetőleg oltalmi bejelentést tanúsító okiratot és a nyilvánosságra hozatal elhalasztása iránti kérelmet.

[3] A doktori értekezés benyújtásával egyidejűleg be kell nyújtani a minősített adatra vonatkozó közokiratot.

[4] A doktori értekezés benyújtásával egyidejűleg be kell nyújtani a mű kiadásáról szóló kiadói szerződést.

Acknowledgements

The past four years work has been a team effort. I am lucky to be surrounded by people who have made it possible. I am eternally grateful to my family, without their support, and love my research as well as the completion of this dissertation would not have been possible.

I am thankful for my academic supervisor: Anna Veres-Székely, who's guidance and motivation have been an insurmountable help over the years. It is from her that I have gained the most knowledge, and over the years her support as a colleague and friend has been more than indispensable. Anna, thank you, for your endless time, and for all the occasions you sat down with me one-on-one to mentor me in article writing. I will never forget all the times you stayed behind in the lab to "just" talk and have a heart-to-heart.

It goes without saying, that the background research for this dissertation could not have been attained alone. I am indebted to my team and my colleagues. They've lent extensive time and effort over the years, taking major roles in conducting the experiments and contributing to data analyses and article writing. From my lab I would like to highlight and thank all efforts of Eszter Kótyuk, Szabolcs Zimonyi, Luca Csirmaz and Fanni Vikor, with whom I have worked closely, both in their research and mine, as well as in our collaborative projects. Our team building programs were essential to let out some steam and thus, our time in the lab was made light-hearted and fun with their presence.

I am much obliged to Katalin Varga, head of the Affective department of ELTE PPK for all her help and support. I must also mention Zoltán Kekecs, for mentoring and willingness to provide guidance and energy, with long hours of online chats (while being abroad or at conferences).

Mentioning all names of those who have helped me over my academic career is all but impossible. I am indescribably grateful to all those mentioned and those who are not. I am excited for future research and hope to be able to indulge in the help of my colleagues for a long time coming.

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Table of Abbreviations

MAT	Multiple Arousal Theory
SCR	Skin Conductance Response
SCL	Skin Conductance Level
NS-SCR	Non-Specific SCR
EDA	Electrodermal Activity
HGSHS	Harvard Group Scale of Hypnotizability
PCI	Phenomenology of Consciousness Inventory
ANS	Autonomic Nervous System
SNS	Sympathetic Nervous System
STAI	State and Trait Anxiety Inventory
NTP	Network Time Protocol
BLE	Bluetooth Low Energy
WSGC	Waterloo Stanford Group scale
SHSS	Stanford Hypnotic Susceptibility Scale
UNI	Unilateral Measurements
BI	Bilateral Measurement
SCS	Stanford Clinical Scale
cAIC	Conditional Akaike Information Criterion
CI	Confidence Interval
b	Beta Coefficient

Link to Appendixes listed in the dissertation text, published articles and manuscript:

https://www.dropbox.com/sh/zknnqug3uzc8b3i/AAB5EFpsqHMj_oUUomkgH0GQa?dl=0

List of publications containing results of the dissertation

Kasos, K., Zimonyi, S., Gonye, B., Köteles, F., Kasos, E., Kotyuk, E., Varga, K., Veres, A., Szekely, A. (2019). Obimon: An open-source device enabling group measurement of electrodermal activity. Psychophysiology, (2018), 1–15. https://doi.org/10.1111/psyp.13374 (IF: 3.140)

Kasos K, Kekecs, Z., Csirmaz, L., Zimonyi, Sz., Vikor F, Kasos, E., Veres, A., Szekely A. (In press: DOI: 10.1111/psyp.13645) Bilateral comparison of traditional and alternate electrodermal measurement sites. Psychophysiology. (IF: 3.140) Accepted manuscript: https://www.researchgate.net/publication/341826726_Bilateral_comparison_of_traditional_and_alternate_electrodermal_measurement_sites

Kasos, K., Zimonyi, S., Kasos, E., Lifshitz, A., Varga, K., & Szekely, A. (2018). Does the Electrodermal System "Take Sides" When It Comes to Emotions? Applied Psychophysiology and Biofeedback. https://doi.org/10.1007/s10484-018-9398-0 (IF: 1.116)

Kasos, K., Kekecs, Z., Kasos, E., Szekely, A., & Varga, K. (2018). Bilateral Electrodermal Activity in the Active–Alert Hypnotic Induction. International Journal of Clinical and Experimental Hypnosis, 66(3), 282–297. https://doi.org/10.1080/00207144.2018.1460551 (IF: 0.860)

Kasos K, Csirmaz L, Vikor F, Zimonyi S, Varga K, Szekely A. Electrodermal Correlates of Hypnosis: Current Developments. OBM Integrative and Complementary Medicine 2020;5(2):20 http://www.lidsen.com/journals/icm/icm-05-02-017

Note: Co-authors of the above papers have granted permission for these publications to be included in the current dissertation and acknowledged major contribution to accomplishment of the results described in the articles from the first author.

Summary

The focus of this dissertation is the investigation of various emotional arousal using bilateral, multi-site electrodermal activity (EDA) measurements. In their handbook of psychophysiology, Dawson and his colleagues call Electrodermal activity (EDA) "the most widely used – some might add "abused" – response systems in the history of psychophysiology" (Dawson, Schell, & Filion, 2007). My PhD work underlies this statement a hundred percent with several methodological points related to measurement details. In 5 studies, we collected EDA data from 368 participants. Half of the experiments were carried out in group settings, which is relatively scarce in the EDA literature, thus this thesis carries valuable methodological insights.

My results are in line with the Multiple Arousal Theory (Picard, Fedor, & Ayzenberg, 2015), challenging long-standing theoretical concepts of emotional arousal based on objective EDA data measured bilaterally and from multiple dermatomes, instead of the traditional single (non-dominant side) measurements. This dissertation contributes to our knowledge on alternate measurement locations and how they relate to traditional measurement locations. We tested how induced emotions are related to bilaterally measured electrodermal activity and electrodermal laterality differences between the lower and upper body. Results presented here in relation to bilateral measurements from different dermatomes related to active-alert and traditional hypnosis are novel in the literature, widening our understanding on how this altered state of consciousness affects the peripheral nervous system.

To accomplish studies outlined in my dissertation, we needed a system that is wireless, small enough to be placed anywhere on the body and is capable for group measurements. Therefore, the aim of the first study was to validate a new EDA measurement system designed to perform laboratory studies with the capacity for group measurements. Based on results from 3 experiments with 109 participants results confirmed that the Obimon system (see obimon.com) performs comparably to a research grade electrodermal measurement device (Nexus).

The advancement in EDA technology allows for long term ambulatory measurements and finding viable measurement places is crucial for the field. Furthermore, in some instances traditional measurement locations are not available during laboratory experiments. In the second study (N = 115, N = 20) I explored and compared multiple electrodermal measurement locations bilaterally to the traditional non-dominant finger location. Our study is the first to

compare five locations bilaterally and investigate response latencies in addition to skin conductance level (SCL) and skin conductance responses (SCRs).

In the third study (N = 38) I examined electrodermal responses to different emotional stimuli bilaterally from the palmar and plantar surfaces. This investigation tested the assumptions of Multiple arousal Theory and extended its predictions to the lower body and to electrodermal responses along with the level of skin conductance. The novelty if this study is assessment of responses to musically induced emotions from 4 measurement locations. This is also the first study to examine emotional response laterality in a group setting adding new results to the literature of the psychophysiology of emotional responses.

In the fourth and fifth studies (N= 28 and N = 57 respectively) I investigated the bilateral electrodermal effects of hypnosis measured from different locations in active alert and traditional hypnosis. These studies bring attention to how bilateral electrodermal measurements may differentiate between hypnosis and normal waking state. My most important results highlight that EDA patterns of the two sides during the hypnotic induction phase is markedly different for those with high, medium and low hypnotizability. These results are novel in hypnosis research. They widen the scope of the Multiple Arousal Theory, as results clearly demonstrate applicability of the theory for this type of altered state of consciousness.

Results presented here reverberate the call for a paradigm shift in EDA methodology and theory. Based on these findings the One Arousal Model of EDA should be abandoned in favour of Multiple Arousal Theory and unilateral measurements should be replaced by bilateral, multi-site measurements.

Chapter1: Introduction

As personal note, I started working with electrodermal activity during my years as a master student in two labs (the Hypnosis Lab and the Adaptation Lab) at the Institute of Psychology, ELTE-PPK under the guidance of Anna Veres-Szekely. We measured electrodermal activity during traditional and active alert hypnosis to explore the effects of hypnosis on the symphatetic nervous system. I wrote my master thesis on the association between hypnosis and EDA. It was during my master years, when among different theories of electrodermal activity I came across the Multiple Arousal Theory (MAT), and a presentation of this theory by an MIT Professor: Rosalind Picard. Seeing her presentation and reading her work drove my interest toward the topic, and since then my interest towards this topic has grown exponentially. As a PhD student I started testing predictions of her theory and expanding predictions related to the possibility of multiple arousal systems to different dermatomes. While working with electrodermal activity data I believe I've learned a lot about this simple, yet fascinating form of emotional feedback. I believe that EDA measures could be used in a much more complex way than they are used today in most studies and therapy. These are exciting times in this field of research with great advancements in measurement technology as well as in data analysis. I would like to be in the front row, promoting a paradigm shift in the field, where multi-site measurements are norms not exceptions. I hope that my dissertation will contribute to our better understanding of emotional arousal.

Electrodermal activity

The measurement of electrodermal activity has been around since the 1800s and has enjoyed tremendous attention in psychophysiology. Ease of measurement and practicality are two major reasons that made the measurement of EDA a favoured tool in research. Besides the above factors, unobtrusiveness of this measurement technique also played a role in it being favoured in psychophysiology (Dawson et al., 2007). EDA has been used in lie detection paradigms, and it has been indexed as a reliable measure of psychological arousal, furthermore, different EDA characteristics proved to be valuable indicators of emotional state in adults, children, and infants.

Compared to other methods that gauge autonomic nervous system (ANS) activity (such as heart rate variability or pupil dilation) one of the advantages of measuring EDA is that it reflects the activity of the sympathetic branch (SNS) of the ANS (Boucsein et al., 2012). By

measuring electrodermal activity we measure the activity of eccrine sweat glands. Eccrine sweat glands are innervated by cholinergic sudomotor fibers originating in the SNS (Dawson, 2007). Ecrinne sweatgalnds are present in proportionately higher numbers on the palmar and plantar surfaces than any other locations on the body. Alternate measurement sites (such as wrists, calves, shoulders) usually have lower number of eccrine sweat glands per square cm (Dawson et al., 2007).

The central control of EDA is complicated. There are different parts of the brain exhibiting excitatory or inhibitory influences on EDA. For example, the hippocampus exhibits inhibitory control on EDA while the amygdala exhibits excitatory influences on EDA (Dawson, Schell, & Filion, 2007). There are at least 2 major central pathways that control EDA. One of them is a limbic pathway exhibiting ipsilateral control. The other major pathway is the motor pathway originating in the motor cortex and involving structures in the Basel ganglia. Structures in this pathway exhibit contralateral influences on EDA (Boucsein et al., 2012; Dawson et al., 2007).

Different central structures play different roles in EDA control. EDA influenced by amygdala activation represent affective processing, EDA generated by the frontal regions reflect attentional processing. These influences are complex and not clearly defined, yet (Dawson, Schell, & Filion, 2007).The hypothalamus for example plays a role in thermoregulatory control.

Although affective processes are handled in many areas of the cortex, the limbic system plays a substantial contribution in processing emotions (Catani, Dell'Acqua, & Thiebaut de Schotten, 2013). Direct stimulation research tells us that the amygdala is the biggest contributor to generating electrodermal activity (Mangina & Beuzeron-Mangina, 1996). Negative emotions are processed mostly by the right hemisphere while positive emotions are processed predominantly by the left hemisphere (Picard et al., 2015). Consequently, an arousal measurement that is sensitive to lateral differences could be extremely useful in portraying a multi-dimensional picture of emotional processes. Moreover, emotional processes and their neurobiological consequences in the limbic system are time sensitive. Thus, a psychophysiological measurement system capable of monitoring real-time changes of the autonomic nervous system can provide extremely useful insight to how these processes evolve in time (Kasos, Zimonyi, Gönye, et al., 2019).

Emotions and autonomic responses

Are there specific autonomic responses for different emotions or the autonomic arousal which goes along with emotions are diffuse and very similar? Whether or not emotions have a specific autonomic mapping has been on the forefront of emotion research ever since William James and Carl Lange proposed that emotions occur as a result of physiological reactions to events. This became known as the James-Lange theory of emotion predicting that different emotions are accompanied by specific autonomic arousal, and that this specific autonomic arousal plays a key role in emotion perception. According to the theory autonomic arousal precedes feeling of an emotion and autonomic arousal is necessary to perceive basic emotions. This view goes against the common sense view: feeling of the emotion causes autonomic changes. The ideas proposed in the James-Lange theory has spurred up a heated debate with contradictory findings (Friedman, 2010).

The greatest challenge of the James-Lange theory came from one of James's former students Cannon and became known as the Cannon-Bard theory of emotion. According to this theory emotional stimuli produces feelings of an emotion and autonomic responses separately. Moreover, this theory does not attribute causal relationship between autonomic arousal and emotion perception. Furthermore, the theory claims that there is no emotion specific autonomic response, rather autonomic responses are very similar (Cannon, 1927)

A new theory blending assumptions of previous theories, emerged in the early 1960s. The Schachter -Singer theory of emotion perception gives credit to autonomic responses, however, suspects environmental clues as crucial factors in determining emotional states. In their view physiological arousal accompanied by cognitive conditions will determine the label of an emotion. Their theory has been challenged on methodological and conceptual levels (see Reisenzein, 1983).

Recently in emotion research a popular theory supporting emotion specificity of autonomic responses surfaced. The facial feedback theory postulates that peripheral feedback strengthens the perceived emotion. Research based on the facial feedback theory also provided contradictory results. The consensus of these results suggest that positive vs negative emotions (and not discrete emotions) seem have ANS specificity (Ekman, 1992).

Pattern classification analysis was used in a number of studies starting from the mid-1980s. This type of analysis allows researchers to simultaneously consider different ANS

measures. The results of these studies support the notion that emotions have a discrete pattern of peripheral activity (Friedman, 2010).

The somatic marker hypothesis (which could be considered as an extension of the James-Lange theory) has grown out of brain imaging data showing that emotional feelings follow peripheral changes. The theory assumes a major role for peripheral feedback in cognitive judgements. This theory has been supported with evidence from electrodermal responses (Damasio, 1996).

In summary in the debate whether emotions are accompanied by a specific pattern of autonomic arousal or there is a general arousal accompanying all types of emotions gained evidence on both sides. It is possible that the methods used to study emotion specific arousal to date have not exploited full potential of this assumption and that empirical support including electrodermal evidence is a path to further explore.

Measuring electrodermal activity

One way to measure Electrodermal activity is to measure skin conductance (SC). Skin conductance has two major components. The skin conductance level SCL (characterized by slow changes) represents the background activity of the symphatetic nervous system. Skin conductance response (SCR) represents faster changing phasic activity and usually last between 1 to 5 seconds after stimulus onset. SCRs have different attributes that are measured and reported in psychophysiological experiments (Dawson et al., 2007). The most important are: 1, response amplitude; 2, response latency; 3, half recovery time; 4, rise time. Important methodological aspects relevant to the dissertation are described in full in Kasos et al., 2020.

There are different existing methods to measure EDA. Two major methods emerged as the most dominant ways in research. One of them is called endosomatic the other exosomatic (Dawson et al., 2007). Endosomatic methods use the actual electrical properties of the body, while exosomatic methods apply a small current (typically lower than 0.5 mV) between two electrodes and measure how well the skin conducts this current. Most systems are designed to measure from the palmar and plantar surfaces, however there are existing newer technologies that are able to measure from alternate locations such as the wrists and the calves.

There are results that show that sleep storms can be captured on the wrists but not on the fingers (Sano, Picard, & Stickgold, 2014). These results imply that in some altered state of

consciousness the fingers are not the most sensitive dermatomes. This in turn may suggest that alternate electrodermal measurement places in an altered state of consciousness could be more sensitive to emotion-related changes in these states as compared to traditional measurement sites.

Contrasting unilateral measurements with the Multiple Arousal theory

The unilateral measurement approach assumes that arousal is the same across the body at any given time and a "one true arousal" can be measured from the non-dominant hand.

Traditional EDA research is based on unilateral measurements taken from the non-dominant hand (Boucsein et al., 2012; Dawson, 2007). It is preferred to measure EDA from the fingers, because they have the highest density of eccrine sweat glands. Thus, measurements have been taken most often from the medial or the proximal phalanges of the index and middle fingers of the non-dominant hand which are the recommended places to measure from (Dawson, Schell, & Filion, 2007c). Selecting the non-dominant fingers follows multiple assumptions; one of them is that the non-dominant side is used less often so the skin suffers from fewer injuries, thus, the skin is more intact than on the dominant side. These unilateral measurements are also presuming that arousal is uniform in the body and there is a "one true arousal" that may be measured from the non-dominant hand. Any differences in measured arousal between the two sides of the body or between different dermatomes are contributed to-for example-; the different number of sweat glands in different parts of the body, to hemispheric differences or to the fact that different dermatomes contribute to thermoregulation with different magnitude. This idea has dominated research until very recently. On the other hand, more recent models (such as Multiple Arousal Theory, MAT) predict that EDA could vary on different dermatomes, depending on several underlying generators of EDA (Picard, Fedor, & Ayzenberg, 2015).

The emerging approach conceptualized in Multiple Arousal Theory (MAT, Picard et al., 2015) that explains dermatome differences regarding EDA in an innovative way. According to the theory different emotional states are related to different cortical and subcortical brain regions. These brain regions act as neurological generators corresponding to unique pathways responsible for EDA. Thus, according to MAT, different dermatomes present different electrodermal levels in response to different emotional states. These differences are caused by different neurological generators corresponding to unique pathways responsible for EDA.

Thus, the theory assumes different subtypes of arousal corresponding to different emotional states. Moreover, different emotional states would cause different patterns of activation across dermatomes. For example, Picard and colleagues found that in situations where the self is threatened (during a high stake presentation) the right side SCL rose above the left SCL in a right handed person (for details see (Picard, Fedor, & Ayzenberg, 2015). This theory has captured much attention in the past couple of years and mostly echoed positive reactions. Nonetheless, this prediction was based on longer term observations. Some question the theory for it does not use traditional electrode placement sites and uses dry electrodes (Sabatinelli, 2016). Others cite that although the idea is useful, the theory lacks predictive power (Richter, 2016). While some welcome it, the new theory calls into question the concept of arousal as it defined presently (Norman, 2016) and it lists more questions regarding affective states, and how they relate to arousal than can be answered (Mendes, 2016). These commentaries on the theory show the interest of the field in a paradigm shift. MAT is potentially a theory that may serve as a beacon in the pursuit of this new paradigm. MAT predicts specifically that negative emotions would trigger greater right sided electrodermal activity on the palmar surfaces compared to left palmar surfaces for a right-handed person. The theory also predicts that positive emotions would either prompt greater left sided activity or a synchronous activity between the left and right side. It also predicts that anxiety especially anxiety related to a threat to the self would cause the right-side activity to elevate over the left activity in a right-handed person. The phasic activity of the SNS has only rarely been investigated bilaterally and has never been tested based on the assumptions of Multiple Arousal Theory. Systematic research and testing of the predictions of this theory is still needed. In addition, electrodermal responses of the lower and upper body have never been compared. Given this unprecedented approach, I suspected that measuring bilateral, instead of unilateral electrodermal activity may provide invaluable information to my research investigating different aspects of affective arousal.

Alternate measurement sites for an altered state of consciousness: hypnosis

Hypnosis by definition is an altered state of consciousness that is characterized by focused attention and reduced peripheral awareness. In this altered state susceptibility (hypnotizability) to suggestions increases (Kekecs, Szekely, & Varga, 2016). Hypnotizability to suggestions varies in the population and follow a normal distribution (Piccione, Hilgard, & Zimbardo, 1989). The hypnotic induction is a process to reach this state, however hypnosis may also be induced spontaneously. It is a state in which emotional processing takes

precedence over the sequential processing of the normal waking state. Research into the effects of hypnosis on the electrodermal system produced contradictory results. However, in the past EDA was measured from the palmar surfaces. Alternate measurement sites were never used to measure EDA during hypnosis. We suggest that hypnosis could serve as a model situation for investigating dermatome differences in electrodermal activity (Kasos, Csirmaz, et al., 2020).

Technological advancements in EDA measurement

Studies in the past usually were single subject experiments (due to the fact that group measurements further complicate requirements set against the systems). Yet, application of group experiments not only allow more swift data collection, but they also open the door to investigating psychological phenomena in a group setting which is practically missing from the literature (Kasos, Zimonyi, Gönye, et al., 2019). Measurement systems to be used in a group setting require mobility and flexibility, features that do not fit those systems researchers used a few decades back. At the same time psychophysiological measurement systems, to date have gone through great advancements. Currently, we have measurement systems that are wireless, which makes their use plausible outside of the laboratory and in group measurements (Kasos, Zimonyi, Gonye, et al., 2019). New devices have many advantages over traditional technology. Devices are able to measure continually for extended hours. New systems are often wireless, therefore problems created by the use of cables are bypassed (Axisa et al., 2004; Lee, Yoon, Lee, & Lee, 2006; Strauss et al., 2005). Some wireless technology allows for the online monitoring of EDA from multiple devices (Kasos, Zimonyi, Gonye, et al., 2019). The particulat system I used (OBIMON) is capable of time synchrony among devices and is one of the most important novel features of the Obimon system. It allows for the seamless management of group measurement. Group measurement data is demonstrated in Figure 1 below. Individual variability of both EDA level and magnitude of responses is apparent based on Figure 1. Nonetheless, effect of a simple audio-guided breath-in instruction is clear, demonstrating sensitivity of this system in monitoring emotional arousal. Obviously, such new systems need to be validated. The main aim of the validation procedure is clear; do measurements using the new system compare to those of devices already in use. However, it seems that solutions for validating devices have been proposed mostly from a technical point of view (Geršak, 2015). Validation of measurement systems that use data from human subjects are rare in the literature. I have had a unique opportunity to use a pre-commercial version of the Open source Bio-Monitor (OBIMON) for electrodermal measurements in my PhD research. However, before

analysing EDA results from my extensive group measurements using multiple electrodermal sites in various experimental settings related to the investigation of emotional arousal, I've carried out a series of experimental setups with the main objective of validating EDA measurements with OBIMON. Results from these validation experiments are summarized in the publication based on **Study 1** (Kasos, Zimonyi, Gonye, et al., 2019).

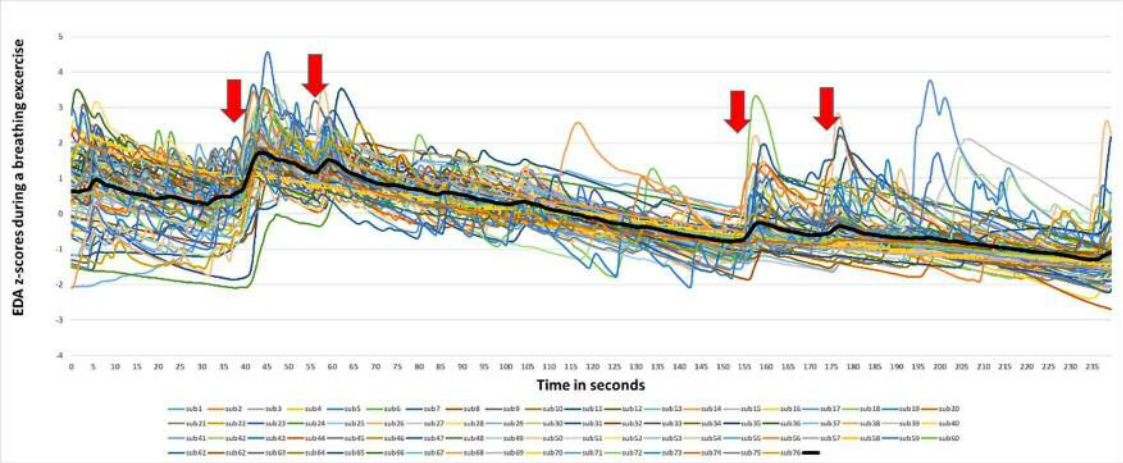

Figure 1: group measurement during a breathing exercise. Bold black line represents the average of individual EDA. Red arrows represent the breathing in instructions.

Exploring bilateral EDA on alternate measurement sites

Recent developments in technology has allowed researchers to step out of the laboratory into "real life" settings and it also paved the way for advanced ambulatory measurements. In some instances, even in the laboratory the hands or the feet may be busy doing some kind of task, therefore alternate measurement places are in need (Kasos, Kekecs, et al., 2020). These advancements require measurement sites that are inconspicuous, comfortable for long term wear, and do not interfere with everyday activities. These measurement sites don't tend to be the traditional hand or foot locations (Kasos, Kekecs, et al., 2020). Thus, exploration of alternate measurement sites is warranted and necessary in this field. There have been explorations of alternate sites in the literature, however the results are contradictory (Payne, Schell, & Dawson, 2016, van Dooren, de Vries, & Janssen, 2012). The most researched alternate location is the wrist. Other locations have been used in research without thorough evaluation for example Hedman et al., 2012 used the lower calf (Kasos, Kekecs, et al., 2020). Although lateral differences have been reported, bilateral exploration of alternate sites is missing from the literature (Kasos, Kekecs, et al., 2020). Latency of responses

at different measurement locations, for example have never been compared. SCR Latency is important, because windows to detect SCRs are set based on latencies measured from the fingers. However, latency of responses may differ at alternate locations. To react to these methodological aspects missing from the literature, I explored 5 different measurement sites bilaterally, comparing SCL, response magnitudes, response latencies and correlations between the non-dominant fingers and other locations in **Study 2.** Within this study I also carried out replication experiments, to assess repeatability and reproducibility of the results. Results are summarized in (Kasos, Kekecs, et al., 2020).

Bilateral phasic EDA measurement comparing the upper and lower limbs

MAT's predictions have been tested recently in a high-stake stress paradigm; measuring the tonic component of EDA (SCL) (Björn 2019). The results of this study were inconclusive, and the authors called for more empirical work testing the theory. In **study 3** (Kasos, Zimonyi, et al., 2018), we explored whether short (7 -second-long) stimuli would trigger different magnitude responses on different locations on the body. This investigation is unique for multiple reasons; the phasic component of EDA had never been tested based on the assumptions of MAT. Musically induced emotions had never been investigated regarding bilateral EDA. In this study we collected data in a group setting adding valuable group measurement information to the existing EDA literature. The lower and upper body had never been compared based on the assumptions of MAT. The purpose of this investigation was to find lateral and dermatome differences in phasic responses to emotional musical stimuli, extending and testing the predictions of Multiple Arousal Theory to phasic activity and comparing the lower and upper body regarding electrodermal laterality.

Bilateral electrodermal activity measured from alternate measurement places in hypnosis

Hypnosis is a state in which emotional processes take precedence over the sequential, and logical processing of normal waking state. Furthermore, the hypnosis induction is hypothesised to produce hemispheric changes that are different for high and low hypnotizable individuals. Studies investigating the effects of hypnosis on the autonomic nervous system thus far, have produced contradictory results (Kasos, Csirmaz, et al., 2020). Some studies found the down regulation of the symphatetic nervous system during hypnosis, but others found rising arousal or no change in arousal (See study 5 for a detailed review regarding EDA and

hypnosis). Since bilateral electrodermal activity was never measured during active alert hypnosis, I was interested to see how the active alert induction effects bilateral electrodermal activity. Based on Gruzelier's induction theory, which predicts a hemispheric dominance shift during the hypnotic induction (John Gruzelier, Sergeant, & Eves, 1988) and inspired by Multiple Arousal Theory I hypothesized that: central hemispheric changes could be captured by measuring electrodermal activity bilaterally. The purpose of this study was to investigate whether hypnosis induction produces different levels of arousal on the two sides of the body compared to a control condition and whether it is different for low and high hypnotizables. In **study 4** (Kasos, Kekecs, Kasos, Szekely, & Varga, 2018) we measured from the shoulders bilaterally during the active-alert hypnosis induction, in a within subject design study With the participation of 28 subjects.

In **study 5** (Kasos, Csirmaz, et al., 2020) I was curious, whether the bilateral differences captured in **study 4** are present during the traditional hypnosis induction and if so, can they be be captured on different dermatomes other than the shoulders? For this purpose, I investigated bilateral EDA measured from the wrists during the Harvard Group Scale of Hypnotic Susceptibility-and contrasted EDA of low medium and high hypnotizables. This study has many novelties: first, bilateral EDA had never been measured from the wrists during hypnosis; second, it was the first hypnosis session for our participants; third, we analysed low, medium and high hypnotizable individuals; fourth, we measured in a group setting; fifth, in a second follow up experiment we replicated one of the most prominent effects which was found in experiment 1 (study 5) during which we measured from the same participants 2 weeks apart in 5 repeated sessions.

To summarize, the purposes of this dissertation were to validate new technology capable of group measurements and find alternate electrodermal measurement locations for research and ambulatory purposes. Furthermore, to contrast the traditional view of EDA with Multiple Arousal Theory by investigating dermatome differences induced by hypnosis and emotional stimuli. Moreover, to test the predictions of MAT regarding phasic electrodermal activity and to extend its predictions to different dermatomes than the palmar surfaces.

Chapter 2: Studies 1-5

Study 1:
Obimon: an open-source device enabling group measurement of electrodermal activity

Abstract

Electrodermal activity (EDA) provides means to gauge the activity of the sympathetic nervous system. Assessment of EDA for research purposes requires measurement systems sensitive to small changes in arousal in the full measurement range, collecting, storing and monitoring data.

The objective behind designing a new open-source device was to be able to measure EDA simultaneously on many subjects, monitoring their activity in real-time remotely, and collecting high precision data suitable for analyses. To assure feasibility of simultaneous measurements on multiple subjects, the devices must be compact and wearable, without compromising data quality.

Experiments were carried out using synchronized devices in group and single subject environments. Validity of EDA measurements of Obimon was demonstrated compared to a reference system (Nexus) during a breathing exercise, a short movie and while exposed to loud computer-generated tones, using Pearson correlation, Passing-Bablok regression and Bland Altman analysis. Seamless management of several Obimons and real-time visualization of EDA via android phone/tablet application from a large number of participants was demonstrated. Based on analyses of the data collected, we conclude that the Obimon device presented here is a valid and feasible tool for collecting EDA in single or multi-subject environments.

Keywords: Arousal, Electrodermal, Group Measurement, Skin Conductance, Wireless

Full text link to open-access article: https://doi.org/10.1111/psyp.13374

Received: 16 June 2018 | Revised: 19 December 2018 | Accepted: 25 January 2019

DOI: 10.1111/psyp.13374

ORIGINAL ARTICLE

WILEY PSYCHOPHYSIOLOGY SPR

Obimon: An open-source device enabling group measurement of electrodermal activity

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Funding information
Hungarian Academy of Sciences project (LP-2018-21/2018), National Research, Development and Innovation Office Hungarian Scientific Research Funds (K100845, K109549, K124132), Hungarian Ministry of Human Capacities ELTE Institutional Excellence Program (783-3/2018/FEKUTSRAT) and New National Excellence Program student scholarships, Faculty of Education and Psychology, ELTE Eötvös Loránd University

Abstract

Electrodermal activity (EDA) provides the means to gauge the activity of the sympathetic nervous system. Assessment of EDA for research purposes requires measurement systems that are sensitive to small changes in arousal in the full measurement range, collecting, storing, and monitoring data. The objective behind designing a new open-source device was to be able to measure EDA simultaneously on many subjects, monitoring their activity in real time remotely and collecting high precision data suitable for analyses. To assure feasibility of simultaneous measurements on multiple subjects, the devices must be compact and wearable, without compromising data quality. Experiments were carried out using synchronized devices in group and single subject environments. Validity of EDA measurements of Obimon was demonstrated compared to a reference system (Nexus) during a breathing exercise, a short movie, and while exposed to loud computer-generated tones, using Pearson correlation, Passing-Bablok regression, and Bland-Altman analysis. Seamless management of several Obimons and real-time visualization of EDA via Android phone/tablet application from a large number of participants was demonstrated. Based on analyses of the data collected, we conclude that the Obimon device presented here is a valid and feasible tool for collecting EDA in single or multisubject environments.

KEYWORDS

arousal, electrodermal, group measurement, skin conductance, wireless

1 | INTRODUCTION

The measurement of electrodermal activity (EDA) has a long tradition starting in the 1800s, and it has been used in a wide variety of studies related to psychology. EDA is an efficient indicator of arousal reflecting the activity of the sympathetic branch of the autonomic nervous system (Boucsein, 2012). Practicality and ease of measurement have been cited as two of the reasons that made EDA a popular tool in research (Dawson, Schell, & Filion, 2007). Lie detection is one of the most prevalent areas where EDA has proved to be useful (Ben-Shakhar & Elaad, 2003), but elevated EDA levels may also reflect cognitive load on the information processing system (Walczyk, Igou, Dixon, & Tcholakian, 2013). EDA

measurements have also been used to differentiate between states of consciousness (Kasos, Kekecs, Kasos, Szekely, & Varga, 2018) and among electrodermal responses to stimuli conveying various emotions (Banks, Bellerose, Douglas, & Jones-Gotman, 2012; Kasos et al., 2018). Different characteristics of electrodermal activity are important indicators of emotional state and have been studied extensively in adults (Papousek & Schulter, 2001) as well as in infants (Ham & Tronick, 2008).

Handbooks of EDA specify tools for measurement and data processing extensively (e.g., Boucsein et al., 2012; Dawson et al., 2007). There are two basic measurement types: one with (exosomatic) and the other without (endosomatic) passing of a current between two points of the skin. Endosomatic recordings utilize the naturally occurring electrical properties of the skin to measure skin conductance. Eccrine sweat glands mostly under sympathetic control congregate in increased numbers at certain parts of the body. Sympathetic arousal and measured EDA have been closely tied to eccrine sweat gland innervation (Morrison, 2001; Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004). Eccrine sweat glands also take part in thermoregulation; however, they respond with more sensitivity to psychologically significant stimuli than to thermal stimuli (Dawson et al., 2007). The palmar surfaces, the wrist area, the forehead, and the feet house eccrine sweat glands in proportionately higher numbers than other types of sweat glands, thus EDA measurements are usually reported from these body parts. Several measures are used as indicators of electrodermal activity: The tonic level of skin conductance (SCL) varies according to activity, ambient temperature, as well as individual characteristics. The phasic skin conductance response (SCR) reflects the response of the sympathetic nervous system to a certain stimulus. SCR attributes, such as amplitude and latency, provide important characteristics of the electrodermal response but also reflect individual differences of arousability traits (e.g., Crider, 2008). Electrodermal changes recorded in the absence of identifiable stimuli are called nonspecific responses; their amplitude, latency, and frequency may also characterize the individual or the situation (Dawson et al., 2007).

1.1 | Devices for measuring electrodermal activity

The spread and prevalence of wireless technology have inspired the field to develop ever smaller and smarter devices capable of operating without an external power supply and to record data for hours (in some instances, days) without interruption. Adams and colleagues (2017) provided an exhaustive review of existing solutions for EDA measurement. Most of the devices providing precision data sufficient for research purposes are high cost, which makes the simultaneous measurement of individuals in larger numbers financially demanding. Time synchronicity of measurement from multiple devices is another challenging problem. Finally, use of some available devices are restricted to certain parts of the body (e.g., Boyer et al., 2012; Carreiro et al., 2015; Garbarino, Lai, Bender, Picard, & Tognetti, 2014; Poh, Swenson, & Picard, 2010; Seoane et al., 2014). Existing tools used for EDA measurement are usually closed source, with a few exceptions. We argue that making the device open source has a significant benefit for at least two reasons. It provides an opportunity for researchers to tailor the software's profile for their specific needs while providing full transparency of the collected data—essential for research purposes.

1.2 | Validation of EDA systems

Validating devices and systems designed for electrodermal measurement is imperative. Savić and Geršak (2015) offer a solution for validating EDA systems from a purely technical specification point of view (e.g., resolution, precision, etc.). Although it is essential to ascertain that a device performs according to technical expectations, it is also important that its sensitivity to changes in arousal is comparable to other devices in the field.

Interestingly, comparisons or validations of different EDA measurement systems using data from human participants, instead of relying on electrical calibration testing, are rare in the literature. Schmidt and colleagues (2016) conducted a comparative study of a low-cost EDA measurement system with a commercial reference system (an MP150 GSR100C module from BIOPAC Systems). In this study, data from three subjects were used to evaluate EDA responses elicited by internal or external stimuli. Subjects were asked to produce a sound (the letter *A*) and to bite their tongue (these were considered as internal stimuli). Hand clapping by the experimenter was used as external stimuli. Measurements have been carried out consecutively, and not synchronously, due to authors' concern about possible sensing errors resulting from voltage interference.

Poh and colleagues (2010) validated a wearable sensor for long-term EDA assessment using synchronous measurements. They asked 26 participants to perform different types of tasks: physical ($N = 16$), cognitive ($N = 15$), and emotional ($N = 13$) while their EDA was measured from the index and middle finger on the right (reference system: Flexcomp Infinity) and the left (tested device) hands. Measurements from the distal forearm were collected as well. EDA from one participant was also measured continuously during daily activities for a week. Authors reported statistically significant Pearson's correlation coefficients between the filtered recordings from the two systems. Raw EDA signals were processed using a 1,024-point low-pass filter (Hamming window, cutoff frequency of 3 Hz) in MATLAB.

1.3 | Application for group assessment

Measuring EDA simultaneously in a group setting is sporadic in the literature; however, there are a few examples of group measurements going back almost 70 years (Asheim, 1951; Hagfors, 1970; Kaplan, 1963; Kaplan, Burch, Bloom, & Edelberg, 1963). Some existing EDA devices allow multiple measurements simultaneously; nonetheless, in a typical EDA measurement, a single person is monitored with a single device, even when data are later analyzed in groups (e.g., patients vs. controls). This setup allows a lot of room for externally induced "noise" (e.g., effect of loud noises, such as an ambulance passing by, different temperature and humidity on different days of measurement, etc.). When nonsimultaneously collected data are analyzed in a group design, these external artifacts cause unnecessary variability and may lead to false results. Furthermore, group assessment in real time is fundamental in some areas of research (e.g., developmental or social psychology).

Aggregating measurements from multiple subjects also requires accounting for unwanted effects of individual variability of both SCL and SCR. It is of vital importance for the device to measure with uniform sensitivity and noise across the full range of 1–100 μS. A low-level auditory stimulus, for example, may elicit skin conductance changes ranging from 0.1 to 10 μS (again, depending highly on individual arousability).

In this article, we introduce Obimon, a new, low-cost, small and open-source EDA device capable of synchronized measurements and monitoring of precision data from multiple devices. The applied system design assures uniform resolution and precision across the entire measurement range. We present data from three experiments to underlie reliability and feasibility of this EDA measurement system using individual or group settings in psychological research. In Experiments 1 and 2, we compared the Obimon to a reference system (Nexus) during synchronous measurements from individuals. Experiment 3 presents use of the Obimon system optimized for group setting.

2 | METHOD

2.1 | Participants

Participants were university students from several Hungarian universities, and their efforts were compensated via course credits. Participants were right-handed (based on self-report) in the first and second experiments. Exclusion criteria for the study included the use of psychiatric drugs, sedatives, and any psychiatric illness based on self-report. The study protocols were designed in accordance with guidelines of the Declaration of Helsinki and were approved by the Research Ethics Committee of the Faculty of Education and Psychology, Eötvös Loránd University. Three experiments were conducted independently, with different participants. Twenty subjects took part in the first experiment (N male = 4, N female = 16, mean age = 23.31, SD = 5.59), 14 were involved in the second experiment (N male = 3, N female = 11, mean age = 19.92, SD = 1.33), and 76 (N male = 14, N female = 62, mean age = 22.3, SD = 1.2) took part in the third experiment. One participant was excluded for malfunction of equipment from the first experiment.

2.2 | Design and procedure

The study consisted of three parts: first, we validated electrodermal measurements with the newly developed Obimon device, using Nexus as the reference system during a breathing exercise and a short movie in Experiment 1. Next, we compared measured response magnitudes by the tested device (Obimon) and the reference system (Nexus) to loud computer-generated tones (Experiment 2). Last, we applied the Obimon device for group measurement of a breathing exercise (Experiment 3).

All participants filled out an informed consent form, then electrodes were placed on their hands and devices were connected. They were asked to sit as still as possible during the experiments to avoid movement artifacts. Both Nexus and Obimon were synchronized to Internet time as was the computer that presented the stimuli for the participants. Time synchronization allowed us to locate specific events in the data.

In the first experiment, after time was synchronized, the experimenter started the 4-min breathing exercise audio recording and stayed in the room throughout the process, which was immediately followed by a short (approximately 5 min) movie. The reference device (Nexus) was connected to the electrodes on the left hand, and the tested device (Obimon) was connected to the electrodes on the right hand. Electrodes were placed on the medial phalanges of the left and right index and middle fingers.

In the second experiment, participants listened to 26 computer-generated sounds after the two exercises described in the first experiment. Placement of the reference system (Nexus) and Obimon was counterbalanced to rule out systematic differences in measurement that lateral differences may cause.

In the third experiment, we applied the Obimons for group measurement of a simple breathing exercise. Electrodes were attached to the medial phalanges of the middle and index fingers of the nondominant hand.

2.3 | Materials

A 4-min breathing exercise in Hungarian was used in all three experiments. Breathing instructions have been used

in electrodermal research to elicit responses since at least the 1960s (Blain, Mihailidis, & Chau, 2008; Edelberg & Burch, 1962; Hygge & Hugdahl, 1985; Rickles & Day, 1968; Rittweger, Lambertz, & Langhorst, 1997). The audio recording is available (Appendix S4 of the online supporting information). At the beginning of the recording (the first 35 s), participants were instructed to sit as still as possible, and an explanation was given of what was going to happen during the exercise. Starting from the 38th second, participants were asked to take a deep breath and hold their breath for five counts, which was said out loud on the recording. Next, they were instructed to slowly exhale. Starting from the 54th second, they were prompted again to take a deep breath, hold their breath, and slowly exhale. Afterward, participants were instructed to breathe normally, and further explanation was given of what would happen next: repeating the previous breathing exercise with eyes closed. At 1 min 40 s, participants were asked to close their eyes and keep them closed for the rest of the exercise, followed by a silent (30-s) block. At 2 min 20 s, instructions for the breathing section with eyes closed started, and the breathing exercise was repeated. Lastly, at 3 min 22 s, participants were instructed to sit still with eyes closed for another 30 s. In the first and second experiment, besides the breathing exercise participants watched an approximate 5-min movie (Appendix S5 of supporting information). The movie describes a cartoon character playing chess with his imaginary alter ego. Watching the movie may evoke emotions of happiness, at times compassion, and possibly sadness. At the 27th second of the movie, human hands slap down a chessboard on a wooden table. We chose to analyze responses to this event, considered as a psychologically significant stimulus.

In the second experiment, we employed a common psychological paradigm to examine autonomic reactivity to loud tones, eliciting subjects to orientate to changes in the environment (see, e.g., Mueller-Pfeiffer et al., 2014). Twenty-six 1000 Hertz computer-generated loud beeping sounds were played. Interstimulus intervals were randomized between 27 and 52 s. The sounds were played at 90 dB from JVC HA-RX900 headphones. Participants' responses were measured in a single subject environment with an experimenter always present.

Skintact FS-RG1 disposable (32×41 mm) Ag/AgCl electrodes (Leonhard Lang GmbH, Innsbruck, Austria) were used for the measurement of electrodermal activity with an electroconductive gel that was used to establish contact between the electrode and the skin (Posada-Quintero et al., 2017).

2.4 | System design of the tested device and measurement details

Figure 1 represents the overall system architecture of the new EDA device (see obimon.com). Recent advancements in high precision analog front-end design allow compact yet more precise measurements of small signals such as skin conductance.

Many commercial EDA devices perform complex analog signal preconditioning in order to amplify and convert the signal suitable for input to an analog-to-digital converter. In contrast, the Obimon utilizes a 22-bit resolution A/D converter with very low noise specification (MCP3551/3) eliminating the need for complex preamplification or filtering, nor is it needed to subtract an estimated SCL value before analog-to-digital conversion, further improving the precision of measurements. For comparison, several small footprint EDA devices use 10- or 12-bit resolution (e.g., Affanni & Chiorboli, 2015; Boquete et al., 2012; Kappeler-Setz, Gravenhorst, Schumm, Arnrich, & Tröster, 2013; Poh et al., 2010; Savić & Geršak, 2015; Schmidt et al., 2016). The difference in resolution is from 100 to 1,000 times.

Another important design choice made was the use of a so-called zero-drift operational amplifier (MCP6V31) on the

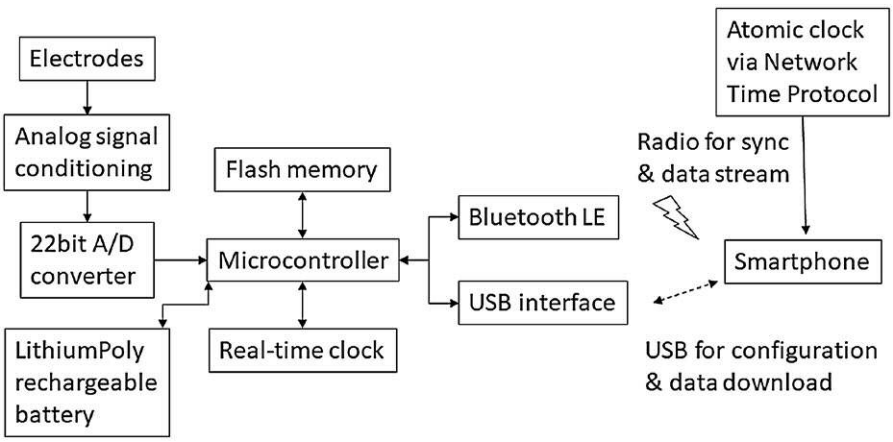

FIGURE 1 Functional system block diagram

input signal, which has significantly lower offset errors and noise at low frequencies than traditional instrumentation amplifier-based EDA designs.

The third significant design choice was due to the requirement of having uniform precision across the entire measurement range. Some existing EDA devices measure the resistance (MOhm) actually and then calculate the inverse in software to get the desired conductance value in units of μS. As a result, these devices tend to have much lower resolution at high EDA ranges. This means that subjects having high SCL value (e.g., > 10 μS) will have significantly lower measurement quality than subjects having low SCL (e.g., < 3 μS). Additionally, small EDA signals may completely disappear or may be masked by noise. To eliminate this problem, in the case of the Obimon, we applied a constant voltage (0.4 volts) EDA method where the sensed current across the body is passed into the aforementioned zero-drift amplifier in a transimpedance configuration. In other words, the sensed current is directly converted into voltage and then to digital value through the AD converter. A significant benefit of this design is that, since the sensed current is proportional to conductance, the device has constant resolution and precision across the entire measurement range regardless of the subject's base SCL value.

The contacts of the electrodes are placed directly on the enclosure of the device itself, so that the leads can be of minimal length, reducing the noise on the very low-level electrical signals. Placement of the Obimon device is possible on most body parts; however, fingers or palms of children and adults and the feet of babies are the most comfortable places for measurements (see Figure 2).

Numerous sources (e.g., Braithwaite, Watson, Jones, & Rowe, 2013) suggest a high oversampling rate of 100 or even 1,000 samples per second and postfiltering in software. In Obimon, this step is delegated to the device itself, as the necessary oversampling and filtering is done before the converted digital data are stored (approximately 30,000 samples per second oversampling). The resulting sample rate has been chosen to be eight low-noise, high precision measurement samples per second and is directly applicable to EDA measurements without further smoothing and/or filtering. The sampling rate could be changed up to 60 samples per second if needed.

Time synchronization is an important requirement when performing measurements on multiple devices. Obimon supports two ways of time synchronization. In both cases, the time synchronization is obtained with the help of the publicly available Obimon app run on a smartphone or tablet. The smartphone application, when running as a service, synchronizes itself to a precision global clock using Internet Network Time Protocol (NTP). It is possible to synchronize each Obimon manually by connecting it to a smartphone by a USB cable. When connected, Obimon automatically synchronizes to the NTP time within less than a second (used in Experiment 1 and 2 in the present study). Alternatively, synchronization can be broadcast wirelessly every second to all Obimon devices nearby from a designated Obimon device set to "transmit mode." Obimon devices set to "listen to transmission of time synchrony" receive such broadcast signals prior to measurements and adjust their clocks (used in Experiment 3 in the present study). The first manual method is applicable for small-scale experiments of one or only a few devices, whereas the second method is more appropriate when there are many devices in an experiment, and one can be designated to broadcast only "perfect" time synchrony. Once synchronized, Obimons use their own crystal-driven clocks to time stamp every sample.

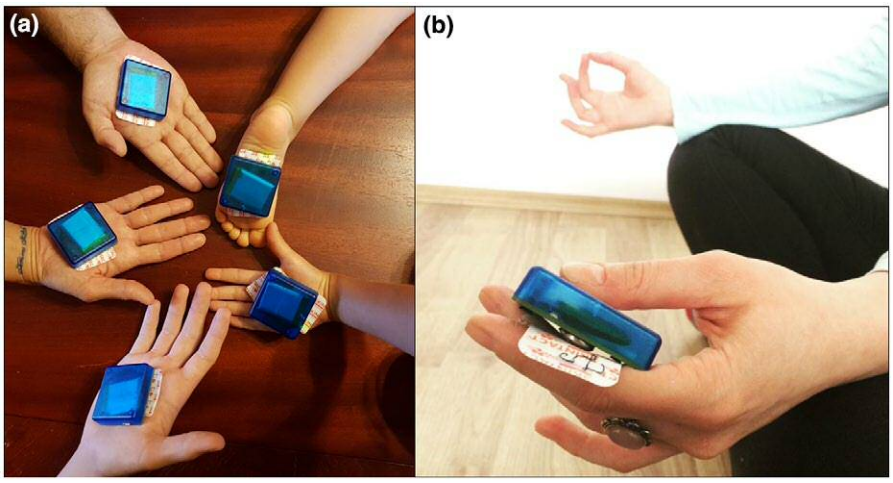

FIGURE 2 Most comfortable placement of the Obimon is on the palm or on the foot, but measurement on the finger is also convenient. (a) Upper left, clockwise: Device is placed on the palmar surface of the right hand of a 45-year-old male, left foot of a 4-year-old girl, and right hand of a 6-year-old girl, a 16-year-old male, and a 47-year-old female. (b) Direct contact of the electrodes with the device placed on the medial phalanges of the left index and middle fingers of a young female, while meditating

The EDA samples with their time stamp are stored on a nonvolatile FLASH memory chip inside the Obimon device. This on-board memory is capable of storing up to 2 million samples or approximately 72 hr of data. Since every sample has a coordinated universal time attached, it is very easy to identify exact measurement sessions and synchronize data from numerous devices later. Samples are also transmitted wirelessly using Bluetooth Low Energy (BLE) technology. BLE has the advantage that all recent smartphones support this technology, so there is no need for an extra receiver device. Also, BLE supports very low power operation, so the integrated battery can supply the device for 24–36 hr while measuring and more than 30 days while idle.

Since the recorded data can grow very large, we chose to use USB as the means to download the contents of the memory to an Android phone. The format of data is TSV (tab separated value) and can be stored or emailed from the Android application.

It is often necessary to monitor the measurements in real time. An important feature of the Obimon Android application is that it can listen to all Obimon devices broadcasting measurements in the vicinity of the smartphone or tablet. In practice, the receiving range is around 100 m. There is a limitation of the total channel capacity of BLE, however, so the transmit frequency needs to be adjusted if the number of active devices is very high in close proximity. The application allows adjustment of the transmit rate, so that the radio channel is kept under saturation. Screen size may also limit the number of devices that can be meaningfully tracked at the same time. It is important to note that the storage on the device stores all data, regardless of the transmit frequency setting.

2.5 | The reference system

The NeXus-10 MKII device and the BioTrace+ (v 2015) software (Mind Media BV, Herten, the Netherlands) were used as the reference system. It is a reliable and extensively utilized system in psychophysiological research (Bogdány, Boros, Szemerszky, & Köteles, 2016; Dömötör, Doering, & Köteles, 2016; Köteles, Dömötör, Berkes, & Szemerszky, 2015; Szemerszky, Dömötör, Berkes, & Köteles, 2016). Skin conductance data were recorded with a sample rate of 32/s and down-sampled to the recording rate of the Obimon system in the first experiment, while left at 32/s rate in the second experiment.

2.6 | Data analyses

Raw data were inspected for artifacts and to determine that the exclusion criteria fulfilled the guidelines provided by Kocielnik and colleagues (Kocielnik, Sidorova, Maggi, Ouwerkerk, & Westerink, 2013). More than a 20% second-to-second rise and more than a 10% second-to-second drop in baseline SCL was deemed as an artifact. Typical skin conductance values measured from the palmar surfaces range between 2 and 20 μS (Dawson et al., 2007); however, there is great individual variability. Therefore, a minimum of 0.05 μS and a maximum of 60 μS for SCL filter were also applied, as recommended by Kleckner and colleagues (2017). Raw data were used to compare Obimon to Nexus (Experiment 1, breathing instructions) and to present group measurement (Experiment 3). To demonstrate the capacity of Obimon to detect responses to psychologically significant stimuli, we chose a scene from the beginning of the short film in the 27th second when human hands suddenly banged down a chessboard on a wooden table (Experiment 1). Moreover, we exposed participants to 26 loud computer-generated short tones (Experiment 2). For analyzing SC responses, we used Ledalab 3.4.9 (Benedek & Kaernbach, 2010). Gaussian smoothing was applied to raw data to decrease error noise. SCR and SCL were separated by optimized continuous decomposition analysis (Benedek & Kaernbach, 2010). We set a 4-s window 1 s after stimulus onset for analyzing SCRs. The minimum threshold for SCR responses was set to 0.01 μS.

2.7 | Statistical analyses

We employed three methods to test the validity of the measurements taken by Obimon. Based on the practice of other studies to validate EDA devices (e.g., Poh et al., 2010), Pearson correlation was used to test the degree of association between the tested and the reference device. We used Passing-Bablok regression as one of the recommended analyses for method comparisons (Passing & Bablok, 1983). The Passing-Bablok regression is based on the following premise: if two measurement methods are equal, then we can express this with the following formula $Y = X$. This formula can also be expressed in terms of a regression equation $Y = 1X + 0$, where 1 is the slope and 0 is the intercept. However, we accept some measurement error so we calculate the 95% confidence interval for the slope and also for the intercept. After regressing Y on X, the Passing-Bablok regression yields a regression equation and also calculates the 95% confidence interval for the slope and for the intercept. If the calculated confidence interval for the constant (intercept) includes 0 and the calculated confidence interval for the slope includes 1, we may conclude that the two methods are equivalent.

To complement the correlation and regression analysis, Bland-Altman (Bland & Altman, 1986,1999) analysis was conducted to examine whether there is a trend in measurement differences between Obimon and Nexus. Bland-Altman analyses have been used extensively in the medical field to validate devices designed to measure various physiological phenomena, cited in over 11,500 publications (Myles & Cui, 2007). It has been used to validate devices measuring cardiac output and EEG devices (e.g., Bogdány et al., 2016; Niedhart et al., 2006; Opdam, Wan, & Bellomo, 2007). The method

proposed by Bland and Altman is a graphic method to assess the agreement between values measured by a reference and tested device, and it is based on the premise that we do not know which device measures the true value of a property. As a compromise, Bland and Altman suggest using the average of the reference and tested values (x axis) plotted against the difference (reference value-tested value) between measurements taken by the reference and tested devices. The Bland-Altman plot allows for easy visualization of the agreement of our data by constructing the average difference and the upper and lower limit of agreement, which is 1.96 *SD* away from the solid line. If there was a perfect agreement between devices, all observations would fall on the solid line and the average difference between devices would be 0—in this case, the devices would measure exactly the same value. However, we expect some deviation from the solid line, but as long as observed values remain 95% of the time in between the dashed lines, we may conclude that the tested device measures in agreement with the reference device. Bland-Altman analysis assumes a normal distribution of the differences, thus a test of normality is suggested. In case the differences are not normally distributed, a logarithmic transformation of the data is recommended. To test any systematic differences between the values measured by the reference and tested device, a one sample t test is performed to see if the average difference is significantly different from 0. If the t test is significant, we can conclude that the tested device consistently measures either a lower or a higher value than the reference device. The third step is to test whether there is a significant relationship between the average values of the two devices and the differences. If there is a significant correlation, then there is a systematic trend in differences. If there was a significant correlation, then, for example, those who have low skin conductance would measure close to the average (solid line); however, those who have higher skin conductance would measure further from the average (solid line). Since we do not measure from the same body part, differences in skin conductance values are expected. With the use of Bland-Altman analysis, we are more interested in whether there is a visible trend in the distribution of differences. In a Bland-Altman plot, differences should be randomly distributed with no significant correlation between measurement differences and average measurement.

3 | RESULTS

3.1 | Results of Experiment 1: Breathing exercise

3.1.1 | Validating Obimon during a breathing exercise and a short movie

Average within-subject correlation of EDA measurement by Obimon on subjects' right hand and EDA measurement by the reference (Nexus) on their left hand was used to assess validity of the tested device. First, we calculated a correlation value for each subject using SCL values measured at the left and the right fingers at 1,921 time points (8/s) during the breathing exercise. Then, we averaged these 19 within-subject correlation values.

The average within-subject correlation between the reference (Nexus) and tested (Obimon) measurements during the breathing exercise of all 19 participants of Experiment 1 resulted in an average within-subject Pearson $r = 0.92$. Correlation values of the participants ranged between 0.43 and 0.99. Correlation for a randomly chosen participant (Number 13) was $r(1919) = 0.99$, $p < 0.001$ (Figure 3a). Distribution of within-subject correlations is depicted in Figure 3b. Raw data, correlations, and figures for all participants are provided in Appendix S1 of the supporting information.

Passing-Bablok regression was conducted using a single pair of data points for every participant (the average skin conductance for the 4 min of the breathing exercise) to assess whether the measurements taken by Obimon and Nexus differ significantly (Figure 4a). The assumption of linearity was not violated according to the CUSUM test of linearity with a p value of 0.336. According to the Passing-Bablok regression, the slope's confidence intervals include 1, slope = 1.101 (95% CI 0.898–1.295). The intercept's confidence intervals include 0, intercept = −0.359 (95% CI −1.252–0.793). According to our results, the values measured by the two devises are not significantly different.

To assess if there is a systematic trend in differences, we conducted Bland-Altman analysis using the average skin conductance for the 4-min interval of the experiment (Figure 4b). The Bland-Altman plot shows that only one participant's test device (Obimon) score deviated more than 1.96 standard deviations from the average difference. The one sample t test testing the hypothesis that the average difference (mean = −0.22, $SD = 0.88$) is significantly different from 0 produced a nonsignificant result $t = -1.12$, $p = 0.278$. The Pearson correlation between the average of Nexus and Obimon and the differences between Nexus and Obimon resulted in $r(17) = -0.30$, $p = 0.173$. These results show that the Obimon measures are in agreement with the reference system Nexus. The average difference between the two devices is not significantly different from zero, and importantly there is no systematic trend in measurement differences (differences are randomly distributed in the plot).

3.1.2 | Results of the SCR analysis of psychologically significant stimuli from a short movie

To test sensitivity of the devices to electrodermal responses to psychologically significant stimuli in a real-life situation (e.g.,

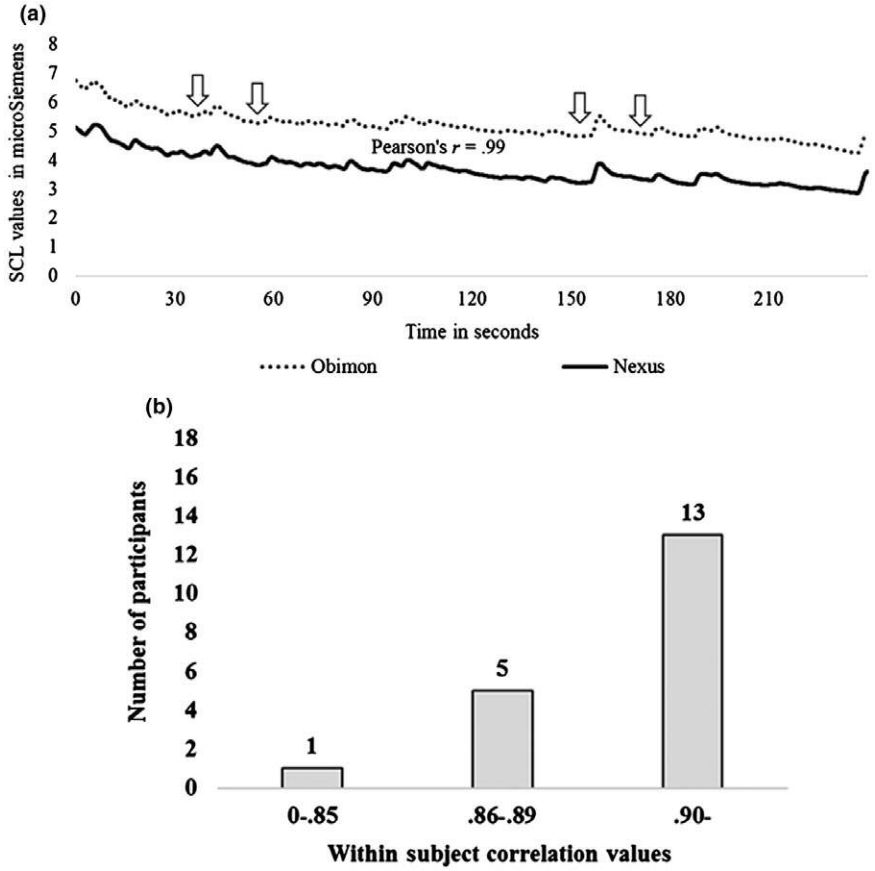

FIGURE 3 (a) Breathing exercise measured by the reference (Nexus) device on the nondominant hand and the tested (Obimon) system on the dominant hand for Participant 13. Arrows represent the "breathe in" instruction of the breathing exercise at 38, 54, 151, 172 s. (b) Distribution of within-subject correlations

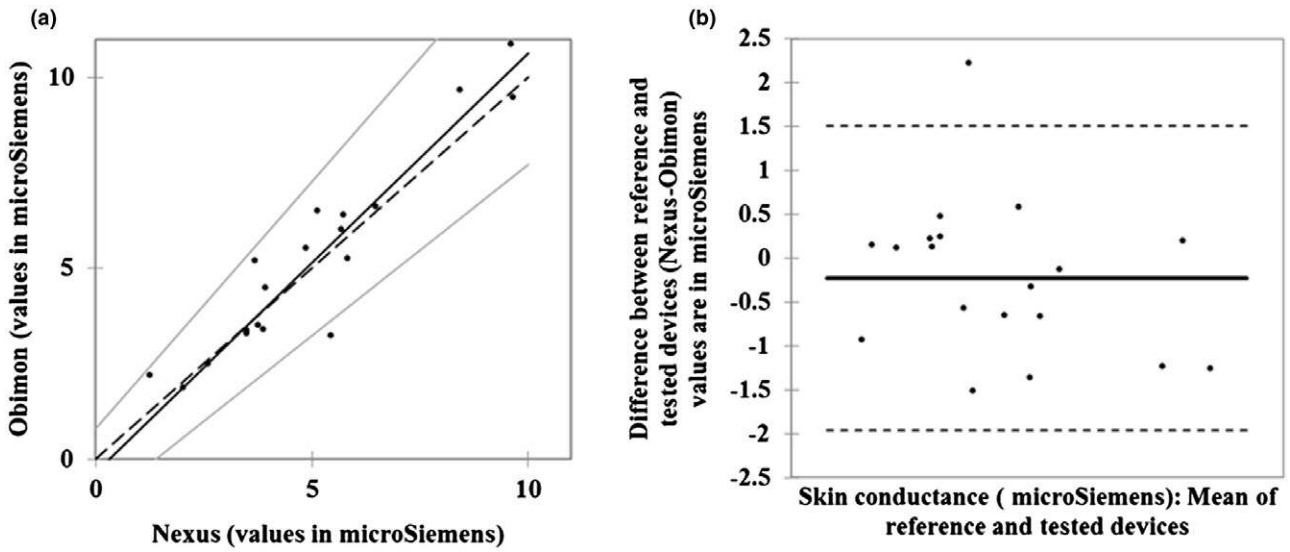

FIGURE 4 (a) The 4 min of the breathing exercise for all participants. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Bland-Altman plot of skin conductance level measured by the reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested device, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

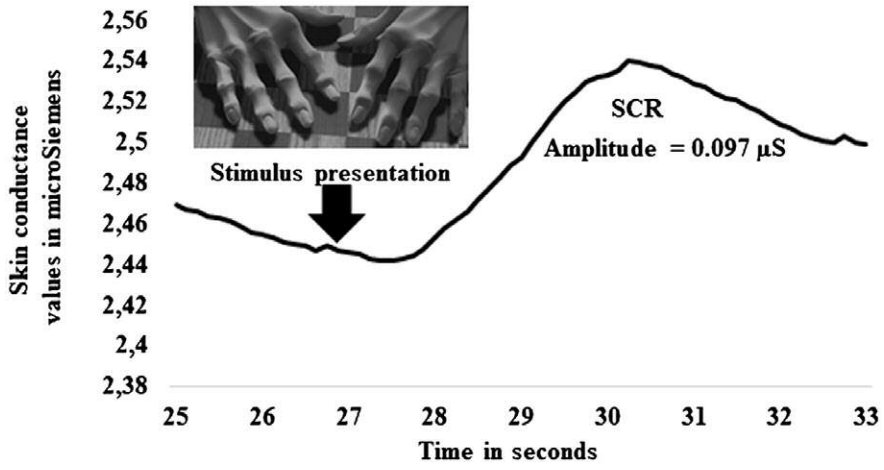

FIGURE 5 Participant 8 was selected randomly to demonstrate a typical SCR detected by Obimon at the 27th second of the movie, when human hands slap down a chessboard on a wooden table

while watching a movie), we selected a scene from the movie that participants watched in Experiment 1 (Figure 5). We analyzed data only when responses were detected on both hands (from the reference device: Nexus connected to the left hand, from the tested device: Obimon connected to the right hand). Of the 19 participants, six showed no electrodermal responses to this stimulus, and in two cases responses were detected only by Obimon. This left 11 participants with valid bilateral responses.

Pearson correlation of the SCR amplitudes was conducted to assess the relationship between the measurements of Obimon and Nexus. The analysis yielded a significant between-subjects correlation, $r(9) = 0.93$, $p < 0.001$. According to the Passing-Bablok regression (Figure 6a), the slope's confidence intervals include 1, slope = 1.334 (95% CI 0.941–2.147). The intercept's confidence intervals include 0, intercept = −0.014 (95% CI −0.529–0.090). The assumption of linearity was not violated according to the CUSUM test with a $p = 1.00$. This analysis shows that the SCR values measured by the two devices do not differ significantly. The Bland-Altman analysis (Figure 6b) shows that the measurement differences between the two devices are close to 0 and the Pearson correlation between average SCR detected (x axis) and bias (y axis) did not reach significance, thus differences are randomly distributed without displaying a systematic trend.

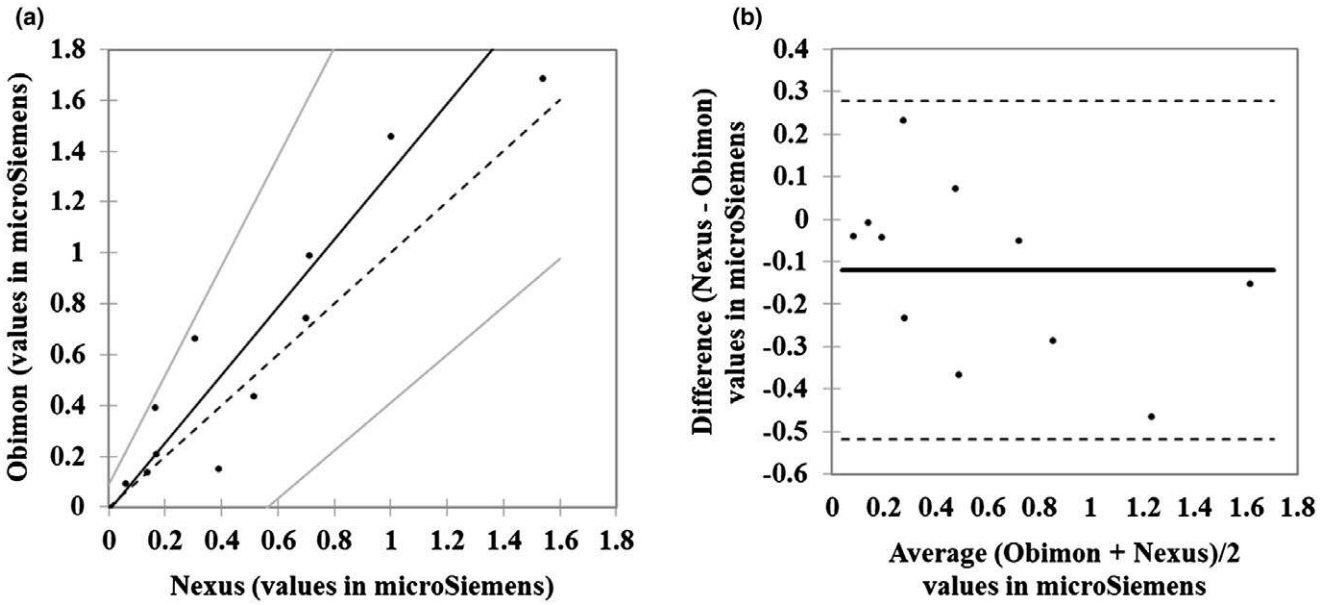

FIGURE 6 (a) Skin conductance responses to psychologically significant stimulus. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Skin conductance responses to psychologically significant stimulus. Bland-Altman plot of SCR to psychologically significant stimulus measured by the reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested device, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

3.2 | Results of Experiment 2: SCRs to loud tones

We obtained SCR data from the two devices after presenting subjects with 26 loud tones (intended to elicit orientation to environmental changes) to validate measures of peripheral reactivity. Out of the possible 364 responses (14 participants × 26 tones), Obimon detected 357 responses (98.0%) and Nexus detected 358 responses (98.3%). For the analysis of SCRs, we used Ledalab 3.4.9 (Benedek & Kaernbach, 2010). SCR amplitudes were extracted by optimized continuous decomposition analysis, where response amplitude corresponds to the sum of SCR amplitudes (which are reconvolved from phasic driver peaks) in the determined response window (Benedek & Kaernbach, 2010). Average response magnitude was calculated for all 14 participants by using all 26 response amplitudes (including 0 responses) and averaging them (Dawson et al., 2007; Payne, Schell, & Dawson, 2016). Between-subjects Pearson correlation between average response magnitudes detected by Obimon and Nexus devices resulted in $r(12) = 0.862$, $p < 0.001$. Within-subject correlations were calculated for all participants based on the 26 SCR amplitudes obtained from the two devices (Table 1). Within-subject correlation between Obimon and Nexus was $r = 0.75$ on average, indicating that responses measured by the two devices are alike.

Passing-Bablok regression was conducted (Figure 7a) to evaluate the agreement between the devices. The slope's confidence intervals include 1, slope = 1.160 (95% CI 0.724–1.837). The intercept's confidence intervals include 0, intercept = −0.012 (95% CI −1.104–0.457). According to the CUSUM test, the assumption of linearity was not violated, $p = 0.938$. The SCR values measured by the two devices do not differ significantly. Bland-Altman analysis (Figure 7b) shows that the measurement difference between the two devices does not differ significantly from 0, $t(13) = -0.76$, $p = 0.46$. The Pearson correlation between average SCR magnitude detected (x axis) and bias (y axis) did not yield significant results; according to our analysis, there is no systematic trend in the distribution of the differences.

3.2.1 | Differences contributed to age and gender

To rule out systematic bias in connection to age in the first and second experiment, Pearson correlation was conducted between age and measurement differences between devices. The results for the Pearson correlation between SCL differences measured by the two devices and age (Experiment 1) are as follows: $r(17) = 0.10$, $p = 0.676$. The results of the Pearson correlation between differences in SCR magnitude and age (Experiment 2) are as follows: $r(12) = 0.16$, $p = 0.572$.

To rule out systematic bias in connection to gender, independent samples t test was conducted with the dependent variable SCL differences measured by the two devices (first experiment) and the independent variable gender $t(17) = 0.72$, $p = 0.542$. Independent samples t test was conducted with the dependent variable SCR magnitude differences (second experiment) and the independent variable gender $t(12) = -0.39$, $p = 0.701$.

Based on our results, neither gender nor age contributes to differences in measurement.

TABLE 1 Average response magnitudes (in microSiemens) for Obimon and Nexus (after presentation of loud, computer-generated tones) and within-subject Pearson correlations

Participant	Obimon response magnitudes	Nexus response magnitudes	Within-subject correlations (Pearson's *r*)
1	0.71	1.08	0.91
2	0.62	0.55	0.93
3	2.95	2.38	0.94
4	1.87	1.14	0.97
5	1.21	1.04	0.80
6	1.81	2.17	0.80
7	2.78	2.02	0.47
8	2.14	2.32	0.85
9	1.51	2.40	0.56
10	1.30	1.59	−0.40
11	1.28	0.91	0.80
12	0.64	0.55	0.96
13	3.08	2.68	0.92
14	1.23	0.94	0.94

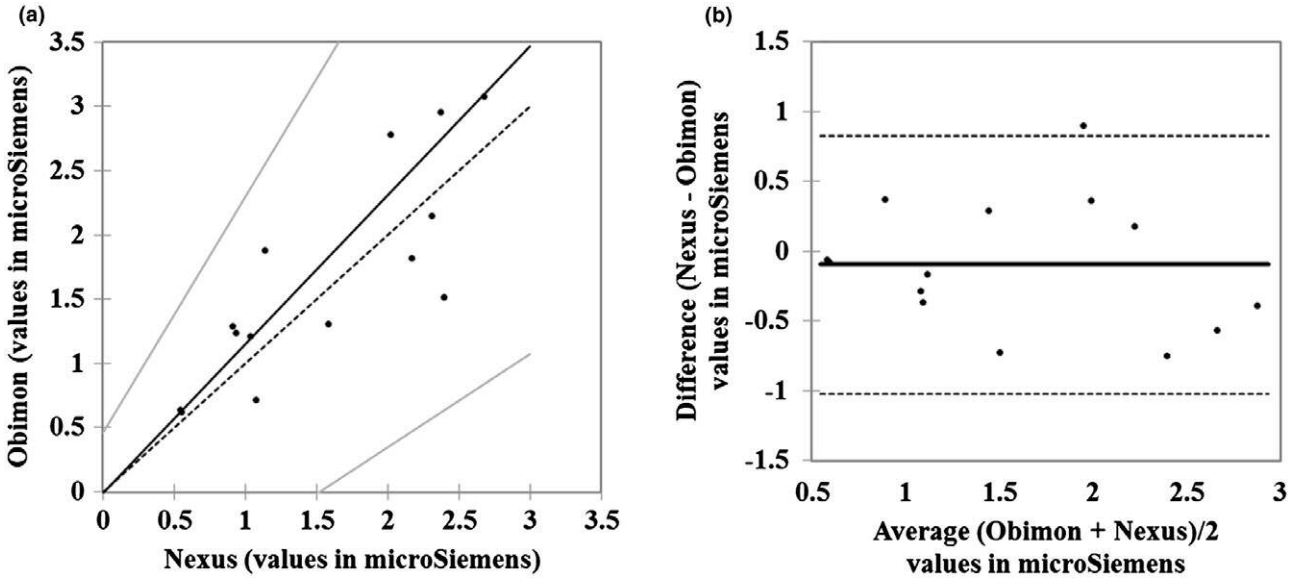

FIGURE 7 (a) SCR magnitudes to computer-generated tones. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Bland-Altman plot of SCR magnitudes measured by reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested devices, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

3.3 | Results of Experiment 3: Group application

With the participation of 76 students, we measured skin conductance during the breathing exercise, as previously described. The electrodes were placed on the nondominant hand, and the participants were instructed to sit as still as possible during the exercise. When averaging all participants' electrodermal activity, responses to the breathing instructions become clearly visible (Figure 8). The SCL of participants (see Appendix S3) show high variability, which is well portrayed by the area between the lower and the upper bound lines representing +1 and −1 standard deviation away from the average. It is noteworthy that the response to the first breathe in instruction at 38 s is the strongest response translating into higher amplitudes. The second response 14 s later is smaller in amplitude. During the third and fourth instructions, participants had their eyes closed, responses are smaller than the first two responses, but they show a similar pattern.

4 | DISCUSSION

In this article, we introduce a new device designed to measure electrodermal activity in psychological experiments. The Obimon opens new avenues in EDA research and therapy since this compact and wearable device not

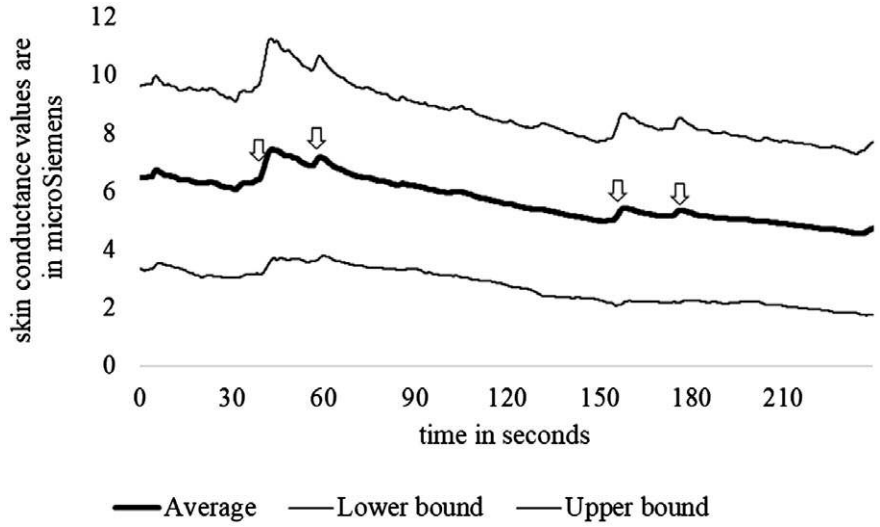

FIGURE 8 Average skin conductance level during the breathing exercise. Average = average skin conductance during the measurement; lower bound = average minus one standard deviation at every time point; upper bound = average plus one standard deviation at every time point. Arrows represent the "breathe in" instruction of the breathing exercise at 38, 54, 151, 172 s

only allows for the collection of high precision data but also enables simultaneous measurement from a large number of subjects. It is possible to use a designated Obimon device for time synchronization of all other devices in a group. This feature is unique in the field. Obimon's wireless technology allows the effective and seamless recording and display of EDA data in a group setting. EDA read from multiple devices can be displayed simultaneously in a real-time line chart. Monitoring measurements remotely in real time could serve as biofeedback for individual use, it could provide important additional information for therapeutic or research purposes, and it could also be utilized in practical fields of EDA, such as lie detection. The absence of cables also reduces the possible number of malfunctions and reduces measurement noise. The Obimon is open source, allowing researchers to tailor the software's profile to their specific needs.

To evaluate this new device, we carried out simultaneous measurements with Obimon and the reference system, which allowed for a direct comparison between the two systems. For stimuli, we used a short breathing exercise, a scene from a short movie, and in a separate experiment 26 computer-generated tones, mimicking the EDA level changes and electrodermal responses typical in psychological experiments.

In Experiment 1, we demonstrated that measurements taken with the Obimon have high correlation (during the breathing exercise and when measuring responses to psychologically significant stimuli) with the reference system (Nexus). Based on the results of the Passing-Bablok regression, the measured SCL and SCR values do not differ significantly. The Bland-Altman analysis revealed that the electrodermal activity measured by Obimon and Nexus is without significant bias. Although our analysis did not reveal significant differences between the two devices, we cannot completely rule out that device differences were masked by differences caused by laterality since we placed Obimon always on the right hand and Nexus on the left hand (lack of counterbalancing in this experiment is an obvious limitation). We also attribute the high but not perfect correlations to the fact that we measured from opposite sides of the body. Differences between the two sides of the body have been reported (Banks et al., 2012; Kasos et al., 2018; Picard, Fedor, & Ayzenberg, 2016). Great individual differences in electrodermal activity of different body parts have also been reported in the literature. For example, Payne and colleagues (2016) reported a strong average within-subject skin conductance correlation between the left finger and left toe ($r = 0.66$). However, the range of correlation for individuals ranged between $r = 0.31$ and $r = 0.99$. This wide range could result from different density of sweat gland distributions or different thickness of the skin. Although simultaneous measurements are desirable when it comes to validation of newly developed devices, the tested and reference devices cannot occupy the same anatomical location. When validating a device, setting acceptable differences prior to the measurement would be advantageous. However, this is practically impossible because of great individual differences in responding at different body parts. Thus, measurement differences cannot be completely separated from those coming from laterality, body parts, or differences in values measured by the two devices. Counterbalancing measurement locations can minimize laterality effects. This is a critical point that we recommend employing when comparing devices in simultaneous measurements. Therefore, in Experiment 2, we counterbalanced measurement locations. Our results showed high between- and within-subject correlation between average response magnitude measured by the two devices. Further, Bland-Altman analysis and Passing-Bablok regression did not reveal significant differences between measured average response magnitude. Counterbalancing minimized the chance that lateral differences masked differences in electrodermal activity measured by the two devices. Thus, we can be more confident that measurements by the two devices did not significantly differ.

Obimon opens new perspectives regarding real-time group measurement of electrodermal activity. Our results from Experiment 3 demonstrate that a large number of participants (limited only by the devices at hand) can be measured simultaneously, with a high degree of temporal precision. Measuring EDA in a group-design could reduce noise created by environmental differences and, thus, enhance precision necessary in this line of research. Our results show great individual variability in electrodermal activity. Most participants displayed EDA levels around 6 μS, but 68% of the participants displayed levels anywhere between 2 and 12 μS. Our results are lower than relevant results, which reported 12.36 μS average skin conductance for their participants (Payne et al., 2016).

According to previous findings, EDA measurements could be sensitive indicators of individual differences (e.g., Naveteur & Freixa i Baque, 1987; Yoshino, Kimura, Yoshida, Takahashi, & Nomura, 2005) and pathological characteristics (e.g., Baker et al., 2017; Kochanska, Brock, Chen, Aksan, & Anderson, 2015; Thorell, 2009). Obimon in a group setting could be appropriate to assess large numbers of individuals simultaneously to identify individual characteristics using the same stimuli in the same environment. Measuring covert responses of large groups could also prove valuable in research concerning group behavior and group dynamics. Moreover, measurements outside of the laboratory call for devices that are easy to use, can be attached to alternate measurement spots, are wireless, and allow online monitoring.

One of the limitations of the present study is the narrow age range of the participants and the unbalanced gender

distribution in our sample. The other limitation is that we did not measure from the palms, a common place from which to measure electrodermal activity.

In summary, in the present article we introduced and successfully validated the Obimon device, which is suitable for measuring electrodermal activity with appropriate precision necessary in research. System characteristics of the Obimon device and its open source software allowing group assessment and real-time display were portrayed. Along with the obvious advantages mentioned above, the ease of use of the device to collect high precision data makes it suitable for individual, clinical, and research purposes.

ACKNOWLEDGEMENTS

This work was accomplished with support of the Hungarian Academy of Sciences (through project: LP-2018-21/2018), the National Research, Development and Innovation Office (through Hungarian Scientific Research Funds: K100845, K109549, K124132), the Hungarian Ministry of Human Capacities (through the ELTE Institutional Excellence Program: 783-3/2018/FEKUTSRAT and student scholarships awarded by the New National Excellence Program). We are grateful for support of the Faculty of Education and Psychology, ELTE Eötvös Loránd University, Budapest, Hungary.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Kasos K, Zimonyi S, Gonye B, et al. Obimon: An open-source device enabling group measurement of electrodermal activity. *Psychophysiology*. 2019;e13374. https://doi.org/10.1111/psyp.13374

Study 2:
Bilateral comparison of traditional and alternate electrodermal measurement sites

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 from 5 measurement sites (fingers, feet, wrists, shoulders and calves). In a counterbalanced, randomized, within-subjects design study, participants (N = 115) were engaged in a 4-minute-long breathing exercise and were exposed to emotionally laden and neutral stimuli.

High within-subject correlations were found between the electrodermal activity (EDA) measured from fingers bilaterally (r = 0.89) and between the left fingers and both feet (r = 0.72). Moderate correlations were found between EDA measured from the left fingers and wrists (r = 0.30 and r = 0.33). Correlations were moderate between the left fingers and the shoulders (r = -.03 and r = -0.6) or calves (r = 0.05 and r = 0.14).

Response latency was the shortest on the fingers while it was longest on the lower body. Short response windows typical in former studies would miss some of the responses from the palmar surfaces and a substantial number from other evaluated locations.

The fingers and the feet were 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, and response amplitudes show a similar pattern from the first measurement time to another one three days later.

Keywords: *anatomical location, electrodermal, latency, skin conductance, SCR*

Manuscript accepted in Psychophysiology: https://onlinelibrary.wiley.com/journal/14698986

Bilateral comparison of traditional and alternate electrodermal measurement sites

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Author Note

This work was accomplished with support of the Loránd Eötvös Research Network (project number: LP-2018-21/2018). We highly appreciate the opportunity to use MONA prototype devices in our study and are most grateful for all technical support of Obimon Systems Ltd. We are grateful for the support of the Faculty of Education and Psychology, ELTE Eötvös Loránd University, Budapest, Hungary and appreciate a student scholarship awarded to Szabolcs Zimonyi by the New National Excellence Program helping to fulfill data collection and analyses related to this project).

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Abstract

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1.Introduction

The ecological validity and generalizability of acute laboratory measures of psychophysiological parameters have been challenged multiple times (Schwarz, 2012). These limitations drive methodological and technical advances toward measurements in real-life settings and ambulatory monitoring. The rising popularity of wearable devices increases the feasibility of non-invasive data collection (Frank H. 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 electrodermal activity (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 when 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 artefacts. Also, electrodes located at the traditional measurement sites (palmar and plantar surfaces) are not comfortable for long-term wear. Thus, recording electrodermal activity 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; R. W. 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 minute before the start of the experiment (Payne et al., 2016). Some, however, suggest that a hydration time of 25 to 120 minutes 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 non-stationary 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 that 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 has 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 second to 4-5 seconds after stimuli onset. This 4-5 second 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 non-dominant foot compared to the non-dominant 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 electrodermal activity measured at alternate and traditional anatomical sites. Further goals included the assessment of measurement sites regarding response latency to psychologically significant stimuli.

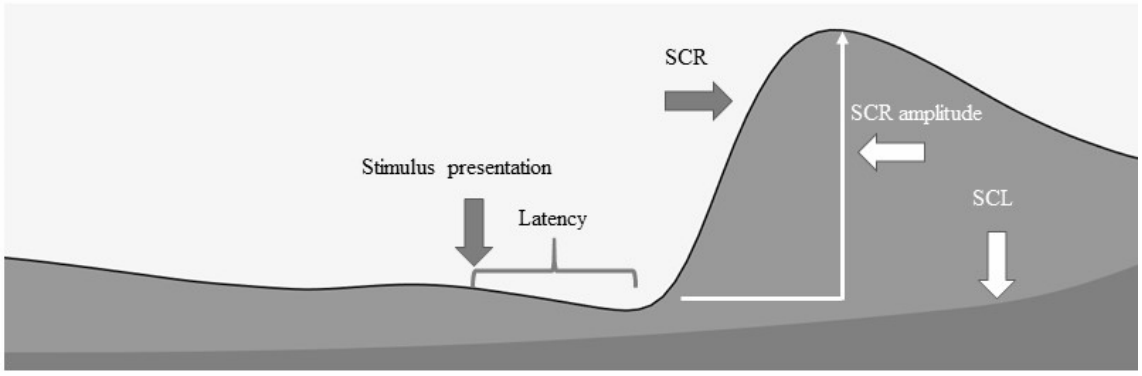

Figure 1. EDA characteristics explored in the present article.

2.Method

2.1 Participants

To counterbalance the 5 types of stimuli used in the experiment in a latin square design 120 Caucasian participants were recruited. Data of 5 subjects were lost due to failed equipment or human error, thus one hundred and fifteen 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 electrodermal activity 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 degrees Celsius.

The outline of the experiment is presented in Figure 3. Rest period measures were taken while the participants were listening to a four-minute-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 musical segments of 7 seconds in length (conveying emotions of fear, sadness, happiness, and peacefulness) and one 7-second-long, emotionally neutral computer-generated tone with a frequency randomized between-subjects (between 650 and 1300 Hertz using 50 Hertz increments). The order of the stimuli was counterbalanced and randomized. After each musical segment, a sixty-second-long inter-stimulus interval was used to let the skin conductance level return to baseline. Participants rated the segments they have just heard during this break: they identified what type of emotion they have 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 minutes. When finished, the devices were removed, and the participants were debriefed.

Electrodermal measurement sites

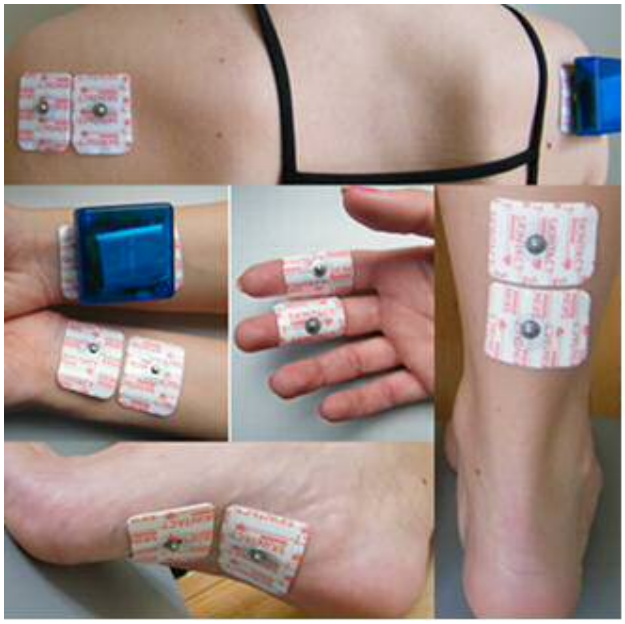

Figure 2. Electrode placement sites for bilateral measurements during the experiment.

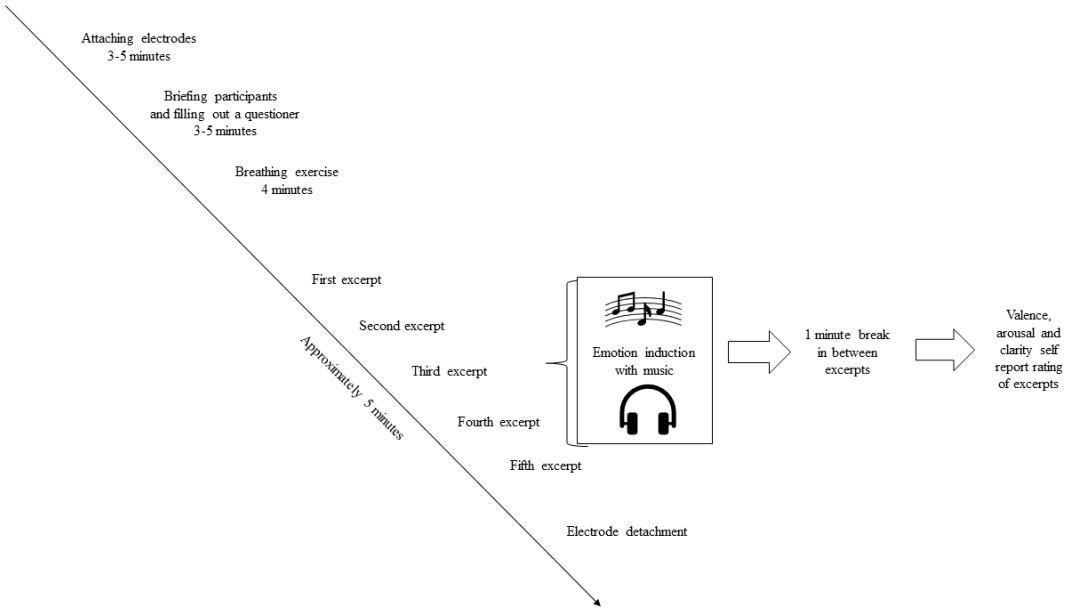

Figure 3. Schematics of the experimental proceedings.

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

(Zuckerman & Neary, 1976; Kasos, Zimonyi, et al., 2018; Kekecs, Szekely, & Varga, 2016; Mueller-pfeiffer et al., 2014; Weger, Meier, Robinson, & Inhoff, 2007). The music used in experiment 2 (Appendix 2) was meticulously validated for the emotions induced and the persistence of the induced emotions (Ribeiro, Santos, Albuquerque, & Oliveira-Silva, 2019).

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 disposableAg/AgC1 electro des (32x41 mm in size, Skintact FS-RG1; Leonhard Lang GmbH. Innsbruck, Austria). Detailed description of the electrode used is available in Appendix 3. Electroconductive gel of the pre-prepared electrodes ensured proper contact between the electrode and surface of the skin. Raw data was inspected for artifacts based on guidelines provided by (Kocielnik, Sidorova, Maggi, Ouwerkerk, & 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 electrodermal activity measured on the raw data was flagged as a potential artefact and was later visually inspected to confirm the presence of artefacts. Segments that contained artefacts were excluded from the analysis. Electrodermal activity was analyzed with Ledalab 3.4.8 (Benedek & Kaernbach, 2010b, 2010a). After Gaussian smoothing to decrease error noise, skin conductance level (SCL) and response (SCR) was obtained by optimized Continuous Decomposition Analyses (Benedek & Kaernbach, 2010b, 2010a) (refer to Figure 1). A four-second window was used for extracting electrodermal responses starting one second after stimulus onset to five seconds after the stimulus onset. A threshold of 0.01 microSiemens was used for SCR extraction.

The 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 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 de-trended EDA data

Pearson correlation is often reported in studies that compare anatomical measurement sites (Payne et al, 2016). However, when the data are non-stationary, 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) = 0.63, which suggests a quite 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 datasets without trend. A method to remove the trend from a set of nonstationary data is to take the difference between two consecutive values (X_{t+1}-$X_{t)}$. The new values will only represent changes that take place from sampling time to sampling time (see the de-trended raw data of the previous example in figure 4B). This method is referred to as the first differences method and it was recommended for non-stationary data (Granger & Newbold, 1974). The Pearson correlation obtained from the de-trended data is *r* (1917) = 0.46 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 2A. 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.

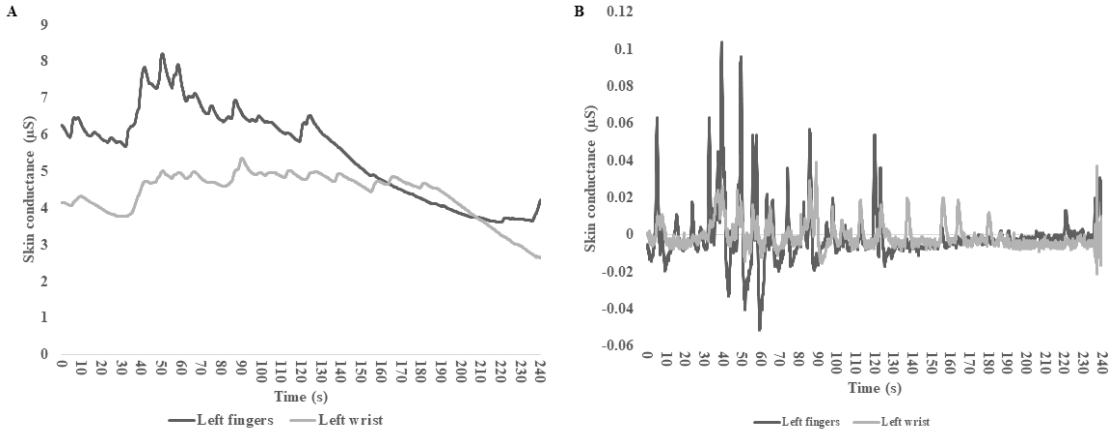

Figure 4A. Raw EDA data for a single subject (1920 data points) measured from the left fingers and the left wrist.

Figure 4B. Detrended EDA data for a single subject (1919 data points): difference between two consecutive values (X_{t+1}-$X_{t)}$ measured from the left fingers or the left wrist.

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-minute rest period (8 measurements per second resulted in a total of 1920 data points).

Within-subject Pearson correlations were also computed for each of the 5 types of stimuli between the left fingers and all other sites (the 7 seconds segments each resulted in 56 raw datapoints). The 5 Pearson correlations obtained for the 5 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 datasets 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 also allows us to study the effect of each level of multi-level categorical predictors individually (such as each measurement site). At the same time, it also helps us to assess the effect of including the multi-level categorical predictor as a whole in the analysis as well (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, 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, 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 (non-dominant 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 from and it is recommended and costumery in the literature 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 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 1.

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 1150 possible measurements (10 measurement sites x 115 participants). 3636 responses to the breathing instructions were analyzed out of the possible 4600 responses (4 breathing instructions x 10 measurement sites x 115 participants). 5257 valid responses were analyzed out of the 5750 possible responses to musical and neutral stimuli (5 responses x 10 measurement sites x 115 participants).

3.2 Rest period results

3.2.1 Rest period SCL

The average SCL for each subject within the 4-minute 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 = 2156.34) had significantly better model fit than the interaction model (cAIC=2164.35) and the side only model (cAIC = 2808.13), indicating that location of the electrodes (on the fingers, the foot, the wrist, the calf, or the shoulder) holds important information about resting SCL. On the contrary, interaction of side (left or right) and location was not prominent. Results of the main effects model (R^2 = 0.427, *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.

	b	*95% CI lower bound*	*95% CI upper bound*	*standard beta*	*p-value*
Intercept	2.72	2.58	2.86	0.00	< 0.001
Side	0.02	-0.06	0.11	0.01	0.620
Foot	0.01	-0.14	0.15	0.00	0.902
Wrist	-1.21	-1.33	-1.08	-.46	< 0.001
Calf	-1.20	-1.33	-1.07	-.45	< 0.001
Shoulder	-1.54	-1.68	-1.41	-.57	< 0.001

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.

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 = 0.53, *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.

	b	*95% CI lower bound*	*95% CI upper bound*	*standard beta*	*p-value*
Intercept	0.88	0.83	0.93	0.00	< .001
Side	0.01	-0.02	0.05	0.01	.529
Foot	0.08	0.03	0.14	0.07	.005
Wrist	-0.55	-0.60	-0.50	-.54	< .001
Calf	-0.59	-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.

3.2.3 Rest period response frequency

During rest period, EDA response indicated whether a "breathing in" instruction elicited a response or not (an SCR amplitude threshold of .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.

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

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.

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 were found between the left finger and right finger and the left finger and both feet. Electrodermal activity 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 dataset the correlation between the left and right fingers remain virtually unchanged. However, association was weak between the left finger and other body parts in this case.

	Raw-data		*De-trended data (method: first differences)*		*De-trended 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

Table 4. Average of within subject correlations with reference to the left finger during the 4 minutes breathing exercise. Significant correlations are bold and marked with asterisk, *p < .05, **p < .01, ***p < .001.

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 5 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 = 0.497, *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, and SCRs at the feet did not differ significantly from those at the fingers. Again, side was not a significant predictor in this model.

	b	95% CI lower bound	95%CI upper bound	standard beta	*p*-value
Intercept	0.90	0.84	0.95	0.00	< .001
Side	0.03	-0.01	0.06	0.04	.420
Foot	0.01	-0.05	0.06	0.01	0.774
Wrist	-0.53	-0.59	-0.48	-0.53	< .001
Calf	-0.62	-0.68	-0.59	-0.54	< .001
Shoulder	-0.60	-0.67	-0.54	-0.51	< .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.

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.

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

Table 6. Absolute and relative respond frequency during stimuli presentation.

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. Electrodermal activity 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.

	Raw data		*De-trended data (method: first differences)*		*De-trended 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 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 $p < 0.001$ level.

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 second 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 5 types of stimuli and then averaged between subject.

Once again, the comparison of the linear mixed effects models with the SCR latency observed as an outcome variable yielded main effects model ($R^2 = 0.084$, $CI = 0.055 – 0.127$, see details in Table 8) as the best model fit (main effects model cAIC = 1538.68; interaction model cAIC = 1544.72; side-only model cAIC = 1623.66). 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 than shoulders or wrists. Side was not a significant predictor in this model either.

	b	*95% CI lower bound*	*95% CI upper bound*	*standard beta*	*p-value*
Intercept	2.36	2.25	2.46	0.00	< .001
Side	0.03	-0.05	0.11	0.02	.428
Foot	0.36	0.24	0.47	0.21	< .001
Wrist	0.26	0.15	0.38	0.16	< .001
Calf	0.54	0.41	0.66	0.30	< .001
Shoulder	0.15	0.02	0.28	0.08	.027

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.

3.3.5 Cumulative frequencies

Cumulative frequencies were calculated for all 10 measurement locations by summing detected response frequencies at 0.5 second intervals starting at 1 second after stimuli onset to 5 second after stimuli onset (Figure 5 shows traditional measurement locations and Figure 6. describes alternate sites). For example, Cumulative response frequency at 3 seconds after stimuli onset for the left finger is close to 80 % (majority of the detected responses at this measurement location was within a 3 seconds interval after stimuli onset). On the contrary, this response frequency ratio characterized the left foot only by 3.5 seconds. Latencies measured at alternate locations show that cumulative frequencies are highest for the left shoulders at 2 seconds and remain highest up to 3.5 seconds after stimuli onset.

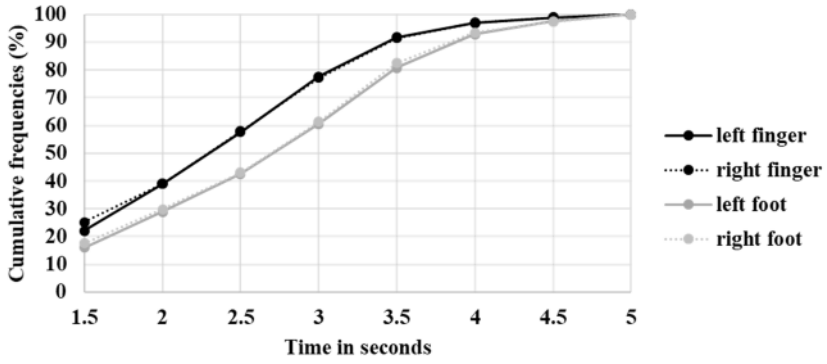

Figure 5. Cumulative percentage of detected responses in a 4 second response window (measured from the traditional measurement locations).

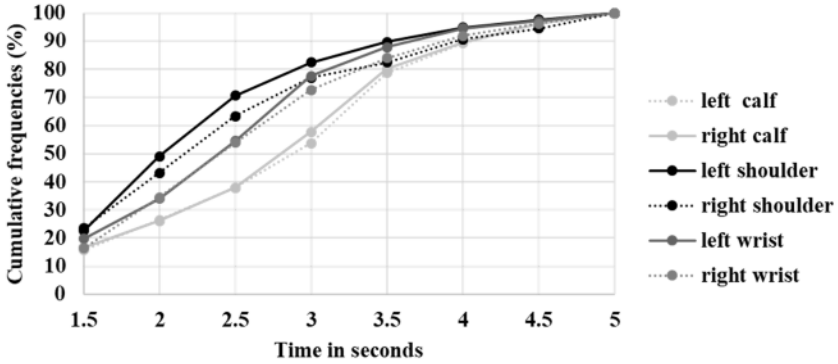

Figure 6. Cumulative percentage of detected responses in a 4 second response window (measured from alternate sites).

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 days later. The detailed description and results of that experiment can be found in 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 non-dominant fingers. We measured EDA from 5 anatomical sites bilaterally, during breathing exercise and psychologically significant stimuli in the first experiment. In the second experiment, we measured from 5 sites bilaterally during a 3 minutes 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 to the upper body. We found that all measured EDA characteristics remain stable within individuals from one 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 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 4 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 electrodermaly 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 minutes passed between the breathing instructions and the stimuli presentation), we performed post hoc comparison of response rates of that 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 minutes using

medium to heavy load, absolute response frequency of the left shoulder was 96%. This suggests that alternate measurement locations do get more electrodermaly 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 (Appendix 2) the hydration time was 20 minutes before taking EDA measurements. We found 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 responding 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 one 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 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 minutes wait period. The lower calves became comparable to the wrists after the 20 minutes wait period (Appendix 2).

We found higher SCL during 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 although lower than the correlation between the left and right fingers. Nevertheless, correlation of the detrended EDA show 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 from sampling time to sampling time 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. On the other hand, 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 body parts (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 regarding how they affect 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 is 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 non-specific responses. It is recommended to shorten the response window from the traditional 1 - 5 seconds after stimuli onset to a 1 - 3 seconds 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 indicate for example that a 1-3 second 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 second 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 non-dominant fingers with comparable response magnitudes. The other evaluated alternate sites in our study yielded low response frequencies and lower correlations with the non-dominant 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 non-dominant 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 (Rosalind W. Picard, Fedor, & Ayzenberg, 2015) explains these differences with the notion that different electrodermal arousal could be present in the same time in different parts of the body. Depending on the underlying neural activation (whether a person 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 the theory. Correlations between the non-dominant 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 definite answers.

4.1 Limitations

Limitations of the present study include loss of data due to movement artefacts, and equipment failure. Also, 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 effect electrodermal measurements, is unknown.

4.2 Conclusion

In the present study we contrasted EDA measured at 5 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 minutes) 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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Study 3:

Does the electrodermal system "take sides" when it comes to emotions?

Abstract

Traditionally, electrodermal research measurements were taken from the non-dominant hand. This was considered a valid measurement of arousal for the whole body. Some, however argue for a complex and asynchronous electrodermal system in terms of lateral and dermatome differences in emotional responding.

The present study measured skin conductance responses to emotionally laden musical stimuli from the left and right index and middle fingers, as well as the left and right plantar surface of right-handed participants (N=39). The seven-second musical segments conveyed four emotional categories: fear, sadness, happiness and peacefulness. Our results suggest, that the electrodermal system responds to emotional musical stimuli in a lateralized manner on the palmar surfaces. Fear, sadness and peacefulness prompted right hand dominance while happiness elicited left hand dominant response. Lateralization of the palmar and plantar surfaces differed significantly. Moreover, an association between lateralization of the electrodermal system in response to fear and state anxiety was found.

Results of the present study suggest that the electrodermal system displays lateral preferences, reacting with varying degree of intensity to different emotions. Apart from lateral differences, music induced emotions show dermatome differences as well. These findings fit well with the Multiple Arousal Theory, and prompt for revaluating the notion of uniform electrodermal arousal.

Keywords: Electrodermal · Emotion · Music · Laterality · Arousal

Full text link to open-access article: https://doi.org/10.1007/s10484-018-9398-0

Applied Psychophysiology and Biofeedback
https://doi.org/10.1007/s10484-018-9398-0

Does the Electrodermal System "Take Sides" When It Comes to Emotions?

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Abstract
Traditionally, electrodermal research measurements were taken from the non-dominant hand. This was considered a valid measurement of arousal for the whole body. Some, however argue for a complex and asynchronous electrodermal system in terms of lateral and dermatome differences in emotional responding. The present study measured skin conductance responses to emotionally laden musical stimuli from the left and right index and middle fingers, as well as the left and right plantar surface of right handed participants (N = 39). The 7-s musical segments conveyed four emotional categories: fear, sadness, happiness and peacefulness. Our results suggest, that the electrodermal system responds to emotional musical stimuli in a lateralized manner on the palmar surfaces. Fear, sadness and peacefulness prompted right hand dominance while happiness elicited left hand dominant response. Lateralization of the palmar and plantar surfaces differed significantly. Moreover, an association between lateralization of the electrodermal system in response to fear and state anxiety was found. Results of the present study suggest that the electrodermal system displays lateral preferences, reacting with varying degree of intensity to different emotions. Apart from lateral differences, music induced emotions show dermatome differences as well. These findings fit well with Multiple Arousal Theory, and prompt for revaluating the notion of uniform electrodermal arousal.

Keywords Electrodermal · Emotion · Music · Laterality · Arousal

Introduction

In electrodermal research it is important to understand whether different emotional stimuli favor either side of the body, if they manifest with the same proportionate intensity in all parts of the body, and how our anxiety effects lateral preferences. There are indications, that the sympathetic nervous system (SNS) has no problem "taking sides" when it comes to emotions, leading to a lateralized electrodermal response to emotion evoking stimuli (Banks et al. 2012).

According to Boucsein et al. (2012) electrodermal activity (EDA) is related to the activity of the sympathetic branch of the autonomic nervous system (ANS). One way to record EDA is to measure skin conductance. Skin conductance can be divided into phasic and tonic components, both being informative measures of the SNS. The phasic component of skin conductance response (SCR) measures quick transient changes and it is mostly used to study cognitive processes along with emotional responses. The other component is skin conductance level (SCL) which describes the background activity of the SNS, mainly used as a measure of general arousal (Dawson et al. 2007).

Studies regarding EDA asymmetry yielded conflicting results to date. Early electrodermal research reported lateral differences between the two hands (Baitsch 1954; Fisher and Abercrombie 1958; Fisher and Cleveland 1959; Obrist 1963). Others on the other hand found no such asymmetry (Hugdahl et al. 1982; Gross and Stern 1980; O'Gorman and Siddle 1981) or found that asymmetry was not influenced by the type of stimuli presented (Erwin et al. 1980; Maltzman and Boyd 1984). For a detailed review of early reports on the subject see Freixa i Baqué et al. (1984). Nonetheless,

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10484-018-9398-0) contains supplementary material, which is available to authorized users.

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Published online: 20 June 2018

in electrodermal research skin conductance responses were typically measured only from the non-dominant hand, and these values were considered as valid measurements of arousal for the whole body (Hempel et al. 2005; Lane et al. 1997; Petrovic et al. 2008; Kekecs et al. 2016). Recent literature (intended as a guide for analyzing EDA) overlooks the issue of laterality, promoting unilateral recordings (Braithwaite et al. 2013).

Recently Banks et al. (2012) pursued the potential for a lateralized response to emotions. Their study employed six types of stimuli. Five basic emotions using emotionally expressive faces (fear, sadness, happiness, anger, disgust), and a neutral stimulus. Their results showed larger electrodermal response amplitude on the right side to anger, disgust and fear. Sadness, happiness and neutral stimuli, on the other hand, showed greater amplitude on the left side. These results are important because they show the lateral nature of the sympathetic nervous system (SNS) regarding five basic emotions in a social context. The study used a wide response window after stimuli onset (9 s), which is unorthodox in electrodermal research, and it makes results difficult to compare to other studies in the field.

Based on recent findings there may be more to differential electrodermal responding than only the lateralization of the autonomic nervous system. The most recent theory explaining the multi-dimensional nature of arousal, its neurological underpinnings and its manifestation in electrodermal activity is the Multiple Arousal Theory of EDA (Picard et al. 2015). According to this theory different levels of arousal could be present at the same time in different parts of the body in response to emotional stimuli. These differences are caused by different neurological generators corresponding to unique pathways responsible for EDA. The ipsilateral or contralateral influences of these pathways have been debated, yielding conflicting results. There is indication for contralateral influence during tasks that the investigators considered left or right hemispheric (Myslobodsky and Rattok 1977). In contrast ipsilateral influences were also assumed by Sourek (1965). Some explain their results in terms of contralateral inhibition (Lacroix and Comper 1979; Boyd and Maltzman 1983). However, the same results could be interpreted in terms of unilateral excitation (Freixa i Baqué 1984; Miossec et al. 1985). There are indications that motor influences are contralateral and excitatory (Gruzelier et al. 1988). Mangina and Beuzeron-Mangina (1996) found that direct stimulation of the four cortical areas examined in their study exert symmetrical bilateral influences on EDA while stimulation of the 8 limbic structures that were studied have an ipsilateral influence. Overall, results show that some of these pathways have contralateral influences on EDA (for example motor influences), some of them, such as the frontal cortical convexities exert bilateral, while others such as limbic structures, exert ipsilateral influences (Picard et al. 2015). The Multiple Arousal Theory also suggests that some dermatomes are more prone to show higher skin conductance than others when exposed to emotions. The most studied manifestation of this feature is laterality differences in EDA. Granted, if EDA is measured from the palmar surfaces, Multiple Arousal Theory predicts that, emotions more likely processed by the right hemisphere (such as fear and sadness) would elicit lateralized responses favoring the right hand. Emotions that are more likely processed by the left amygdala (e.g. anger) would generate greater responses on the left hand. However, the same lateral differences might not hold on the legs, or on other dermatomes of the body.

One way to convey and elicit emotions is by utilizing music (Juslin and Laukka 2004; Wells and Hakanen 1991; Sloboda 1992; Gabrielsson 1993). With its inherent dynamics and temporal characteristics, it is well suited for modelling emotion, eliciting real life responses which develop dynamically in time.

In their initial study Peretz et al. (1998) showed that participants were able to differentiate between two emotions (sad and happy) conveyed by musical stimuli in a time interval, as short as 0.25 s. In their later research using music conveying fear, sadness, peacefulness and happiness, participants were able to confidently differentiate between these emotions under 4 s (Vieillard et al. 2008). In electrodermal research musical segments eliciting emotions have only been used in a single unilateral study (Khalfa et al. 2002). These segments were 7 s long. They used three basic emotions (fear, sadness and happiness), and one complex emotion (peacefulness). Peacefulness was chosen as the opposite of fear. Researchers concluded that electrodermal responses to happiness and fear were significantly larger than responses to sadness and peacefulness. In the present study we investigated the effects of similar 7 s long musical segments measuring responses bilaterally from the palmar and plantar surfaces.

Results from previous electrodermal measurements suggests that anxiety relates to arousal. Based on unilateral EDA research, elevated level and variability of EDA is typical in those, with higher state anxiety: e.g. increased number of nonspecific responses and retardation of habituation were reported (Katkin 1965; Maltzman et al. 1971). Association between trait anxiety and SCL, as well as SCR amplitude and longer latencies was also reported (Naveteur et al. 1987). Bilateral long-term EDA measurements suggest that state anxiety evoking situations, especially those that involve some kind of personal threat, push the electrodermal system towards right side dominance (Picard et al. 2015). Bishop and colleagues (2004, 2007) using FMRI investigated, how anxiety affects response of the amygdala to emotional faces. They found that those who scored higher on state anxiety showed more activation of the amygdala in response to fearful faces as compared to those with low state anxiety.

These results suggest that state anxiety of participants have a moderating effect on the amygdala's activation. In electrodermal research little attention has been payed so far to the moderating effects of state anxiety on bilateral responding to emotional stimuli.

The purpose of this study is to assess how emotions (elicited by music excerpts conveying different emotions) lateralize the electrodermal system. Based on previous results (Banks et al. 2012; Picard et al. 2015) and the predictions of the Multiple Arousal Theory, we hypothesized that emotionally laden stimuli will produce lateralized EDA responses. If measured from the palmar surface, happiness will presumably favor the left side, while fear is expected to favor the right side. This is in line with results of Lanteaume et al. (2007) who found, that positive emotions are more likely processed by the left amygdala and negative emotions are more likely processed by the right amygdala. We also investigated sadness and peacefulness, emotions, which yielded contradicting results regarding laterality, earlier. We also assessed, if electrodermal laterality is different on the palmar and plantar surfaces.

In addition, we investigated the moderating effects of anxiety on the laterality of electrodermal responses to emotion, conveyed by musical segments. We hypothesize that higher anxiety will be associated with a more right-sided response to emotional stimuli.

Methods

Participants

The study protocol was approved by the ethical board of the Eötvös Loránd University. Thirty-nine right-handed participants' (mean age = 20.75, SD = 1.75) electrodermal responses to short 7 s long musical excerpts were analyzed in the study. Participants received course credit for attendance. Exclusion criteria for the study were: self-reported use of psychiatric drugs, use of sedatives, any psychiatric illness, auditory impairments. Out of the 39 valid cases 8 plantar surface measurements could not be used due to excessive sweating, 10 participants were lost due to missing questionnaire data.

Procedure

Informed consent form was filled out and detailed information concerning the procedure was provided. Participants were tested in small groups of 2–5, in a quiet lab at the Psychology Institute at Eötvös Loránd University. The room's temperature was between 21 and 24 °C. Participants were asked to sit facing the walls to make sure the facial expressions of the other participants were not visible. The electrodermal activity sensors were attached by the experimenter to the left and right intermediate phalanges of the index and middle fingers and the left and right plantar surfaces as described in van Dooren et al. (2012). At the start of the experiment, a guided breathing exercise was played in Hungarian which lasted 4 min. The purpose of the exercise was to provide participants with the opportunity to adapt to experimental conditions.

Four 7 s musical excerpts (see Vieillard et al. 2008) were played in a randomized order. The musical fragments used here and their classification to emotional categories was developed by Vieillard et al. in a study which aimed to provide suitable musical material for research on emotions (2008). The musical excerpts were meticulously validated for classification, and discrimination accuracy of arousal and valence.

Each stimulus presentation was followed by a 45 s break allowing the skin conductance level to return back to baseline. During the breaks between segments, participants were asked to rate the musical segments regarding the type of emotion (fear, sadness, happiness, peacefulness). They were also asked to rate the segments, on a Likert scale ranging between 1 and 10, regarding their clarity, whether they were calming or stimulating (self-reported level of arousal), and their valence. Once finished, participants were debriefed, thanked for their participation and the devices were removed.

Equipment and Data Processing

The State Trait Anxiety Inventory (STAI) is a self-report questionnaire consisting of two subscales: one for state and one for trait anxiety (Spielberger et al. 1970). Both subscales consist of 20 questions. We used the state anxiety subscale, measuring how participants felt at the moment. The scores can range between 20 and 80, higher scores representing grater anxiety. It has been suggested that scores over 40 points may signal clinically significant anxiety (Addolorato et al. 1999; Julian 2011).

For the measurement of skin conductance, the Open-Source Bio monitor (Obimon) was used with an 8-Hz sampling rate (Kasos et al. submitted). Skin conductance was recorded with 2 (32 × 41 mm) disposable pairs of Ag/AgC1 electrodes (Skintact FS-RG1; Leonhard Lang GmbH. Innsbruck, Austria). Electrodermal activity was analyzed with Ledalab 3.4.9 (Benedek and Kaernbach 2010). In order to decrease error noise, the data was first smoothed with a Gaussian window. Skin conductance response (SCR) was obtained by optimized continuous decomposition analyses (Benedek and Kaernbach 2010). The 4-s window for analyzing electrodermal response was set 1 s after stimuli onset. Only SCRs larger than 0.05 μS were analyzed.

EDA laterality coefficients were calculated with the formula below (Papousek and Schulter 2006; Schulter and

Papousek 1992, 1998), where negative values represent right side advantage and positive values represent left side advantage expressed in percentage. Thus, a result of 14 for example means that the left side response is 14% higher than the right-side response.

Laterality coefficient

$$= \frac{(left\ hand\ SCR\ amp. - right\ hand\ SCR\ amp.)}{(left\ hand\ SCR\ amp. + right\ hand\ SCR\ amp.)} \times 100$$

Results

Subjective Ratings of the Musical Excerpts

Participants rated how clearly the emotion was conveyed by the musical segments on a scale ranging from 1 to 10. Friedman test was conducted with 36 valid responses to see if any of the emotions conveyed were rated different from the others with the following results $\chi^2(3) = 42.12$, $p < .001$ (Fig. 1). Post hoc analyses of clarity ratings of each emotion were conducted using a Bonferroni corrected p value of .008. Wilcoxon signed rank tests show that fear and happiness were rated clearly higher on clarity than sadness and peacefulness.

Ratings of arousal and valence were also portrayed for the four stimuli types used (see Fig. 2). The Friedman test (conducted with 36 valid responses) for valence ratings yielded significant differences of the four emotions: $\chi^2(3) = 39.81$, $p < .001$. Pair by pair Wilcoxon signed ranks tests showed that the stimulus conveying fear was rated more unpleasant than happiness $Z = -4.45$, $p < .001$; sadness $Z = -4.36$, $p < .001$ and peacefulness $Z = -4.56$, $p < .001$ (p values are significant after the stringent Bonferroni correction for multiple testing: .05/6 = .008).

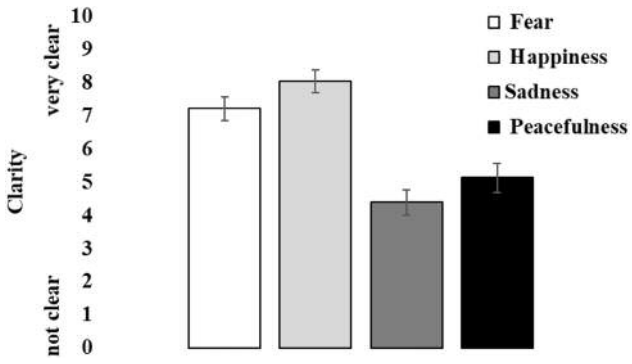

Fig. 1 Clarity ratings for all four types of stimuli. Higher values represent higher clarity. Error bars represent ± 1 standard error of the mean

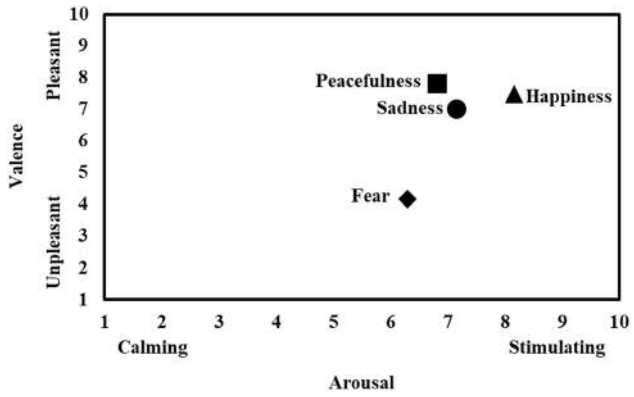

Fig. 2 Subjective ratings of arousal and valence on a 10-point scale, where lower values represent lower arousal and less pleasant stimuli while higher values represent higher arousal and more pleasant stimuli

The Friedman test (N = 36) on the subjective ratings of arousal also showed significant differences: $\chi^2(3) = 14.32$, $p = .002$. The Wilcoxon signed rank tests (using the Bonferroni adjusted p value of .008) showed, that participants rated the musical excerpts expressing happiness significantly more arousing than fear $Z = -2.78$, $p = .005$ and peacefulness $Z = -2.93$, $p = .003$.

Laterality Coefficient Results on the Palmar Surface

The electrodermal response of 36 subjects to different emotional stimuli was compared using a within subject design. Figure 3 represents mean laterality values of fear, sadness, happiness and peacefulness stimuli types.

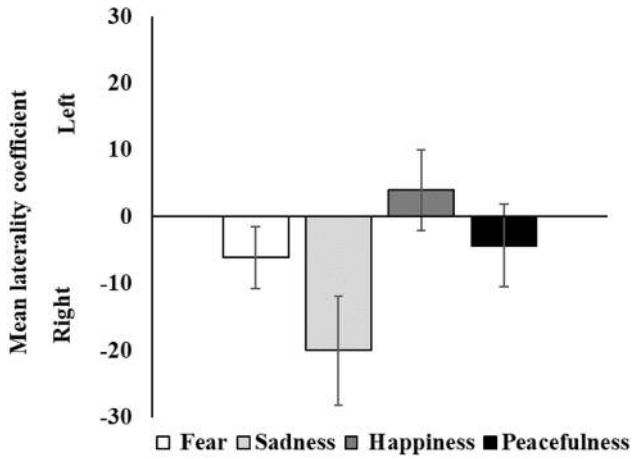

Fig. 3 Mean laterality coefficient of stimuli types representing different emotions (palmar surface). Error bars represent ± 1 standard error of the mean. The Y axis represent the percentage difference between the two sides. Numbers below zero represent right side dominance, while numbers above zero represent left side dominance

Zero laterality coefficient means that the two sides of the body respond in absolute synchrony. To test if any of the emotions lateralized the electrodermal system significantly we ran a one sample t-test with 0 as a test value representing absolute synchrony. According to the results of the one sample t-test only sadness lateralized the body significantly $t(38) = 2.54$, $p = .019$, Cohen's $d = .45$. Thus, participants responded to sad musical excerpts with a clear right dominance.

The laterality coefficient was used as a dependent variable in a one-way ANOVA yielding a significant effect of emotion type of the stimuli used $F(1, 38) = 4.88$, $p = .01$, $\eta^2 = .11$. Responses to stimuli conveying happiness was most lateralized to the left, on the other hand peacefulness, sadness and fear was lateralized to the right, and sadness appeared to be the most "right-sided". To see which emotion was significantly different from one-another, a post hoc analysis was conducted. The paired sample t tests comparing lateralization of all stimuli pairs revealed only one significant difference between sad and happy stimuli $t(38) = -2.83$, $p = .007$ (level of significance was Bonferroni-corrected for the six analyses).

State Anxiety and Laterality

Mean value of state anxiety scores: 37.66 (SD = 7.54) in our sample is in line with the published scores: 36 (SD = 10) for this age group (Spielberger et al. 1970). Association of individual scores of self-reported state anxiety and the laterality coefficient of individual EDA responses for each stimuli type (described above) was investigated using the Spearman correlation coefficient. Results showed a significant negative correlation between laterality of responses to fear and state anxiety $r = -.410$, $p = .027$ (see Fig. 4). Higher anxiety scores were associated with more right lateralization towards fearful stimuli. There were no other significant correlations.

Results Regarding the Plantar Surface

Figure 5 represents lateralization on the plantar surfaces regarding the four types of emotional musical stimuli used. First, we compared, whether any of the induced emotions are lateralized enough on the plantar surface to differ significantly from absolute synchrony (represented by 0 laterality coefficient). One sample t-tests resulted in a non-significant trend for the fear response $t(30) = 1.71$, $p = .098$. No other significant results were found.

Laterality of electrodermal responses to different emotional musical stimuli was also compared using a within subject design, using the laterality coefficient as the dependent variable in a one-way ANOVA. The results yielded no significant differences in lateralization of the four stimuli types, as measured on the plantar surfaces (Fig. 5).

The association between anxiety and the laterality coefficient was also investigated, and no significant results were found using the Spearman correlation coefficient.

Results Comparing the Palmar and Plantar Surfaces

To compare the palmar and plantar surfaces regarding responses to emotional stimuli we used a two-way, mixed-design ANOVA, with the within subject factor of emotion (fear, sadness, happiness and peacefulness) and the between subject factor of body parts (palmar and plantar). No significant main effects were found. Results yielded a marginally significant interaction effect of emotion and body parts F(3,

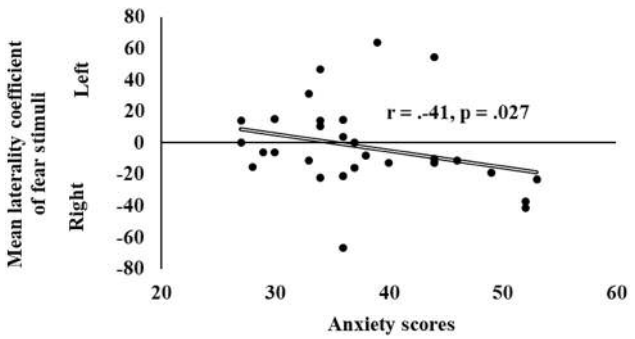

Fig. 4 Relationship between anxiety and lateralization towards fearful stimuli. The Y axis represent the percentage difference between the two sides. Mean laterality coefficient numbers below zero represent right side dominance, while numbers above zero represent left side dominance

Fig. 5 Mean laterality coefficient of stimuli types representing different emotions (plantar surface). Error bars represent ± 1 standard error of the mean. The Y axis represent the percentage difference between the two sides. Numbers below zero represent right side dominance, while numbers above zero represent left side dominance

28) = 2.70, p = .05, effect size = .08. Responses to emotional stimuli seem to show different pattern of lateralization when measured from the palmar as opposed to the plantar surfaces. Fear and sadness were lateralized more to the left on the plantar surfaces, while these two emotions showed a right lateralization on the palmar surfaces. Happiness and peacefulness on the other hand showed no lateral differences as measured on the two body parts.

Discussion

To our knowledge, this is the first study to compare electrodermal laterality differences regarding emotions elicited by music. We explored laterality differences between the two sides of the body, as well as between the upper and lower body. Also, association between participant' self-reported anxiety and electrodermal laterality were examined for the first time in the present study. Our results support predictions of Multiple Arousal Theory concerning laterality differences on the palmar surfaces (Picard et al. 2015). We found markedly different electrodermal reactions for fear and sadness on the palmar surfaces, on the other hand, no similar differences could be observed using EDA data from the plantar surfaces. We conclude that different type of emotions lateralize the electrodermal system in a unique way.

Apart from the objective electrodermal laterality measures, participants also provided subjective ratings of clarity, as well as arousal and valence of the four types of musical segments. The present study shows different patterns of subjective ratings of arousal and valence, as compared to those reported in other studies for similar musical excerpts (Khalfa et al. 2002; Vieillard et al. 2008). The most striking difference is related to the arousal ratings of peacefulness and sadness. In this paper we presented arousal ratings amongst which only happiness differed from fear and peacefulness. This might be due to cultural differences: based on a recent review, different cultures favor emotions that are rated either low or high on arousal (Lim 2016).

One would always expect some deviation from synchrony in regards to electrodermal activity between the two sides of the body, since the distribution of sweat glands are not exactly symmetrical (Freedman et al. 1994). According to our results only sadness tilted the balance significantly to the right side, as compared to absolute synchrony represented with 0 value on the laterality scale. When comparing laterality of the different emotions, we found sadness and happiness taking opposite sides: happiness lateralized to the left and sadness to the right when comparing the palms. These results confirm our hypothesis that emotionally laden musical stimuli elicit lateralized electrodermal responses.

Lateralization of happiness and fear confirm all previous findings (Banks et al. 2012; Picard et al. 2015). On the other hand findings on sadness were the opposite of the findings of Banks et al. (2012). The differences may be due to methodological reasons, or caused more likely by the different stimuli categories used in our studies (faces vs. music). Different types of stimuli aiming to elicit the same emotion category were found to bring about dissimilar central activation (Reiman et al. 1997). Reiman et al. (1997) in their study either exposed participants to visual stimuli or they were prompted to recall an emotionally laden memory. Different activation was found for the same type of emotion when triggered by recall or visual stimulation. Another study found that viewing sad faces was associated with the activation of the left amygdala, which in turn has an ipsilateral influence on EDA (Lane et al. 1997). It has been postulated before, that there could be more than one central pathway to the mediation of EDA (Kimble et al. 1965), and it was later confirmed by Boucsein et al. (2012) and Picard et al. (2015). A possible explanation based closely on Multiple Arousal Theory is that if different central pathways are activated with different type of emotion eliciting stimuli, the activated pathways could have various degree of influence on EDA. This could easily result laterality differences between visually and auditorily induced emotional responding.

The plantar surfaces did not show statistically significant laterality differences of the four studied emotional types, only a trend for left side dominance was found for the fear response deviating from absolute synchrony. Comparing EDA responses to emotional stimuli of the plantar with those of the palmar surfaces, we reported an interaction effect: laterality response to sadness on the feet did not shift significantly away from synchrony as opposed to the robust effect witnessed on the hands. On the other hand, responses to happiness and peacefulness inducing stimuli were similar on both body parts. Thus, there seems to be more to electrodermal responding than a simple lateral difference between the two sides of the body. Our findings underline that different dermatomes are prone to respond to certain type of emotional stimuli which is postulated by Multiple Arousal Theory. More specifically, the feet and the palms show a divergent pattern of responding to the same type of musical segment.

Electrodermal laterality and anxiety was investigated for the first time in our study. Participants' self-reported state anxiety was associated with their laterality responses to four types of emotional stimuli. Results showed that higher anxiety elicited more right sided fear responses on the palmar surfaces. This emotional laterality effect was specific to this emotion only, and to the palmar but not the plantar surfaces. These results support the laterality effects observed in the electrodermal responses to fearful stimuli. They are in line with the findings of Bishop and colleagues

(2004, 2007) who found that state anxiety moderated the activity of the amygdala's response to fearful stimuli.

Limitations

Limitations of this study include data lost from the plantar surfaces due to excessive sweating. Securing equipment on such surfaces is essential. The correlation between anxiety and the electrodermal lateralization of the emotion fear should be handled with care due to low sample size.

Conclusions

The complex nature of the electrodermal system in terms of differences in emotional mapping has not been fully appreciated. Results of the present study confirm that electrodermal responses are not uniform across the body. The autonomic nervous system displays lateral preferences by reacting with varying intensity to different emotions. Music induced emotions show not only lateral preferences but dermatome differences as well. These findings fit well with previous results (Banks et al. 2012; Picard et al. 2015) and prompt for revaluating the homogeneous concept of electrodermal arousal. With the use of bilateral EDA measurement from dermatomes across the body in electrodermal research, we could gain better understanding of how differentiated emotional responses are.

Acknowledgements This work was supported by the Faculty of Education and Psychology, Eötvös Loránd University (ELTE-PPK), the New National Excellence Program of the Ministry of Human Capacities (ÚNKP), and by the Hungarian Scientific Research Funds (OTKA K100845).

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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Study 4:

Bilateral Electrodermal Activity in The Active-Alert Hypnotic Induction

Abstract

Despite our ever-increasing understanding of the way the hemispheres interact during hypnosis, bilateral measure of electrodermal activity (EDA) has remained largely overlooked in research. The present study rectifying this void, measured bilateral EDA in active-alert induction and a control condition in 32 participants. Participants were used as their own control in counterbalanced order, they were exposed to active alert hypnosis induction (hypnosis condition) and listened to music (control condition) the same day with at least 30 minutes rest between conditions. In both conditions participants received test suggestions. Skin conductance level (SCL), was measured from both sides of the body and compared using laterality scores between conditions and hypnotizability groups. Our results suggest that high hypnotizables in response to the active-alert induction show a shift to right side dominance while low hypnotizables shift to left side electrodermal dominance. However, in the control condition there was virtually no change in laterality. Additionally, we found that the extent of self-reported hypnosis experiences connected to an altered state of consciousness were also associated with a shift in laterality toward the right side. Our results underline the importance of the shift to right hemispheric activity as well as the use of bilateral psychophysiological measurement in hypnosis. The correlation between electrodermal laterality and subjective experience is noteworthy, for it relates the phenomenology of hypnosis to psychophysiology, underscoring the importance of the hemispheric changes that take place and their importance in shaping subjective experience. This work also highlights the unique changes in EDA that are brought about by the induction process.

Link to this article: https://doi.org/10.1080/00207144.2018.1460551

July–September 2018
volume 66 number 3
ISSN 0020-7144

THE INTERNATIONAL JOURNAL OF
Clinical and Experimental
HYPNOSIS

Official Publication of The Society for Clinical and Experimental Hypnosis
Official Journal of the Canadian Society of Clinical Hypnosis – Ontario Division
The Official Journal of the Society of Psychological Hypnosis (American Psychological Association Division 30)
The Official Journal of the International Society of Hypnosis

Routledge
Taylor & Francis Group

International Journal of Clinical and Experimental Hypnosis

ISSN: 0020-7144 (Print) 1744-5183 (Online) Journal homepage: http://www.tandfonline.com/loi/nhyp20

BILATERAL ELECTRODERMAL ACTIVITY IN THE ACTIVE–ALERT HYPNOTIC INDUCTION

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To cite this article: Krisztian Kasos, Zoltan Kekecs, Eniko Kasos, Anna Szekely & Katalin Varga (2018) BILATERAL ELECTRODERMAL ACTIVITY IN THE ACTIVE–ALERT HYPNOTIC INDUCTION, International Journal of Clinical and Experimental Hypnosis, 66:3, 282-297, DOI: 10.1080/00207144.2018.1460551

To link to this article: https://doi.org/10.1080/00207144.2018.1460551

Intl. Journal of Clinical and Experimental Hypnosis, 66(3): 282–297, 2018

ISSN: 0020-7144 print / 1744-5183 online
DOI: https://doi.org/10.1080/00207144.2018.1460551

BILATERAL ELECTRODERMAL ACTIVITY IN THE ACTIVE–ALERT HYPNOTIC INDUCTION

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Abstract: Shifts in hemispheric dominance were previously proposed to play a role in hypnosis. Participants (N = 32) were exposed to an active–alert hypnosis induction and a music-control condition while electrodermal activity was registered bilaterally, providing information on alterations in hemispheric dominance. The results suggest that highly hypnotizable participants show a shift to right-sided and low hypnotizable participants demonstrated a shift to left-sided electrodermal dominance in response to the induction, whereas no change in laterality is present in the control condition. Additionally, the authors found that self-reported hypnosis experiences were also associated with a shift in laterality. These results underline the importance of the shift to right hemispheric activity in hypnosis and underscore the importance of hemispheric changes in shaping subjective experience.

Recent research into the neuropsychological correlates of hypnosis has moved away from the dichotomy of the left and right hemispheres toward implicating more specific areas of interest. Examples include changes in functional connectivity among brain regions (Cojan et al., 2009), more specifically, the decrease in frontal functional connectivity (Cardeña, Jönsson, Terhune, & Marcusson-Clavertz, 2013) and the implication of the prefrontal cortex in hypnosis (McGeown, Mazzoni, Venneri, & Kirsch, 2009). For recent reviews, see Landry, Lifshitz, and Raz (2017) and Jensen and colleagues (2017). On the other hand, earlier the topic of

Manuscript submitted May 15, 2013; final revision accepted November 5, 2017.
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laterality enjoyed broad interest as several studies have confirmed the role of the relative increases in right hemispheric activity during hypnosis (Cikurel & Gruzelier, 1990; Edmonston & Moscovitz, 1990; Graham & Pernicano, 1979; Gruzelier, Brow, Perry, Rhonder, & Thomas, 1984; MacLeod-Morgan & Lack, 1982; Sackeim, Paulhus, & Weiman, 1979). However, the contribution of the left side of the brain has also been noted, as verbal processing of the hypnotic induction and subsequent suggestions predominantly take place in the left hemisphere (Jasiukaitis, Nouriani, & Spiegel, 1996). Focused attention, which is an important part of the hypnotic induction, is generally related to left-sided processes as well (Jasiukaitis, Nouriani, Hugdahl, & Spiegel, 1997). The changes brought about by hypnosis are thought to involve a shift to right hemispheric dominance either as a result of increased right or decreased left hemispheric activation (Gruzelier et al., 1984). Our current understanding of hypnosis in terms of laterality implies a complex interaction of the hemispheres intervened with dynamical changes in the activation of the left and right sides of the brain (Bob & Siroka, 2016).

A reliable method to measure changes in hemispheric dominance is to measure electrodermal activity (EDA) bilaterally, (Hugdahl, 1984). Cortical activity asserts an inhibitory influence on EDA, each hemisphere controlling electrodermal activity of the contralateral side of the body. Thus, when cortical activity increases in the right hemisphere relative to the left, electrodermal activity becomes higher on the right side of the body compared to the left side (Gruzelier, 1985). EDA has been used extensively to assess the effect of hypnosis on the sympathetic nervous system (SNS). Those studies finding a measurable effect usually showed a down-regulation of the SNS during hypnosis (Bauer, 1980; Davis & Kantor, 1935; Kekecs, Szekely, & Varga, 2015), whereas others found no effect (Edmonston & Pessin, 1966; Plapp, 1967; Stern, Edmonston, & Ulett, 1963). Additionally, EDA also proved sensitive to individual differences in hypnotizability; high hypnotizables displayed higher EDA than medium, and low hypnotizables at baseline and smaller reduction in their EDA levels at rest periods between cognitive stress tasks (Jorgensen & Zacharia, 2002). However, most earlier studies used unilateral EDA measurement only, disregarding the potential discrepancies brought about by a shift in laterality during hypnosis. Studies that did measure EDA bilaterally found that it provided useful information related to hypnotic phenomenon. For example, high hypnotizables were found to have decreased information transfer between hemispheres compared to low hypnotizables (Bob & Siroka, 2016). Furthermore, a study that bilaterally measured skin conductance orienting responses to standard tones found right-side dominance in the amplitude of orienting responses during hypnosis (Gruzelier, 1985).

Because hypnosis is elicited by induction, it is reasonable to assume that the proposed shift in hemispheric activity occurs, at least partially,

during the induction process. Therefore, the hypnotic induction presents itself as an excellent target for the investigation of EDA laterality changes associated with hypnosis. One earlier study, measuring bilateral EDA on 20 students and 10 cardiac patients, analyzed tonic bilateral skin conductance during the induction and found higher, although not significantly different, right-side EDA during the induction process in both low and high hypnotizable subjects (Gruzelier, 1985). However, the study did not look at changes in lateral dominance and employed traditional hypnosis; thus, any results showing changes could be attributed to the effects of relaxation. A design that uses a nontraditional hypnotic induction procedure such as active–alert hypnosis (Bányai & Hilgard, 1976) could control for this factor.

Subjective experiences connected to the hypnotic state—such as loss of sense of time, amnesia, and regression to childhood memories—are traditionally associated with right hemispheric processes (Gruzelier et al., 1984). One may argue that a strong case could be presented for the importance of laterality shift in hypnosis, if a link between peripheral psychophysiological measures and subjective hypnotic experiences would be demonstrated. There have been previous attempts to connect EDA and subjective hypnotic experience. Tart in 1963 investigated the correlation between self-reported subjective hypnotic depth and skin conductance level and found a strong correlation between the two (Tart, 1963). Contrary to Tart's findings, Orne, while exploring the association between EDA, self-reported hypnotic depth, and scores obtained on a hypnotizability scale found no correlation between self-reported hypnotic depth and EDA. (Orne & O'Connell, 1968). However, both of these studies employed unilateral EDA measurement. Factoring in laterality information might resolve these contradictory findings.

The present study aimed to assess shifts in hemispheric dominance asserted by hypnosis, by focusing on laterality changes in electrodermal activity that take place during the active–alert hypnosis induction. Furthermore, we aimed to fill a void in our knowledge by investigating the relationship between bilateral EDA changes and subjective experience.

We hypothesized a shift in EDA laterality from left to right during the hypnotic induction, which could be moderated by hypnotizability. In order to explore the differential effects that can be found in EDA across the sides of the body, we also planned to analyze changes on the left and the right sides separately, and compare the bilateral results. The investigation regarding the association between EDA laterality and subjective hypnotic experience was exploratory, with no specific hypotheses, although we expected that a shift toward the right side may be related with experiences traditionally associated with hypnosis.

Methodology

Participants

Participants were invited to take part in the study on a voluntary basis and were not offered compensation. All of those who participated had been involved in a standardized group hypnosis session beforehand, in which their hypnotizability was measured with the Harvard Group Scale of Hypnotizability, Form A (HGSHS:A, Shor & Orne, 1962; Hungarian version: Költő, Gősi-Greguss, Varga, & Bányai, 2015). For this study, we invited participants who fell in the lower (0–4) or the upper end (8–12) range of the HGSHS:A. Exclusion criteria for the study were self-reported present use of psychiatric drug, use of sedatives, or any psychiatric illness.

Design

Procedure. The study followed a within/between-subject mixed design. After signing informed consent, participants were exposed to two experimental conditions: hypnosis and a music control condition, consecutively on the same day with at least 30 minutes of rest in between. In the rest period, participants filled out psychological questionnaires regarding their experience, of which only the Phenomenology of Consciousness Inventory (PCI, Pekala, 1991) will be reported here. Study conditions were presented in a random, counterbalanced order.

In the hypnosis condition, a standard active–alert induction was used (Bányai & Hilgard, 1976; Miller, Barabasz, & Barabasz, 1991), with the test suggestions from the Waterloo-Stanford Group C standardized scale (Bowers, 1998) to measure hypnotizability. Suggestions that require the use of both hands, moving hands, age regression, and negative visual hallucination were omitted, as movements or opening the eyes might alter EDA (for details, see Kekecs et al., 2015). The results regarding the data gathered in the test suggestion phase will be reported elsewhere. Although the induction was standardized, it was delivered by different hypnotherapists; thus, induction length varied between 7.5 and 9 minutes. Test suggestions were read by the hypnotherapists to the participants in both hypnosis and music conditions from a standardized script.

The music condition differed from the hypnosis condition only in that the hypnotic induction and deinduction were replaced with music containing a collection of carefully selected pieces differing in type to control for preferences. The music pieces in place for the induction (12 minutes) and deinduction (2 minutes) were approximately the same length as the hypnotic induction and deinduction and have been previously used in other experiments (Kekecs et al., 2015).

Instruments. The PCI measures subjective experiences in relation to alterations in consciousness along 12 dimensions and 14 subdimensions in 53 items. The Hungarian version of the PCI was used in this experiment to assess phenomenological experiences (Szabó, 1989; Varga, Jozsa, Bányai, Gosi-Greguss, & Kumar, 2001). The PCI has adequate construct and discriminant validity for the assessment of subjective states associated with hypnosis (Pekala, 1991).

Equipment. The active alert hypnosis sessions were held in a sound-attenuated chamber, which was built for conducting hypnosis experiments in a silent environment. Electrodermal activity was measured with OpenEDA, an open-source biomonitor with a four-Hertz sampling rate (Kekecs et al., 2015). For electrodermal measurements, Skintact FS-RG1 disposable Ag/AgCl electrodes (Leonhard Lang GmbH, Innsbruck, Austria) were used with a solid gel electrolyte. The disposable electrodes were placed on the left and right shoulders of the participants (Van Dooren, De Vries, & Janssen, 2012). The shoulders were selected to measure EDA, as the design of the experiment called for the movement of the dominant arm during the test suggestion phase. The shoulders have been indicated as an adequate spot for electrodermal assessment (Van Dooren et al., 2012).

Data Processing. Electrodermal activity was analyzed with Ledalab 3.4.9 (Benedek & Kaernbach, 2010). In order to decrease error noise, the data was first smoothed with a Gaussian window. Afterward, skin conductance level (SCL) was obtained by optimized continues decomposition analyses (Benedek & Kaernbach, 2010). Average SCL was obtained for the 1st, 3rd, 5th, and 7th minutes of the induction. To determine the difference in bilateral skin conductance levels, the obtained SCL data were transformed into a laterality coefficient (Schulter & Papousek, 1992). The right SCL value was deducted from the left SCL value, and the result was divided by the sum of left and right SCL. The values of the calculated laterality coefficient range between 1 and –1. Positive values indicate left electrodermal dominance, and negative values indicate right electrodermal dominance. The shift in EDA laterality was calculated by deducting the laterality coefficient measured in the 1st minute from the laterality coefficient measured in the 7th minute. Thus, positive values of shift in laterality mean a shift toward the left side.

Statistical Analysis. To examine the difference in electrodermal patterns in the two conditions for high and low hypnotizables separately for the left and right side of the body, mixed ANOVA was conducted using the within-subjects factors of time (1st, 3rd, 5th and 7th minutes) and condition (hypnosis and music), and the between-subjects factor of hypnotizability (high and low). The first 7 minutes of the induction and the music control condition were analyzed for all experiments, because we could be sure that this period was part of the

induction process in all sessions. The same mixed ANOVA was repeated for the left and right side SCL as an outcome separately. The Spearman correlation coefficient was used to explore the association between the shift in laterality and the PCI subscales, because data were skewed.

Results

There were 32 participants in the study (mean age = 29.51, *SD* = 9.74, 12 female). Five participants were dropped from the analysis for reasons of electrode detachment or equipment malfunction. Additionally, two participants who were enrolled as high hypnotizables based on their group hypnotizability screening scored as low hypnotizable during the active-alert hypnosis session, and thus were categorized as low hypnotizables in terms of data analysis. One more participant was dropped from the Spearman correlation for missing PCI scores.

The three-way mixed ANOVA conducted on SCL measured from the left side of the body revealed a significant main effect of time, $F(3,24) = 4.525$, $p = .006$ (see A and C of Figure 1). EDA levels rose most prominently over time in the high hypnotizable group. However, there were no other significant main effects or interactions. A three-way mixed ANOVA was also conducted on the SCL measured from the right side of the body (see B and D of Figure 1). Significant interaction between condition, time, and hypnotizability—$F(3,24) = 3.38$, $p = .023$—was found. At the beginning of the induction, high hypnotizables showed lower skin conductance on average than low hypnotizables. During induction, SCL values of high hypnotizables rose considerably (see Figure 1B). On the other hand, low hypnotizables initially had higher skin conductance than high hypnotizables, which remained unchanged during the induction. The pattern of SCL changes is opposite in the music condition (see Figure 1D). In this condition, low hypnotizables showed lower skin conductance compared to high hypnotizables initially, whereas high hypnotizables had higher skin conductance in the beginning, which displayed a downward tendency. There were no other significant main effects or interactions.

Results showed a significant interaction of condition, time, and hypnotizability on the laterality coefficient, $F(3,24) = 3.00$, $p = .036$. High and low hypnotizable participants displayed different patterns of laterality changes over time in the hypnosis and music condition (Figure 2). In the first 5 minutes of the induction phase, the lateral disposition of both high and low hypnotizables were balanced. However, by the 7th minute high hypnotizables shifted toward right-side dominance and low hypnotizables toward left-side dominance. On the other hand, in the music condition, low hypnotizables displayed clear left-side advantage from the beginning as opposed to high hypnotizables, who showed right-side dominance. These values were unchanged throughout this condition (Figure 2B).

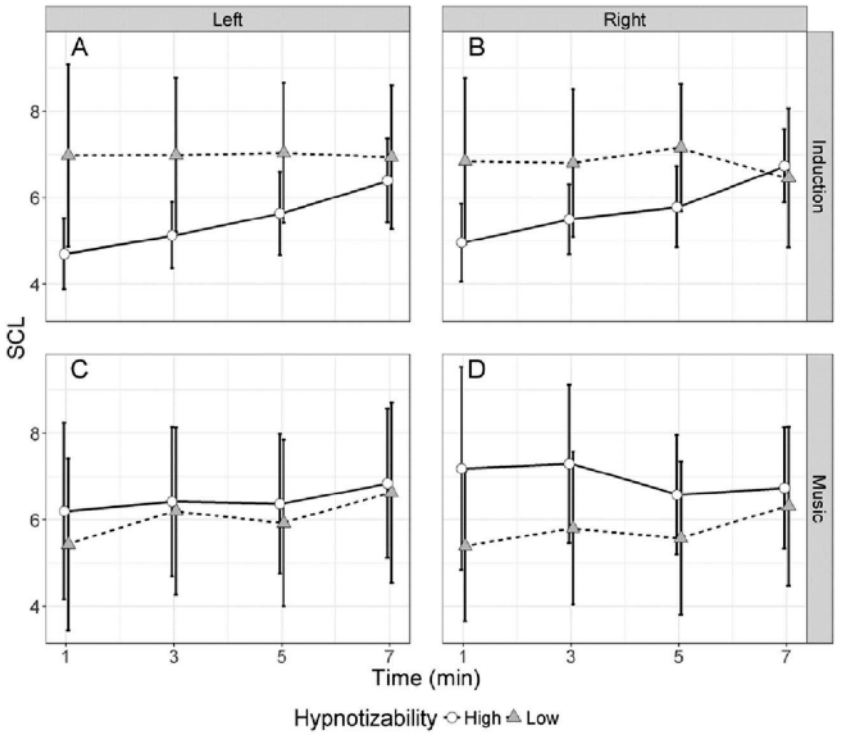

Figure 1 **Left- and right-side SCL during induction and music. Error bars represent ± 1 standard error of the mean.**

To explore the relationship of the phenomenology of hypnosis with the shift in laterality, subjective experience was characterized by the PCI dimensions, and the laterality shift was measured by the difference of laterality coefficient in the beginning and at the 7th minute of the induction. Spearman correlation results between PCI and the lateral shift are presented in Table 1. Significant correlations were found between the lateral shift and several dimensions of the hypnotic experience in the induction phase. When laterality displayed a shift to the right (laterality shift values are negative), participants rated their altered experience, body image, perception, and altered state of awareness with higher scores. At the same time, they scored low on self awareness, rationality, volitional control, and memory. Importantly, the music condition showed no significant correlation with any factors of the PCI.

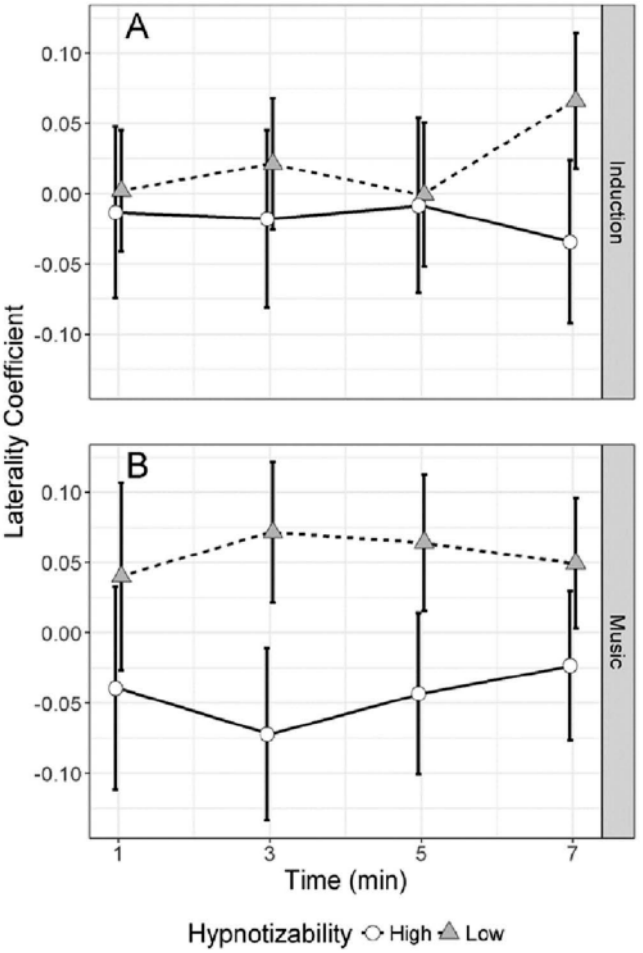

Figure 2 **Lateral activity during induction and music. Error bars represent ± 1 standard error of the mean.**

Discussion

Our study aimed to investigate changes in laterality during hypnosis induction by measuring electrodermal activity bilaterally during active–alert hypnosis. We also explored the association of the shift in laterality with subjective hypnosis experiences. According to our results, high hypnotizables display a shift to right-dominant lateral asymmetry during the induction, whereas low hypnotizables show a left-dominant shift in their laterality. On the other hand, neither high nor low hypnotizables exhibit

Table 1
Spearman's Correlation Between the Shift in Laterality and Dimensions of the PCI.

	Condition	
PCI dimensions	Hypnosis	Music
Altered experience	−.48*	.10
Body image	−.40*	−.03
Time sense	−.33	.16
Perception	−.47*	−.09
Meaning	−.28	.07
Positive affect	−.23	−.05
Joy	−.39	−.17
Sexual excitement	.09	−.24
Love	−.25	.16
Negative affect	−.02	.07
Anger	−.06	.09
Sadness	−.25	.07
Fear	−.13	−.02
Attention	.05	−.07
Direction	−.00	.08
Concentration	−.14	−.29
Imagery	−.05	.06
Self-awareness	.47*	.03
Altered state of awareness	−.40*	.07
Arousal	.00	.23
Rationality	.56**	−.25
Volitional control	.41*	−.23
Memory	.62**	.22
Internal dialogue	−.16	.08

Note: *$p < .05$, two-tailed. **$p < .01$, two-tailed.

laterality shifts in the music control condition. These results confirm that the hypnotic induction affects low and high hypnotizable participants in different ways, and these differences translate to significant differences in EDA laterality. Furthermore, we found that experiences that are usually associated with hypnosis—such as altered state of awareness, alterations in body image, and perception measured by the PCI—are associated with a shift toward the right during the hypnosis induction. These results support that hypnosis and hypnotic experiences are associated with a shift in hemispheric dominance to the right. In addition, our results validate and call for the use of bilateral EDA measures in hypnosis research.

The results revealed a significant difference in the pattern of EDA laterality between conditions that was moderated by hypnotizability. High hypnotizables showed a shift to right-side dominance, whereas low

hypnotizables demonstrated a shift to left-side dominance during the induction but not the control condition. This shift in electrodermal dominance toward the right side in high hypnotizables would imply a decrease in left hemispheric activation. This is in line with the prevailing view of the changes associated with the hypnotic induction—that is, high hypnotizables are claimed to demonstrate left frontal activation, which gives way to right posterior dominance with left hemispheric inhibition (Gruzelier, 1996). On the other hand, evidence from neuropsychological tests show that low hypnotizables often show the opposite pattern, and display left hemispheric activation in response to the induction process (Gruzelier & Warren, 1993). This left hemispheric activation would result in left-sided electrodermal dominance. Our results, that low hypnotizables, as opposed to high hypnotizables, react to the induction with left-sided electrodermal dominance support this line of reasoning. Shift to left EDA dominance in the induction in low hypnotizables may represent activation of left hemispheric attentional networks. This activation is possibly produced by repeated suggestions for focused attention and the verbal processing of the hypnotic induction, which is also a contributing factor to left hemispheric activation (Rainville et al., 1999). Low hypnotizables may be less able to inhibit left hemispheric processes, which seems to be important in inducing hypnosis among high hypnotizables. Contrary to low hypnotizables, high hypnotizables—who are suggested to have higher cognitive flexibility (Crawford & Allen, 1983), which is further increased by the induction process (Crawford, 1989, 2001)—may be able to shift from an effortfully focused attentional style to a style in which focus is effortless, and this effortless focus helps to get deeply absorbed in hypnosis (Crawford, Brown, & Moon, 1993). The right hemispheric dominance, indicated by the right shift in electrodermal activity observed in our study, may be one of the mechanisms that allow for the deep absorption in hypnosis and the effortless attentional focus of high hypnotizables described by others.

Subjective experiences regarding the hypnosis session correlate with the direction and amount of the shift in electrodermal laterality. Additionally, out of the eight dimensions that were correlated with the shift in laterality, seven have been found to correlate to hypnotic susceptibility in the past (Varga et al., 2001). When a shift to right-side dominance occurs, participants undergo experiences traditionally associated with hypnosis, such as an altered state of awareness or changes in their ability to recall events. Specifically, the more substantial the shift toward the right side in electrodermal laterality during the induction, the higher the scores were for altered experience, altered state of awareness, perception, and body image. When activity increases in the left hemisphere, participants experience the opposite to the hypnotic experience—that is, higher rationality, self-awareness, volitional control, and memory. This further supports the view that changes in hemispheric dominance play a crucial role in the hypnotic experience.

It is worth noting that the PCI was completed in reference to the whole hypnosis session, not just the induction period. This is important because it implies that the first 7 minutes of the induction could predict the self-reported experiences for the entire hypnosis period. Besides, the correlation between the PCI and the electrodermal lateral shift during hypnosis signifies the importance of the hypnotic induction. The fact that we did not find the same correlation with subjective reports and laterality shift in the music condition is in line with previous results that showed differences in brain activity in the presence and absence of a hypnotic induction. For example, a study found differences in the activation of the default mode network after hypnotic induction in highly hypnotizable participants that was not apparent in the condition without hypnotic induction (McGeown et al., 2009). Participants in the present study responded similarly to suggestions in both conditions, although to a lesser extent in the control condition than in the hypnosis condition. However, their lateral EDA changes in the control condition did not correlate with their subjective experience. This is also consistent with previous research that described high hypnotizable participants complying with suggestions without the hypnotic induction but not showing the changes in brain activity that they exhibited with the induction (Derbyshire, Whalley, & Oakley, 2009; McGeown et al., 2009, 2012). This suggests that response to suggestions in a waking state may not result in the same changes in the nervous system as hypnosis with induction. It would be important to clarify whether the relationship between changes in laterality and self-reported experiences are unique to the induction process, or could possibly be brought about with other methods, such as relaxation or meditation.

Limitations

Investigation of the role of laterality shift and self-report experiences was exploratory in our study. Out of the 26 factors of the PCI, eight correlated with electrodermal shift during the hypnotic induction. Further replication is needed to confirm the relationship between subjective experiences and laterality shift.

The emotional effects of music were not controlled for, and this also may have introduced bias in EDA. In the future, a neutral control condition that resembles the hypnotic induction in its narrative could be used (for an example, see Varga, Kekecs, Myhre, & Józsa, 2017). Furthermore, the use of a recorded induction would eliminate the problems of the varying length of inductions.

Conclusion

Results indicate that low and high hypnotizables differ significantly in the way their electrodermal laterality changes during the active–alert induction. Lateral shifts in EDA were also found to be

associated with hypnotic experiences. Furthermore, our results also highlight the importance of the hypnotic induction and its unique role, which leads to altered EDA functioning. Findings provide further evidence supporting the importance of laterality shift from left to right in hypnosis, and the differences in laterality between high and low hypnotizables. This is the first attempt to investigate correlation between hypnotic experiences and electrodermal laterality. With the advancement of technology, it is not inconceivable that researchers and clinicians could monitor electrodermal laterality in real time to achieve better hypnosis results. This could be used to maximize hypnotic depth and the extent of alteration in consciousness in research and in clinical practice. Moreover, our findings underline the importance of measuring EDA bilaterally in the research of the psychophysiology of hypnosis.

Funding

This work was supported by ELTE-PPK.

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Bilaterale elektrodermale Aktivität in der Active-Alert Hypnoseinduktion

Krisztian Kasos, Zoltan Kekecs, Eniko Kasos, Anna Szekely, und Katalin Varga

Abstract: Zzunächst wurde davon ausgegangen, daß Veränderungen in der Hemisphärendominanz eine Rolle in der Hypnose spielen. Die Teilnehmer (N = 32) wurden einer active-alert Hypnoseinduktion und einer Musik-Kontroll-Situation ausgesetzt, während elektrodermale Aktivität bilateral aufgezeichnet wurde, um Informationen über Veränderungen in der Hemisphärendominanz zu sammeln. Die Resultate lassen vermuten, daß hoch hypnotisierbare Teilnehmer eine Verlagerung zur rechten und niedrig-hypnotisierbare Teilnehmer eine Verlagerung zur linken elektrodermalen Dominanz als Reaktion auf die Induktion zeigen, während sich keinerlei Veränderung in der Lateralisation in der Kontrollgruppe zeigte. Zusätzlich fanden die Autoren heraus, daß selbstbeschriebene Hypnoseerfahrungen ebenfalls mit einer Verlagerung der Lateralisation assoziiert waren. Diese Ergebnisse unterstreichen die Wichtigkeit der Verlagerung zur rechten Hemisphärenaktivität während Hypnose und betonen die Bedeutung von Veränderungen in den Hemisphären bei der Formung subjektiver Erfahrungen.

STEPHANIE RIEGEL, M.D.

L'activité bilatérale électrodermale dans l'induction hypnotique active-alerte

Krisztian Kasos, Zoltan Kekecs, Eniko Kasos, Anna Szekely et Katalin Varga

Résumé: Il a été proposé par le passé que le transfert de dominance hémisphérique jouait un rôle dans l'hypnose. Trente-deux participants (N = 32) ont été exposés à une induction hypnotique active-alerte et à un groupe témoin auquel on a demandé d'écouter de la musique pendant que l'activité électrodermale était enregistrée sur le plan bilatéral, fournissant de l'information sur l'altération de la dominance hémisphérique. Les résultats indiquent que chez les participants très sensibles à l'hypnose, il se produit un passage vers l'hémisphère droit en réponse à l'induction, et que chez les participants peu sensibles à l'hypnose, la dominance électrodermique passe vers la gauche, alors qu'on n'a observé aucun changement de latéralité dans le groupe témoin. Les auteurs ont en outre constaté que des expériences d'hypnose autodéclarées étaient également associées à un changement de latéralité. Ces résultats soulignent l'importance du déplacement vers la droite de l'activité hémisphérique pendant l'hypnose ainsi que l'importance des changements hémisphériques dans la formation de l'expérience subjective.

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Actividad electrodérmica bilateral en la inducción hipnótica activa-alerta.

Krisztian Kasos, Zoltan Kekecs, Eniko Kasos, Anna Szekely y Katalin Varga

Resumen: Anteriormente se había propuesto que los cambios en la dominancia hemisférica jugaban un papel en la hipnosis. Se expuso a los participantes (N=32) a una inducción hipnótica activa-alerta y a una condición control con música mientras la actividad electrodérmica se registraba bilateralmente, proveyendo información sobre alteraciones en la dominancia hemisférica. Los resultados sugieren que los participantes altamente hipnotizables muestran un cambio hacia el lado derecho mientras los participantes poco hipnotizables mostraron un cambio a dominancia electrodérmica izquierda como respuesta a la inducción, mientras que no se presentaron cambios en lateralidad en la condición control. Adicionalmente, los autores encontraron que los autoreportes de experiencias hipnóticas también se asociaron con un cambio en lateralidad. Estos resultados subrayan la importancia del cambio hacia la actividad del hemisferio derecho en hipnosis y enfatizan la importancia de los cambios hemisféricos en la conformación de la experiencia subjetiva.

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Study 5:

Electrodermal correlates of hypnosis: past research and current developments

Abstract

Hypnosis proved to be an effective treatment in disorders that affect the autonomic nervous system (ANS). Studies investigating the nature of its effect of hypnosis on the ANS reported contradictory results to date. Measurement of electrodermal activity (EDA) is an objective way to assess the activity of the sympathetic branch of the ANS. This paper starts with a review of the relevant literature to elucidate the effects of hypnosis on EDA. Next, results from two studies, both investigating psychophysiological effects of hypnosis are reported.

In the first experiment subjects engaged in group hypnosis (HGSHS: A) in order to measure their hypnotizability. EDA was measured bilaterally from the wrists. We found significant reduction in EDA levels and the number of non-specific responses during the hypnotic induction phase. This effect was present for all three hypnotizability groups (high, medium and low).

A three-way interaction confirmed that EDA patterns on the left and right sides were characteristically different in these three groups. Left side dominance was typical in high hypnotizables, whereas low hypnotizables were characteristically right sided. EDA levels of the two sides remained synchronous in medium hypnotizables. During the test suggestion phase, we found significant differences in EDA levels depending on test suggestions, moderated by hypnotizability. Suggestions that are harder to respond to elicited higher arousal in high hypnotizables as compared to lows.

In the second experiment five consecutive hypnosis sessions were carried out to confirm reproducibility of the most prominent effect found in Study 1; gradual decrease in the level of skin conductance during the induction phase of hypnosis. We also confirmed that this effect is independent of the hypnotizability level.

We conclude that during hypnosis induction arousal is bilaterally reduced, which effect is persistent across different levels of hypnotizability. At the same time lateral differences define unique EDA patterns in the induction phase, characterizing high, medium and low hypnotizables.

Keywords: Bilateral; electrodermal; EDA; group measurement; hypnosis

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Research Article

Electrodermal Correlates of Hypnosis: Current Developments

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Academic Editor: Giuseppe De Benedittis

Special Issue: Hypnosis: from Neural Mechanisms to Clinical Practice

OBM Integrative and Complementary Medicine
2020, volume 5, issue 2
doi:10.21926/obm.icm.2002017

Received: February 07, 2020
Accepted: March 23, 2020
Published: April 01, 2020

Abstract

Hypnosis has proven to be an effective treatment in disorders that affect the autonomic nervous system (ANS). However, the studies investigating the nature of its effect on the ANS have reported contradictory results. Measurement of electrodermal activity (EDA) is an objective way to assess the activity of the sympathetic branch of the ANS. We aim to elucidate the effects of hypnosis on EDA. Here, we report the results of two studies, both investigating the psychophysiological effects of hypnosis.In the first experiment, subjects engaged in an HGSHS:A group hypnosis session to measure their hypnotizability. EDA was measured bilaterally from their wrists. We found a significant reduction in EDA levels and the number of nonspecific responses during the hypnotic induction phase. This effect was observed in all three hypnotizability groups—high, medium, and low hypnotizables.

A three-way interaction confirmed that EDA patterns on the left and right sides were characteristically different in these three groups. Left-side dominance was typical in high hypnotizables, whereas low hypnotizables were characteristically right-sided. EDA levels of

the two sides remained synchronous in medium hypnotizables. During the suggestion phase, we found significant differences in EDA levels depending on the test suggestions, modulated by hypnotizability. A suggestion, harder to respond to, elicited higher arousal in high hypnotizables as compared to low hypnotizables.

In the second experiment, we performed five consecutive hypnosis sessions to confirm the reproducibility of the most prominent effect found in Study 1—a gradual decrease in the level of skin conductance during hypnotic induction. We also confirmed that this effect is independent of the hypnotizability level.

We conclude that arousal is bilaterally reduced during hypnosis induction, which is persistent across different levels of hypnotizability. At the same time, lateral differences define unique EDA patterns in the induction phase, characterizing high, medium, and low hypnotizables.

Keywords

Bilateral; electrodermal; EDA; group measurement; hypnosis

1. Introduction

Hypnosis is a state of consciousness that is characterized by focused attention and decreased peripheral awareness, accompanied by an increased capacity to respond to suggestions [1]. During hypnosis, the subjects often report changes in time sense, body image, memory, self-awareness, and volitional control, all associated with an altered state of consciousness [2]. Hypnosis is a product of the procedure called hypnotic induction [1]. A hypnotic state is achieved when individuals respond to suggestions in an automatic fashion, ignoring environmental stimuli, other than those pointed out by the hypnotist. In this state, the individual tends to see, feel, and smell in accordance with the hypnotist's suggestions, even though these suggestions may be in contradiction to the actual stimuli present in the environment. The degree to which people respond to suggestions is called hypnotizability. It is typically measured on a scale ranging from low to high. It is a stable, trait-like characteristic that does not change significantly over time; measured 25 years later, the correlation remains high with $r = 0.75$ [3]. We usually divide people into three groups—low, medium, and high hypnotizable individuals. Low and high hypnotizables are often compared in research as the two ends of the continuum [4]. There are standardized procedures to induce hypnosis and to measure hypnotizability. They involve rapport building followed by a hypnotic induction, various test suggestions, and a deinduction [5, 6].

Hypnosis has long been known as a useful therapeutic tool for various psychological and physiological disorders, including chronic headaches, hypertension, and various forms of anxiety [7]. It is particularly efficient for disorders that are characterized by changes in the autonomic nervous system. The reason for this efficacy may lie in the reduction in psychophysiological arousal and the modulation of autonomic activity [8-10]. Forbes and Pekala (1993)[8] reported that self-hypnosis training produced psychological improvements associated with reduced anxiety, reduced pulse rate, and increased skin temperature [8]. Kanji and colleagues (2006)[11] demonstrated that eight sessions of autogenic training lowered state and trait anxiety levels as

well as systolic and diastolic blood pressure [11]. Hypnosis can also be an adjuvant treatment for major depression, a disorder that is associated with autonomic nervous system changes, such as decreased heart rate variability [12]. Chen and colleagues (2017) [12] found that heart rate parameters significantly improved in the hypnotic and post-hypnotic conditions compared to the pre-hypnotic condition. Thus, they concluded that hypnotic treatment might bring improvements in vegetative functions [12].

Measuring electrodermal activity can be an unobtrusive and cost-effective way to gain information about the autonomic nervous system [13]. The ease of use and the widely available technology have made the measurement of electrodermal activity (EDA) a popular tool in hypnosis research. Tools measuring skin conductance (SC) make use of the eccrine sweat glands, which are exclusively innervated by the sympathetic nervous system (SNS) [14, 15]. Thus, the tonic component of skin conductance, skin conductance level (SCL), is an excellent way to gauge the background level of the SNS. In contrast, the phasic component, skin conductance response (SCR), provides information about the autonomic responses to the given stimuli. The tonic component is characterized by slow changes; whereas, the phasic components change faster. Dawson and colleagues provided a detailed description of the different components of skin conductance [15, 16]. Determining the measurement sites for EDA is important since the density of eccrine sweat glands differs in different parts of the body. The most responsive sites to measure electrodermal activity are the palmar and plantar surfaces (for a recent bilateral analysis of traditional and alternate measuring sites, see Kasos et al., under review).

In the following section, we summarized the research results concerning the relationship between EDA and hypnosis. The studies are listed in chronological order.

Table 1 Summary of research results regarding EDA and hypnosis.

Authors & year	**Purpose of the research**	**N**	**Measurement**		**Type of induction**	**Hypnotizability measurement**	**Main findings**
			side	**place**			
Levine, 1930	EDA during hypnosis	6	Bi	palms of hands	-	-	No differences between waking state and hypnosis.
Estabrooks, 1930	EDA during hypnosis	20	Uni	hand	-	-	EDA decreased in hypnosis.
Davis&Kantor, 1935	EDA during hypnosis	71	Uni	medial phalanges of index and middle fingers of the right hand	-	-	Difference between active and passive hypnosis. In the active part of hypnosis, EDA resembled EDA in the awake state while in passive hypnosis resembled EDA during sleep.
Brown & Vogel, 1938	hypnosis during pain stimulation	3	-	-	-	-	No electrodermal signs of pain perception in hypnosis.
West et al., 1952	effects of hypnosis on noxious stimuli	7	-	-	-	-	Hypnotic suggestions reduce electrodermal responses to painful stimuli.
Sears & Beatty, 1956	differentiate between waking state and hypnotic state based on EDA	24	-	-	-	Davis and Husband scale of hypnotic susceptibility	No difference between the hypnosis and awake condition.
Barber & Coules, 1959	EDA during hypnosis	6	Uni	palm	-	-	Three subjects had high, and three had lower EDA during the induction. Subjects showed rising EDA during test suggestions; in addition, active suggestions (for example, suggested hallucination) elicited higher arousal.
Shor, 1962	physiological effects of	16	Uni	palm	-	-	No differences in electrodermal

	painful stimuli in hypnosis						response between hypnosis and simulator group to painful stimuli.
Tart, 1963	effects of self-reported hypnotic depth and EDA	11	Bi	foot	arm levitation,	-	Falling EDA during induction and varied EDA (rising and falling) during test suggestions.
Stern et al., 1963	how hypnotically induced amnesia alters recently acquired behavior and electrodermal correlates	14	-	-	free induction	-	No differences in EDA between hypnosis and control condition. EDA showed an increase at the beginning, followed by a decrease and an eventual increase again in hypnosis.
Edmonston & Pessin, 1966	the relation between hypnosis, learning, and EDA	22	Uni	index and middle fingers	-	not measured	No differences in skin conductance between hypnosis and control group.
Fehr & Stern,1967	effects of hypnosis on relevant and irrelevant stimuli	24	-	-	SSHS:A	HGSHS: A	The hypnosis group showed lower electrodermal orienting responses than the control group.
O'Connel et al., 1968	the relation between self-reported hypnotic depth and EDA	51	Uni right	palm	passive trance induction	HGSHS: B	Arousal correlates with hypnotizability. EDA changes during hypnosis reflect the quality of the rapport more than self-reported hypnotic depth.
Pessin et al., 1968	effects of hypnosis induction on EDA	40	-	-	the modified version of the Stanford scale	not measured	Lower number of nonspecific responses in the hypnosis condition than in the control condition.
Edmonston, 1968	effects of hypnosis on EDA	45	-	-	SHSS:B	HGSHS	The hypnosis group had lower number of spontaneous fluctuations than the control group. The groups did not differ in the number of electrodermal orienting responses.
Serafetinides, 1968	effect of hypnosis on EDA	1	-	-	-	not controlled	More frequent electrodermal responses during hypnosis compared

							to baseline.
Paul & Trimble, 1970	compared live and recorded hypnosis	30	-	-	eye fixation method	not controlled	EDA reduction during hypnosis, no difference between live or recorded sessions.
MC Ammond et al., 1971	effectiveness of relaxation and hypnosis training on stress reactions at the dentist	27	-	-	specific induction performed by the dentist	not controlled	High baseline EDA level subjects benefitted more from hypnosis and relaxation training.
Tebecis et al.,1976	EDA differences between hypnosis and awake conditions	33	Bi	palms	audio recorded self-hypnosis induction	controlled but not specified	EDA decreased during both hypnosis and control condition; however, there was a more substantial decrease in the hypnosis condition.
Bauer & McCanne,1980	effects of hypnosis on the ANS	12	Uni	medial phalanges of the index and fourth fingers	standardized audio recorded induction	HGSHS: A	Lower levels of nonspecific responses during hypnosis compared to post hypnosis. EDA was reduced in both simulator and hypnosis group.
Gruzelier et al., 1985	habituation to auditory stimuli in hypnosis	30	Bi	medial phalanges of the index and middle fingers	audio recorded eye fixation method	scale prepared for this experiment	Both high and low hypnotizables showed higher right-side skin conductance level. High hypnotizables had a lower number of nonspecific SCRs. High hypnotizables showed higher left side responses to tones during baseline compared to right side responses, and this was the opposite in hypnosis. High hypnotizables showed faster habituation to standard tones than low hypnotizables, and hypnosis had a suppressant effect on sensitization.
Gruzelier et al., 1988	differentiate between those who are in hypnosis and	18	Bi	medial phalanges of	Hypnosis induction was	Barber Suggestibility	Induction phase: higher left side SCL compared to the right side in the

	those who simulate hypnosis			the index and middle fingers	audio recorded	Scale	hypnosis group while the simulator group had higher right side SCL compared to left side SCL. Simulators showed more frequent nonspecific SCRs in the beginning stages of the induction. Hypnosis phase: both groups showed higher left side SCL. Habituation to tones facilitated in the hypnosis group, while retarded habituation characterized the simulator group.
Sturgis & Coe,1990	psychophysiological responsiveness during hypnosis	22	Uni	proximal phalanges of the non-dominant hand	the modified version of SHSS:C	HGSHS: A and SHSS: C	No baseline differences between high and low hypnotizables. No differences in EDA between high and low hypnotizables. Lower skin conductance during induction and dream suggestion than during other suggestions.
Kinnunen et al., 1994	detecting deception in the hypnotized	22	Uni	distal phalanges of the index and middle fingers of the non-dominant hand	-	HGSHS: A	No difference in SCR magnitudes between hypnosis and awake condition.
Paul et al., 1996	physiological effects of relaxation and hypnosis	60	Uni	dominant foot	eye fixation method	not controlled	Both relaxation and hypnosis produced lower SCL. Training effect reported in the hypnosis condition. Lower skin conductance in the second session than in the first session.

De Pascalis et al., 1999	psychophysiological effects of hypnotic analgesia	29	Uni	medial phalanges of the index and middle fingers of the left hand	Stanford clinical scale	SHSS: C	The fewer number of SCRs in hypnosis than in awake condition in response to pain stimulation. High hypnotizables had a lower number of SCRs than low hypnotizables. High hypnotizables had lower amplitude responses than medium and low hypnotizables. Higher amplitude responses for all in the waking condition than in hypnosis.
De Pascalis et al., 2004	evaluating the cognitive load of hypnotic analgesia	30	Uni	medial phalanges of the index and middle fingers of the left hand	Stanford clinical scale	SHSS: C	High hypnotizables had lower amplitude SCRs, in response to auditory stimuli in hypnosis, than medium and low hypnotizables.
Kekecs et al., 2016	effect of hypnosis on the ANS	121	Uni	medial phalanges of the index and middle fingers of the non-dominant hand	audio recorded WSGC	HGSHS: A	No differences between low and high hypnotizables. Lower SCL was found between pre and post induction in the hypnosis group compared to the music control condition.
Kinnunen et al., 2016	true hypnosis experience or complying	14	Uni	non-dominant hand	modified version of SHSS	HGSHS: A	In the hypnosis condition there was no difference in SCR amplitude between neutral and critical questions. SCR amplitudes differed in the control condition.

The studies are listed in chronological order. "N" –number of participants; "Uni" –unilateral measurement; "Bi"–bilateral measurements; HGSHS – Harvard Group Scale of Hypnotic Susceptibility [17]; WSGC–Waterloo Stanford Group Scale [5]; SHSS–Stanford hypnotic Susceptibility Scale [6].

The characteristic points related to hypnosis and EDA, based on the above results, may be summarized as below:

1. Regarding EDA levels, eight studies reported lower skin conductance during hypnosis compared to pre-hypnosis, post-hypnosis, or control conditions. Only one study observed a higher level of skin conductance during the hypnotic induction. Three studies found no difference between the skin conductance levels in hypnosis and control condition.
2. Many studies reported that the number of skin conductance responses (SCRs) or nonspecific SCRs were fewer during hypnosis than in control conditions. Others found that high hypnotizable individuals had less nonspecific SCRs than the low hypnotizable subjects. SCRs have smaller amplitudes in hypnosis, which is more prominent in high hypnotizables.
3. A research group published two studies with contradictory results regarding bilateral EDA.

1.1 Methodology in Hypnosis Research

Hypnosis research is riddled with methodological diversity. It would be most effective to use a standard induction procedure to ensure the reproducibility of results. Using standardized scales for measuring hypnotizability would also be beneficial to compare results.

From Table 1, it is clear that the standardized methodology of electrodermal measurements and reporting would be beneficial. Dawson (2007) [16] recommended taking the measurements from the distal phalanges of the index and middle fingers of the non-dominant hand. If those are unavailable, current studies have reported alternative measurement sites (see Kasos et al., under review). In the present study, we took the measurements from the wrists, as some of the test suggestions required use of both the hands, including fingers. SCR window should be set between 1 and 5 s after stimulus onset [15]. The minimum threshold for SCR amplitude should be set to the recommended 0.01 μS [14, 15].

Based on the above methodology, we hypothesized that:

1. SCL will reduce during the full hypnotic induction phase.
2. There will be fewer SCRs at the end of the induction compared to the beginning of the induction.
3. The above differences will be more prominent in those who are more susceptible.
4. There will be lateral differences in EDA during the hypnotic induction and during test suggestions, modulated by hypnotizability.

We performed a follow-up study to demonstrate that the most prominent effects found in Study 1 are reproducible.

2. Methods

2.1 Study 1

We recruited 38 university students as our subjects (N = 38, Mean age = 21.11, SD = 1.75), who were right-handed and had no prior experience in hypnosis. Exclusion criteria included the

presence of mental illness and the use of drugs and alcohol, based on self-reporting. All participants were Hungarians (Caucasian).

Procedure: Participants were invited to take part in a group hypnosis session, where their hypnotizability was measured with the HGSHS: A (Költő, 2015). On arrival, the participants were asked to fill out an informed consent form and briefed about the experiment. We attached the electrodermal sensors to their left and right wrists. The wrists were chosen as an alternative to the traditional palmar locations because certain test suggestions required both to be close together (finger lock and hands moving together), which could cause unwanted artifacts. Participants were asked to sit comfortably but as still as possible, to avoid movement throughout the EDA measurement. A certified hypnotist read the hypnosis script, in the presence of a co-hypnotist. After the hypnosis session, EDA sensors were removed, and the participants were asked to fill out our questionnaires. At the end, the participants were debriefed.

2.2 Study 2

We recruited 19 Hungarian university students as subjects (N = 19, Mean age = 21.58, SD = 4.07), who received course credit for their participation. This optional course was about test-anxiety reduction techniques, and one of the techniques, they could experience was hypnosis. Exclusion criteria included the presence of mental illness and the use of drugs and alcohol, based on self-reporting.

Procedure: participants filled out an informed consent form, in the beginning of the semester. Their hypnotizability was measured with the HGSHS:A on the same day. On the following five occasions, each two-weeks apart, electrodermal sensors were attached to the proximal phalanges of the middle and index fingers of their non-dominant hand. They were asked to sit as still as possible to avoid movement during the measurements. An audio-recorded hypnosis script was played for the participants. In all five sessions, hypnosis was induced according to the Hungarian version of the Stanford Clinical Scale (SCS) (Morgan and Hilgard, 1978–1979), followed by suggestions with the purpose of reducing test-anxiety. The SCS induction was chosen because it is shorter than the HGSHS used in the first experiment. It was an important criterion in keeping the interventions short. The hypnosis sessions lasted between 17 and 20 min. Once the recording was over, electrodermal sensors were removed.

2.3 Data Collection and Processing

Hypnotizability scores were based on participants' reactions to the suggestions in the hypnosis session. Based on the scores, they were divided into three hypnotizability groups—i) low hypnotizables with scores 4 or below, ii) medium hypnotizables with scores between 5 and 8, and iii) high hypnotizables with scores of 9 and above.

First, we measured raw skin conductivity every 125 ms for the first 10 min of the hypnosis session (induction phase) and during suggestions (hypnosis phase). EDA was analyzed in Ledalab 3.4.8 [18]. For smoothing, a Gaussian window was applied. SCL was extracted by optimized continuous decomposition analysis.

Next, we calculated subject-independent EDA measures for the detailed analyses of the induction phase of study 1. We aimed to reduce individual variability in electrodermal levels to detect lateral changes with time, a characteristic of the three hypnotizability groups. Thus, data

were standardized within individuals, using the average SCL values and the standard deviations (SD) of the 2 × 480 data points of induction phase from both wrists, to calculate the Z-scored EDA for every raw data point. Similarly, the number of SCRs was also standardized (Z-scored SCR) within individuals, using the number of SCRs in every two minutes of the induction phase measured from both wrists. The average number and SDs of SCR counts within the 2-minute intervals were used for calculating Z-scores.

Then, we calculated the laterality coefficient. This procedure standardized the values between −1 and +1. Negative numbers represent right side dominance, and positive numbers represent left side dominance [4].

Finally, we applied the analysis of variance (ANOVA) to test the effects of time, suggestions, hypnotizability, and laterality on psychophysiological responses during the induction/suggestion phase. The following EDA measures were dependent variables—Z-scored SCL, laterality coefficient values based on average SCL in every 2 minutes, and z-scored number of SCRs for each 2 minutes. We tested the within subject factors, time and side (left and right), as well as the between subject factor, hypnotizability (low, medium, and high).

3. Result

3.1 Study 1

3.1.1 Detailed Analyses of the Skin Conductance Level of the Hypnosis Induction

In the hypnosis induction phase, a standard set of preliminary instructions and suggestions are communicated to the individuals being hypnotized. The way people reach or fail to reach the hypnotic state is of vital importance; thus, we decided to analyze EDA responses to the first 10 min of the induction phase in a detailed fashion.

Based on the literature, we hypothesized a reduction in SCL during the hypnotic induction, especially in those who score high on the hypnotizability scale. The three-way mixed ANOVA on SCL during the 10-minute induction phase using side (left/right) and time as within-subject factors and hypnotizability (low/medium/high) as a between-subject factor, resulted in a prominent effect of time with $F(4,140) = 2.65$, $p = 0.036$, $\eta p^2 = 0.07$. The level of skin conductance decreased on both sides during the induction process in all three groups. Figure 1 depicts changes in Z-scored SCL during induction, averaged for the left and right hands of the three hypnotizability groups. There were no other main effects.

There were no significant two-way interactions. The analysis resulted in a significant three-way interaction of side, time, and hypnotizability with $F(8,140) = 2.49$, $p = 0.015$, $\eta p^2 = 0.13$. Low, medium, and high hypnotizables showed characteristically different EDA patterns on their left and right sides (Figure 1). The low hypnotizable individuals displayed right-side dominance, while high hypnotizable individuals displayed left-side dominance throughout the induction phase. On the contrary, the left- and right-side SCLs were similar in medium hypnotizables. High and medium hypnotizables showed lower EDA variability compared to that in the low hypnotizables. For the medium hypnotizables, SCL gradually decreased throughout the 10 minutes of induction phase. On the other hand, both low and high hypnotizable individuals showed variable EDA patterns within this timeframe.

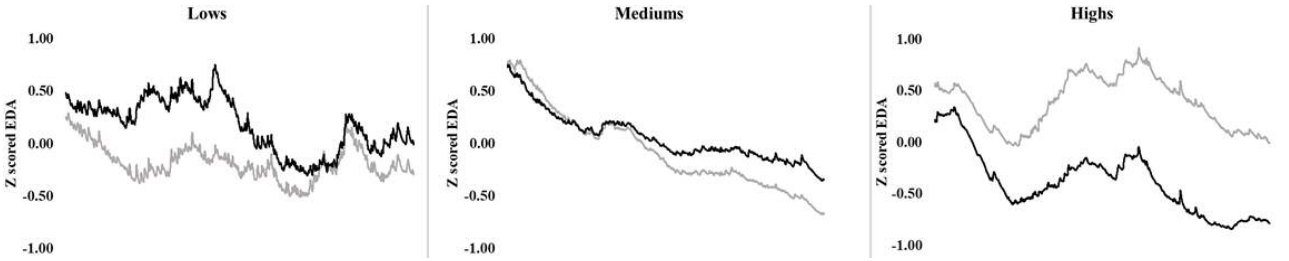

Figure 1 EDA during the induction (10 minutes). Black lines represent EDA measured from the right wrist. Grey lines represent EDA measured from the left wrist.

3.1.2 NonSpecific Responses

We predicted that fewer SCRs would characterize the end of the induction phase compared to the beginning of the induction. Findings from the literature also suggest less nonspecific SCRs in EDA patterns of high hypnotizables as compared to the low hypnotizables. Three-way mixed ANOVA analysis was performed on the number of Z-scored SCRs for every two minutes of the induction phase. We used time and side as within-subject factors, and hypnotizability (low/medium/high) as a between-subject factor. The results showed the main effect of time with $F\ (4,116) = 2.839$, $p = 0.027$, $\eta p^2 = 0.09$. There were no other significant main or interaction effects. The number of SCRs was reduced significantly during the induction, regardless of side or hypnotizability (Figure 2).

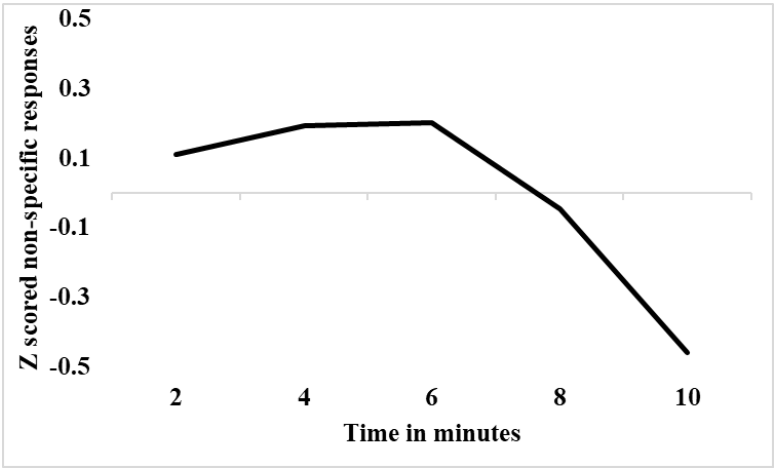

Figure 2 Z-scored nonspecific responses during every two minutes of the induction phase averaged for the two sides of EDA measurement (on the left side) and the three hypnotizability groups (on the right side).

3.1.3 Electrodermal Activity (EDA) Patterns during Test Suggestions

We hypothesized differences in EDA patterns of the three hypnotizability groups during hypnotic suggestions. First, we used a two-way mixed ANOVA to test raw SCL measured from the right-side. The nine suggestions were used as the within-subject factor, and hypnotizability was used as the between-subject factor. The results displayed a significant main effect of suggestions with $F\ (8,272) = 6.00$, $p < 0.001$, $\eta p^2 = 0.15$. The level of arousal changed significantly from one test

suggestion to the other. A suggestion hypnotizability interaction effect was also found, $F(16,272) = 3.14$, $p = 0.001$, $\eta p^2 = 0.16$ (Figure 3, left side).

We also analyzed differences in EDA patterns during hypnotic suggestions on the left side, using the three hypnotizability groups. Similar to the right-side results, the two-way mixed ANOVA, with the suggestions as the within-subject factor and hypnotizability as the between-subject factor, yielded a significant main effect of suggestions with $F(8,256) = 4.53$, $p < 0.001$, $\eta p^2 = 0.12$. A suggestion hypnotizability interaction effect was also detected, $F(16,256) = 3.14$, $p = 0.001$, $\eta p^2 = 0.14$ (Figure 3, right side).

These results demonstrated that EDA changes significantly during the different test suggestions and that this change is modulated by hypnotizability.

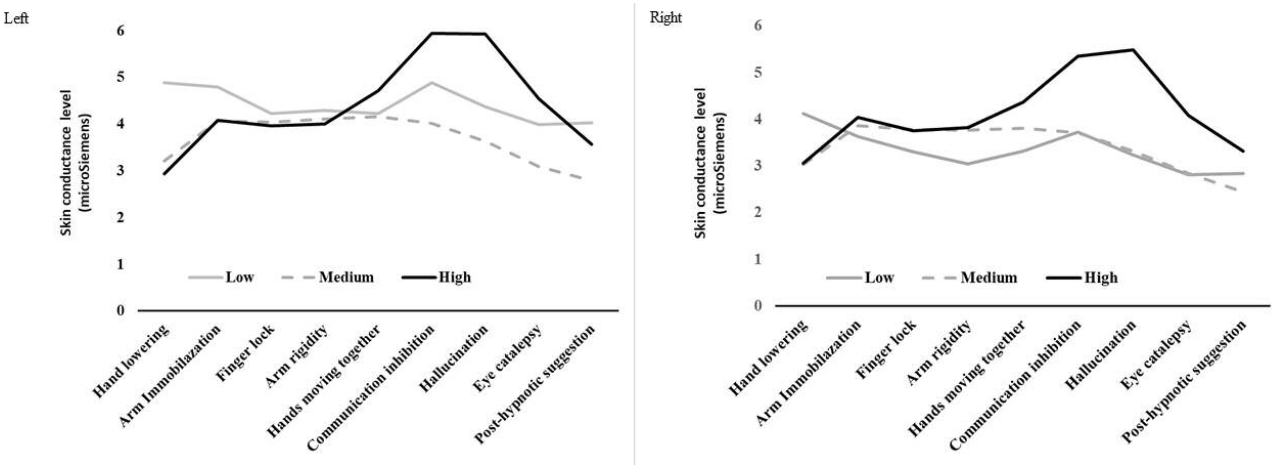

Figure 3 SCL during the test suggestion phase, measured from the left and right sides.

3.1.4 Laterality during Test Suggestions

We hypothesized lateral differences during the suggestion phase of hypnosis, modulated by hypnotizability. To test this hypothesis, we applied two-way mixed ANOVA. We used average laterality during the test suggestions as the within-subject factor and hypnotizability as the between-subject factor. They yielded no significant effects (Figure 4). Electrodermal laterality does not seem to change significantly from suggestion to suggestion. Also, there is no significant difference among the hypnotizability groups. Although, it is clear from Figure 4 that high hypnotizables remained left-dominant throughout the hypnosis, while medium and low hypnotizables were right-side dominant.

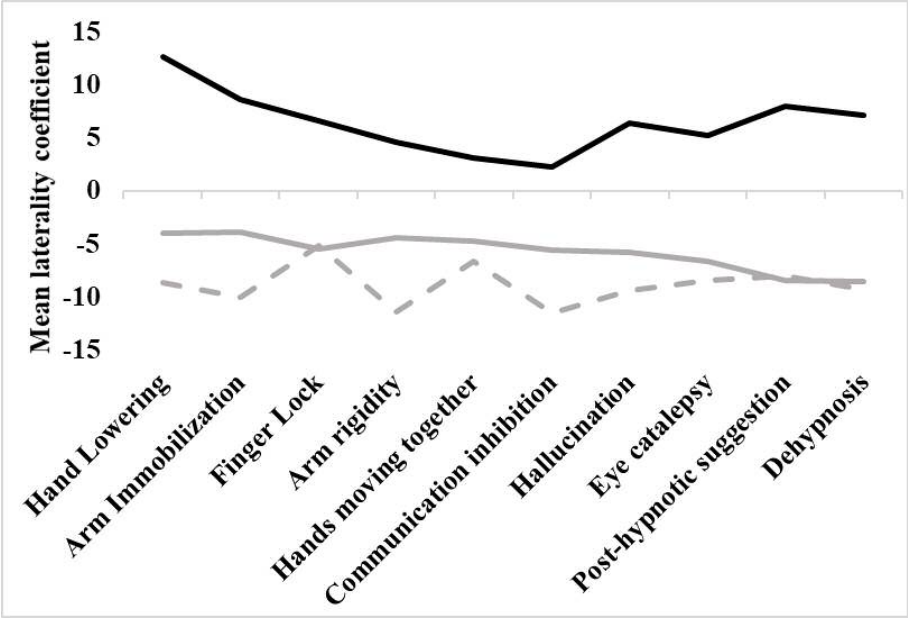

Figure 4 The laterality coefficient during the test suggestion phase. Positive numbers represent left side dominance, while negative numbers represent right side dominance.

3.2 Study 2

We performed a follow-up study to show the reproducibility of the most prominent effect found in study 1, namely, the gradual decrease in the level of skin conductance during hypnotic induction. We also examined the differences in this decrease in high, medium, and low hypnotizables. Two-way mixed ANOVA was calculated for each of the five sessions (Figure 5). We found no significant effects of hypnotizability in any of the sessions. The main effect of time was clear in the first session [$F(3,10) = 7.32$, $p = 0.006$, $\eta p^2 = 0.42$], the second session [$F(3,13) = 5.90$, $p = 0.026$, $\eta p^2 = 0.31$], the third session [$F(5,70) = 6.08$, $p = 0.012$, $\eta p^2 = 0.30$], and the fifth session [$F(6.72) = 5.48$, $p = 0.015$, $\eta p^2 = 0.31$]. The fourth session on the other hand yielded no significant effect of time; although, this result could probably be due to the high variability of SCL. As seen in Figure 5, there was a gradual decrease in the average SCL during the induction phase, characteristic for all the hypnotizability groups, except for the low hypnotizables in session 4.

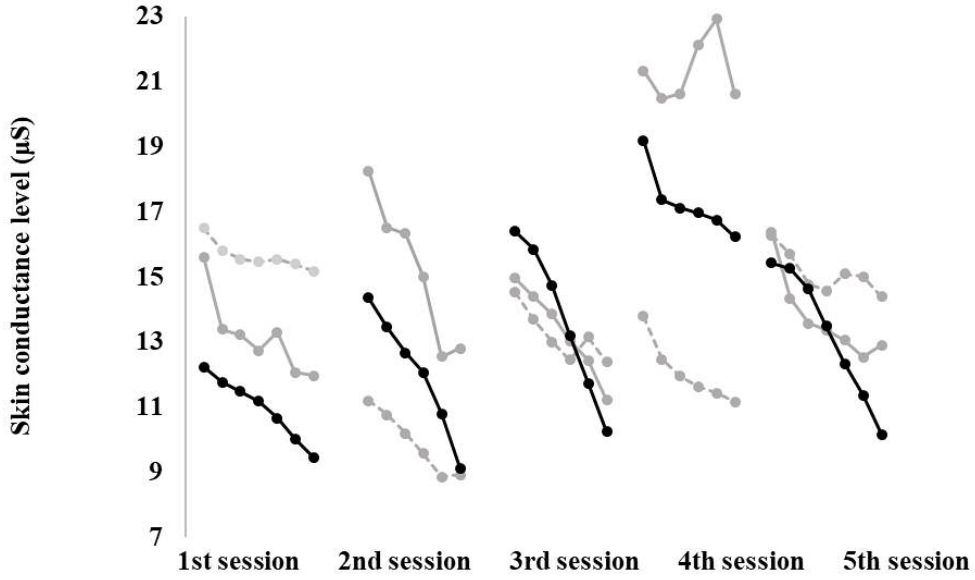

Figure 5 Skin conductance level during the induction period of the five hypnosis sessions of the experiment. Solid black lines represent high hypnotizables, dashed grey lines represent medium hypnotizables, and solid grey lines represent low hypnotizables.

4. Discussion

4.1 EDA Levels during the Induction Phase

By measuring electrodermal activity in the induction and/or test suggestion phases of hypnosis, we identified typical electrodermal attributes related to the hypnotic state. The most prominent of these characteristics is the reduction in skin conductance level (SCL). Several studies have reported similar conclusions (Table 1).

During hypnosis induction, we observed a consistent decrease in skin conductance level across the 10-minute induction phase (Study 1). This effect was bilateral and characteristically different for the three hypnotizability groups. For the low and high hypnotizables, a variable electrodermal activity (EDA) pattern was detected; whereas, in medium hypnotizables, EDA gradually decreased throughout the induction phase. Reduction of arousal in hypnosis may be one of the important factors leading to therapeutic success in treating disorders associated with higher sympathetic arousal [7].

In our follow-up study (Study 2), we intended to reproduce the above findings. Five consecutive measurements from the same subjects demonstrated that the EDA reduction effect of the hypnotic induction remained pronounced for all hypnotizability groups (Figure 5).

4.2 EDA Laterality during Hypnotic Induction

Our results show evident bilateral differences during the hypnotic induction phase. High hypnotizables display left-side dominance, while low hypnotizables display right-side dominance. A number of previous studies had also highlighted these bilateral differences [19, 20]. Our previous study also reported lateral differences during active-alert induction [4].

The medium hypnotizables showed a synchronous EDA activity of the two sides (Figure 1). Picard and colleagues (2015) [21] suggested a high correlation between the left and right sides with respect to EDA [21]. This high correlation has been confirmed in a number of studies (Kasos et al., under review) [13].

However, in high and low hypnotizables, EDA diverged on the two sides and stayed separated for the whole duration of the induction phase (Figure 1). The divergence of the two sides could be an indication of psychological distress. Picard observed right-side dominance in situations when the self was threatened [21]. Translating this to a hypnosis situation for low hypnotizables, they could be experiencing induction as a threatening situation, having to give up control to the hypnotist. This may be causing them to be distressed.

In contrast, high hypnotizables showed a strong left dominance (Figure 1). This may be explained by the multiple arousal theory [21]. According to this, positive emotions would cause EDA to be either close to synchronous or left-side dominant. For high hypnotizables, the induction process could be a positive experience. In addition, Gruzelier's induction theory hypothesizes left-side hemispheric dominance at the beginning of induction [22]. Another study focuses on the verbal processing of induction, which in right-handed subjects would lead to left hemispheric dominance [23]. The amygdala is the foremost contributor to EDA and is mostly concerned with processing emotional information [24]. Hence, we hypothesize a strong emotional component behind the observed lateral differences during the induction process.

4.3 EDA Levels and Laterality during Test Suggestions

During test suggestions in Study 1, we observed that arousal levels fluctuated from one suggestion to the other, as reported previously [25]. The arousal level of high hypnotizables was higher during the hallucination suggestion and communication inhibition suggestion, confirming the findings from prior research [26]. Elevated levels of arousal may be explained by the pronounced cognitive effort required in responding to these suggestions. This implies that responding to suggestions requires considerable effort, as suggested by proponents of the dissociative experience theory and the social cognitive theory [27, 28].

Contrary to the induction phase, lateral disposition during test suggestion was not significantly different among the three hypnotizability groups. Figure 3 shows that high hypnotizables remain left-side dominant, while medium and low hypnotizables remain right-side dominant for the whole duration of the suggestion phase. The suggestions, which are harder to respond to, such as hallucination, cause a more prominent left dominance in high hypnotizables.

The above results imply that responding to more difficult suggestions, such as hallucinations and communication inhibition, comes with a price that high hypnotizables showing higher arousal and a more left-sided electrodermal activation.

4.4 Non Specific SCRs

We hypothesized that a lower number of nonspecific skin conductance responses (SCRs) would be present at the end of the induction phase compared to the beginning. We also predicted that this effect would be modulated by hypnotizability. Our study confirmed that SCRs are fewer at the end of the induction. However, we found no evidence for differences based on hypnotizability. A reduced number of nonspecific responses could be explained by the nature of the hypnotic

induction. During the induction, attention is mainly focused on the hypnotist and the inner experiences, with reduced peripheral awareness, resulting in fewer non-intended responses.

5. Limitations

The limitations of the present paper include the homogeneity of subjects in terms of their gender, age, and race. Our research could have benefitted from a higher number of participants.

6. Conclusion

In this article, we review the correlation between hypnosis and electrodermal activity (EDA) from the past 90 years of studies. We report the laterality and hypnotizability effects of electrodermal activity, during hypnotic induction and suggestion phases.

Most studies have highlighted lowered skin conductance level (SCL) during hypnosis, than pre- or post-hypnosis or in control conditions; however, contradictory findings have also been reported. In our study, we observed a prominent, bilateral reduction of SCL throughout the hypnotic induction phase, regardless of the level of hypnotizability. We also replicated this effect consistently in five independent hypnosis sessions.

Only a couple of studies have previously investigated bilateral EDA during hypnosis, with contradictory results. Our results highlight substantial differences in laterality during the hypnotic induction phase, with patterns characteristically differing depending on hypnotizability. Laterality differs throughout the hypnosis phase—high hypnotizables remained left-side dominant, whereas, medium and low hypnotizables were right-side dominant.

Nonspecific skin conductance responses (NS-SCRs) appear spontaneously, not related to any specific event. According to literature, the number of theseNS-SCRs is fewer during hypnosis than in control conditions. We, too, observe a decreasing number of SCRs in the induction phase. NS-SCR frequency typically shows great individual variety, with high levels of arousal, resulting in a higher frequency of NS-SCRs. Also, some findings indicate that high hypnotizables have less NS-SCRs than low hypnotizables. In contrast, we found no evidence for differences in the rate of NS-SCRs in relation to hypnotizability.

We conclude that arousal is reduced bilaterally during hypnotic induction and is persistent across different levels of hypnotizability. At the same time, lateral differences produce unique EDA patterns in the induction phase, defining high, medium, and low hypnotizables. The post-induction phase produces EDA that varies with suggestions. Typically, difficult suggestions produce higher arousal. Thus, our findings are novel, in terms of lateral differences of EDA in high versus low hypnotizables in the hypnotic induction phase. These results provide an objective, psychophysiological evidence for both, the multiple arousal theory and the left-side hemispheric dominance suggested by the induction theory of hypnosis.

On the basis of our findings, we strongly support that bilateral measurements should be used in hypnosis research. The ability to analyze laterality differences adds valuable information regarding the experiences of hypnosis participants. The changes that take place in a matter of a few minutes, altering one's state of consciousness, make hypnosis induction a magnificent model situation to study electrodermal laterality.

Acknowledgments

This work was accomplished with support of the Hungarian Academy of Sciences (through project: LP-2018-21/2018). We highly appreciate the opportunity to use Obimon EDA prototype devices in our study and are most grateful for all technical support of Obimon Systems Ltd. We appreciate the support of the Faculty of Education and Psychology, ELTE Eötvös Loránd University, Budapest, Hungary, and support of the Hungarian Ministry of Human Capacities through the student scholarships awarded to Luca Csirmaz and Szabolcs Zimonyi by the New National Excellence Program. We would like to thank Éva Bányai, András Költő, Balazs Nyíri (the hypnotists) for their support, and Alexandra Kasos for her invaluable comments on the manuscript.

Author Contributions

Krisztian Kasos: data collection, data analysis, statistical analysis, prepearing and writing manuscript. Luca Csirmaz: data collection, data analysis, writing and contributing to manuscript, Fanni Vikor: data collection, data analysis, contributing to manuscript, Szabolcs Zimonyi: data collection, Katalin Varga: providing essential theoretical knowledge regarding hypnosis, organizing and supervising hypnosis sessions, Anna Szekely: statistical analysis, writing and prepearing manuscript.

Funding

Hungarian Academy of Sciences (through project: LP-2018-21/2018).

Competing Interests

The authors have declared that no competing interests exist.

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Chapter 3: Discussion

The goal of this dissertation was to thoroughly examine the merit of multi-site measurements of electrodermal activity as a valuable index of emotional arousal in the framework of recent theories of electrodermal activity, with a special focus on the Multiple Arousal Theory, proposed by Rosalind W Picard in 2015. Five empirical studies were conducted (including 9 experiments, N = 368) to validate, explore and test methodological and theoretical aspects of the electrodermal activity changes in real time, linked to emotional arousal, evoked by various stimuli (e.g. laden musical stimuli or hypnotic induction). But as my results show, a simple task, such as taking a deep breath can be quite useful in validation of various methodological issues regarding novel EDA measurement systems. **Study 1** in this dissertation is the first attempt in the literature to systematically and rigorously validate an EDA measurement system, using human subjects and a wide range of psychologically significant stimuli. Moreover, it is the first study to publish group measurement data showcasing a wireless system capable of time synchrony, which could open up a new era of large-scale data collection, an aspect which is essentially missing from the EDA literature. In **Study 2** I've moved away from the "one true EDA" traditions with respect to measurement locations, comparing simultaneous EDA activity changes in real time from 10 measurement sites. This was the first study that investigated bilateral comparisons of traditional and alternate measurement locations. Results of the study partially confirmed existing results, that showed the traditional measurement sites as the most responsive (Payne et al., 2016), but also revealed new insights regarding correlations between the non-dominant fingers and other measurement locations. This was also the first study to assess response latencies at alternate measurement locations, which, again is an important methodological issue that (if miscalculated) could undermine psychophysiological findings. In studies 3, 4 and 5, I tested theoretical concepts of EDA with relation to different levels and state of consciousness. Using short musical segments that convey different emotions in **Study 3** I tested and expanded predictions of Multiple Arousal Theory regarding the electrodermal phasic activity and dermatomes to the lower body. **Study 4 and 5** contributes to our knowledge regarding how hypnosis affects electrodermal activity in both active alert and traditional hypnosis. My findings highlight that EDA patterns are characteristically different in the hypnotic induction phase for those participants, who can be characterized with low hypnotizability as compared to high hypnotizables. These results are novel in the hypnosis literature. Furthermore, they link the Multiple Arousal Theory with

hypnosis theories, explaining the effects of this specific altered state of consciousness in a psychophysiological context.

It makes a difference: open source EDA system that allows real-time measurements

Group measurements are but missing from EDA literature in fact there was only 3 studies in the past that presented group data (Asheim, 1951; H B Kaplan, 1963; Howard B. Kaplan, Burch, Bloom, & Edelberg, 1963). This dissertation includes 4 experiments with group measurements, doubling the number of existing experiments using group measurements. **Study 1** reports validation of a new open source EDA device (OBIMON) capable of group measurements. Apart from specific methodological issues, such as time synchronization, basic features of the Obimon, such as the fact that no wires are used makes it feasible for this type of data collection. We conducted three experiments to test the validity of the system. During this diligent device validation, we used a broad spectrum of stimuli, common in psychological experiments. Our results showed that Obimon measures EDA in agreement with a research grade device (Nexus) that has been often used in psychological research. Group measurements are important because they can speed up data collection. Measuring in a group setting can also reduce experimental noise created by differences in the environment and with this enhance the precision that is essential in research. Group measurements can also help to collect data during group interactions, opening the door to measure group cohesion and group dynamics objectively. EDA measurements could be valuable indicators in identifying individual differences. Obimon could be used in a group setting to measure a large number of individuals, during the presentation of the same stimulus and in the same environment, to pinpoint individual characteristics.

Utilizing the Obimon Android application, real-time visualization of skin conductance changes of multiple participants is also possible. It could be extremely useful in a therapy session, where real-time monitoring of emotional changes is relevant (for example in hypnotherapy). Obvious advantage of such capability could be imagined in a novel lie detection paradigm too, where the person withholding information could be “spotted” based on his/her EDA signal changes, different from other, “naive” individuals. To my knowledge, this special “group-design” lie detection paradigm is not present yet in the current lie-detection literature. Our research group did carry out such experiments using Obimons, however, handling individual differences of EDA is a challenge, especially in a real-time setting, where baseline is not that obvious.

Most electrodermal measurement systems in this field are closed source and quite expensive. They often require with the financial burden of purchasing the software which cannot be modified. Obimon system makes EDA measurements cost effective and research friendly, as the open source software and hardware allows researchers to tailor the system to their individual needs.

Is there only one true EDA?

Traditionally electrodermal activity data is collected from a single site, as the unilateral measurement approach suggests that arousal is the same across the body at a given time. Most handbooks highlight that this single measurement site should be the non-dominant hand, as participants are often required to do something (e.g. press a button) with their dominant hand. However, this assumption has been challenged recently by the Multiple Arousal Theory, which suggests that EDA may vary on different dermatomes, depending on certain situational factors and the person's actual psychological state. Previous research suggests that right-left asymmetry of bilateral EDA is apparent in patients with schizophrenia and depression (Bob et al., 2007). Moreover, a vast amount of research suggests that EDA could be a key indicator in detecting epileptic seizures (Onorati, Regalia, Gaborni, & Picard, 2016; M. Z. Poh et al., 2012; Ming Zher Poh et al., 2012). Interestingly, over the years of data collection, one of our own research participants experienced an epileptic episode, while wearing the Obimon devices (measurements were taken from the wrists) Apart from the huge elevation in arousal during the episode, we also witnessed a massive laterality shift towards the right. This example suggests that laterality differences in EDA may carry invaluable information about the state of the central nervous system. Nonetheless, EDA research currently uses unilateral measurements predominantly, and studies comparing of different measurement sites are scarce.

Study 2 of my dissertation is the first study that explored alternate measurement sites bilaterally and compared them to the traditional non-dominant finger location, providing essential information how SCL, SCR and SCR latency relates to the non-dominant fingers' location. In the first experiment, we measured EDA from 5 locations bilaterally (fingers, feet, wrists, calves and shoulders) during a breathing exercise and during presentation of an auditory stimuli. In the second experiment we measured EDA during a 3-minutes-long musical stimulus and during the presentation of computer-generated tones. Our results revealed that the dominant fingers and both feet show a high degree of correlation with the non-dominant fingers. The fingers and the feet were the most responsive sites to psychologically significant

stimuli in this laboratory setting. The alternate measurement sites were less responsive and showed a lower degree of correlation with the non-dominant fingers. Latencies were longer on the lower body compared to the upper body. Response amplitudes, correlations were reproducible in a few days later. These results provide practical information to be used in further EDA research. We recommend using bilateral palmar or plantar locations in psychological experiments in a laboratory setting, if multi-site measurements are not possible. If hands are not available, then the wrists and calves could be used after adequate hydration time. Although, hydration time did not affect measurements taken from the wrists, prolonged hydration time improved correlation and response frequency measured from the calves.

In order to prove reproducibility of our results, we conducted a follow up experiment using emotionally laden musical stimuli and computer-generated tones. The same participants were exposed to emotional stimuli and computer-generated tones 3 days apart. Based on the results of this follow up experiment, we may conclude that response amplitudes and correlations were reproducible within individuals. Skin conductance latencies on the other hand showed excessive variability.

According to the one arousal model of EDA, differences between the traditional measurement locations and alternate locations would depend on the number and activity of the sweat glands. An alternative explanation of the above results from Study 2 would implicate that the sweat glands of specific measurement sites might have more of a thermoregulatory role than an emotional sweating role. The lower correlation between alternate sites and the non-dominant fingers (which are in many cases negative correlations) support the notion that the level of arousal may indeed be different across the body. Our results are in line with novel findings from the EDA literature, suggesting that it is possible to have rising and falling arousal at the same time measured across different parts of the body. Findings in Study 2 could be interpreted in support of Multiple Arousal Theory, which predicts different arousal in dermatomes depending on individual differences in underlying emotional and cognitive processes. If different dermatomes do not show the same activity, they may correspond to different underlying neuro generators. Other results also support this hypothesis. In a sleep-study for example, sleep storms were detected on the wrists but not on the fingers (Sano, 2014). These results fall in line with the notion that the fingers or feet seem the most responsive during awake conditions, but in an altered state (such as sleep) the wrists become more responsive. Different psychological states may be responsible for the way different dermatomes respond. Our lab investigated EDA in active alert hypnosis and showed that the shoulders become just

as responsive as the fingers. The difference could be attributed to extra hydration time; however extra hydration time did not improve responsiveness of the shoulders in our follow up experiment in Study 2.

Main conclusion from these results is that some of the alternate measurement locations become responsive in an altered state of consciousness, as compared others. These findings clearly undermine the traditional "one true arousal theory".

Multisite EDA responses to emotional musical stimuli underly the Multiple Arousal Theory

In **Study 3** bilateral EDA was measured from the upper and lower body during the presentation of emotion laden short musical segments. This was the first study that compared lateral and dermatome differences in response to emotionally laden musical stimuli. Our results show differences in electrodermal response laterality among musical segments conveying different emotions. These results are partially in line with findings of Banks and colleagues (2012). Differences in the results may be due to differences of stimuli used in our study. Prior research found that different type of stimuli aiming to elicit similar emotions (emotions induced by visual stimuli vs. emotions induced by memories) brought about different central activation (Reiman et al., 1997). These seemingly contradictory findings may not be contradictory if put in the context of the Multiple Arousal Theory. Different central activation may cause different peripheral activation even if the emotion aimed to be elicited is the same. Our results also revealed differences between the upper and lower body in electrodermal laterality.

To summarize, results of Study 3 are important for at least two reasons:

1. This is the first experiment that tested the predictions of the Multiple Arousal Theory on skin conductance responses.
2. The study extends predictions of the Multiple Arousal Theory to the lower body. Negative emotions seem to produce an opposite response on the feet compared to the fingers, however positive emotions produce similar laterality on the feet and fingers.

Connecting subjective hypnotic experience to bilateral electrodermal changes

Unilateral measurements thus far were inconclusive regarding the effect of hypnosis on electrodermal activity (see an extensive literature review on the topic in publication linked to Study 5). In **Study 4**, we tested the hypothesis that differences in bilateral measurements can differentiate between different levels of hypnotizability and condition. In this study we measured EDA bilaterally in a within subject design using two conditions: measurement took place during an active alert hypnotic induction and during a music control condition. This was the first study that connected subjective hypnotic experience to bilateral electrodermal changes.

Our results show that in high and low hypnotizable individuals EDA laterality is different in the control and hypnosis condition. According to our results the same individuals can present significantly different EDA laterality depending on the situation, whether it is a music control condition or a hypnotic induction. High and low hypnotizables also showed different EDA levels, depending on the situation. High hypnotizables showed higher levels during the induction and lower levels during the music condition while low hypnotizables presented the opposite pattern. Those who showed a more significant shift towards right side dominance during the induction, reported changes in experiences that describe an altered state of consciousness.

These results imply that EDA laterality can significantly and systematically change during the course of the day. The two sides may diverge or converge depending on the interaction of individual predisposition and situations. These results confirm the existence of multiple arousals, and also point out that the hypnotic induction is a good model situation to study EDA multi-laterality.

Furthermore, bilateral measures add an additional dimension to data analysis, and critical insight into how the active alert induction effects the electrodermal system. We showed using bilateral measures from an alternate measurement location (the shoulders), that high and low hypnotizables respond differently in different conditions.

These results not only support the predictions of the Multiple Arousal Theory, but also contribute to theories of hypnosis. Theories of what hypnosis is, and what processes are behind the phenomena can be divided into two major lines of thought. State theorist and those who believe there are social psychological factors behind hypnosis.

State theorists think of hypnosis as an altered state of consciousness. They believe that there are differences between how much people are susceptible to suggestions. They called this trait hypnotizability or hypnotic susceptibility. This trait seem to be stable over time (Piccione et al., 1989). State theorist aim to prove that there is a genuine change during hypnosis, thus they are searching for a psychological marker that could prove the fact that someone is indeed in this altered state of consciousness (Barušs, 2003). Persuasive evidence for state theory comes from research that utilizes physiological evidence (J. H. Gruzelier, 1985; J Gruzelier, 1998; John Gruzelier, Brow, Perry, Rhonder, & Thomas, 1984; John Gruzelier, Gray, & Horn, 2002; Raz, 2005; Raz & Campbell, 2011; Raz, Fan, & Posner, 2005; Raz, Kirsch, Pollard, & Nitkin-Kaner, 2006). On the other hand, some considers hypnosis brought about by social psychological factors such as beliefs, attitudes, expectations, and roleplaying.

According to our results the hypnotic induction effects the electrodermal system markedly different for low and high hypnotizables. Thus, these results imply that there is a qualitative difference between high and low hypnotizables. These results support the state theory and the notion that hypnosis is indeed an altered state of consciousness.

Hypnotic induction causes lateral differences on wrist EDA during traditional hypnosis

Study 5 I was curious if laterality differences between different hypnotizables are present during traditional hypnosis and if these differences could be captured on other dermatomes as well besides the shoulders. In Study 5 we measured EDA bilaterally from the wrists during traditional relaxational hypnosis. Our results show bilateral differences among high, medium and low hypnotizable individuals during the hypnotic induction. We revealed differences in EDA levels among different hypnotizable groups during the test suggestion phase. We confirm the hypothesis that the hypnotic induction causes lateral differences among individuals with different levels of hypnotizability. The individual predisposition will determine the direction of the divergence or convergence of EDA of the two sides of the body. We also showed that non-specific responses decrease regardless of hypnotic ability. We also confirmed that the hypnotic induction reduces electrodermal activity regardless of hypnotizability. However, during the test suggestion phase EDA is dependent on the interaction of hypnotic ability and the nature of suggestions. Those who score higher on the hypnotic susceptibility scale show higher arousal during suggestions that are harder to respond to. The hypnotic induction can produce markedly different EDA laterality between low and high hypnotizables. Differences in laterality come about in a matter of a few minutes. These results

provide further evidence that the hypnotic induction is a good model situation to study bilateral differences in electrodermal activity.

Central asymmetries of emotion processing

Importantly, our peripheral findings coincide with EEG frontal asymmetry relating to emotional processing. EEG results suggest cortical frontal hemispheric preference of different emotions. Some of these asymmetries are present at resting levels (Coan & Allen, 2003, 2004). There are results providing evidence that left dominant frontal EEG asymmetry correlates with a more approach driven behavioural activation system while a right dominant EEG frontal asymmetry correlates with tendencies toward withdrawal, avoidant behaviour (Coan & Allen, 2004). According to findings, greater left activity at rest is associated with more intense positive affect in response to positively valanced stimuli, while those with greater right activity responded with a greater negative effect to stimuli involving negative affect especially fear (Coan & Allen, 2004). Emotional movie clips that conveyed happiness for example, were associated with greater left frontal activity in adults. Disgust films elicited greater right temporal anterior activity compared to baseline. Similar pattern of activity was also observed in infants and toddlers (Tomarken, Davidson, & Henriques, 1990). Hemispheric frontal imbalances may also play a role in psychopathology of some affective disorders such as depression and anxiety. In general, greater resting right frontal activity is associated with scores obtained on the Beck's Depression Inventory. Evidence suggests that this association between right frontal dominance is present from early childhood, for example infants with depressed mothers show higher right frontal activity (Henriques & Davidson, 1990, 1991; Schaffer, Davidson, & Saron, 1983). Furthermore, anxious apprehension is associated with greater relative left activity. Anxiety may be associated with both greater left or right frontal activity or relatively greater right parietal activity depending on the anxious apprehension, anxious arousal and negative affect (Coan & Allen, 2004). These findings support our results that some emotions show lateral asymmetries. The general consensus is that positive emotions have greater left and negative emotions have greater right frontal cortical activation, which is in line with our electrodermal findings, and provide central support for our conclusions.

General conclusion

The electrodermal system's complex nature has been overlooked up until recently. Current understanding of the way this system behaves under different circumstances is limited by the one arousal model of electrodermal activity. Results from Studies 1-5 outlined in this dissertation confirm, that arousal is not uniform across dermatomes. This statement has been attested for both major components of EDA (SCL and SCR). We also conclude that there are dermatome differences in SCR, and the lower and upper body shows a different pattern of responses to the same emotional stimulus. Our findings clearly support the notion, that electrodermal activity levels on different dermatomes converge or diverge bilaterally, depending on the situation and psychological predisposition of the individual.

In an altered state of consciousness, alternate measurement sites proved to be very useful in differentiating people with different hypnotizability, both in active alert and traditional hypnosis. During the hypnotic induction, the left and right side diverged in a markedly different pattern in low and high hypnotizables. Since these differences have now been confirmed, multisite measurements are necessary for the further understanding of the nature of this complex system. For this reason, further exploration of alternate measurement sites and dermatomes are needed, using diverse stimuli and different psychological states.

The one arousal model entrenched the idea of the one channel recording of EDA. This dissertation questions this practice. We call for multi-site measurements in both laboratory and ambulatory recordings. In an ideal situation all dermatomes should be mapped and recorded. To accomplish this, we need recording systems that are small, wireless and comfortable to wear. Until such time this idea takes hold, we should at least take bilateral measurements.

Future directions

Future studies should focus on mapping all dermatomes in paradigms, that not only use different emotional stimuli, but also manipulate the psychological state of the participants. For example, a recent study measured bilateral EDA while exposing the participants to a high-stake situation (Bjørhei et al., 2019). These measurements were carried out in a laboratory.

Since ecological validity of laboratory experiments have been questioned, I believe that measurement could be carried out outside of the laboratory to increase ecological validity of findings.

Future device development should consider the use of accelerometer in order to filter out movement artefacts automatically. This issue becomes especially important when measurements last for hours or days in an ambulatory setting and visual inspection becomes cumbersome. Using group measurements with a lot of participants, registration of movements based on researcher observation is impossible. And although EDA patterns clearly show movement artefacts that could (and should) be processed after recording, the number of files to be inspected could reach thousands, which takes a lot of time and effort. Although there are attempts to filter out artefacts using algorithms, a more certain way is to record movements via an accelerometer while recording EDA and use the accelerometer date to clean movement artefacts from the EDA data. Obimon Systems, for example solved this problem by installing an accelerometer in their newest device version. With such a tool, visual inspection becomes unnecessary and automated artefact filtering will be kept to a constant standard.

I propose that in the near future EDA recording methods could take the form of a multichannel recording setup, similar to the common practice of EEG recordings used today. My results call attention to the need of a paradigm shift in electrodermal research. The traditional view of uniform arousal measured by EDA ought to be re-evaluated, and a new paradigm based on the Multiple Arousal Theory should be considered.

Limitations

In some of the experiments we measured EDA in a group setting, which is an innovative way to collect data, however we cannot exclude the possibility that group measurements change some of the aspect of the experiment. For example, motivational states of our participants may change as the size of the group increases or decreases. Moreover, social pressure such as compliance, conformity may affect the arousal state of our participants. Our lab also investigates electrodermal synchrony among participants and we cannot exclude the possibility of electrodermal synchrony effect among our participants. These issues surrounding group measurements should be investigated in the future.

Author's note: All data regarding this dissertation is available upon request from the author (email: kasos.krisztian@ppk.elte.hu).

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