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Lateral asymmetry of emotional arousal as a biomarker of attributional style during darts competitions

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Abstract
According to the Multiple Arousal Theory, electrodermal activity (EDA) is not uniform across the body. However, the psychological meaning of a left or right-sided EDA dominance is still not clear. We explored EDA lateral asymmetry as a psychophysiological marker of optimistic and pessimistic attributional style regarding success and failure in a darts competition. Bilateral EDA pattern of 230 throws of a competing pair was measured by Obimon EDA including accelerometer measurements of movements. First, we confirmed that lateral asymmetry can be measured reliably based on EDA data from both wrists. Second, we assessed attributional styles related to lateral asymmetry based on 80 individual throws. We recorded participants' expectations regarding their upcoming performance, and their attribution of success and failure based on Seligman's definition as *optimist (*internal cause attributed to success, or external cause ascribed to failure) or *pessimist*. The ratio of optimist and pessimist attributions was significantly different for throws with right or left-sided EDA dominance ($p = 0.001$). Optimistic attribution characterized 84% of right dominant, while pessimist 63% of left-dominant EDA during throws. We replicated these findings on 50 throws from 10 more individuals ($p = 0.034$). All individuals were right-handed. We conclude that wrist EDA can be reliably measured during physical movements, such as in a darts game. Lateral EDA asymmetry is a consistent psychophysiological marker of the attitude toward success and failure in a competitive setting, suggesting that lateral asymmetry of emotional arousal may serve as a novel psychophysiological biomarker for attribution style. Results underlie the psychophysiological relevance of bilateral arousal assessment and provide evidence-based verification for the Multiple Arousal Theory.

Keywords Emotional arousal · Electrodermal activity · EDA · Laterality · Darts · Attribution

Introduction

Galvanic skin response to stimuli evoking arousal was discovered more than 150 years ago. Eccrine sweat gland activity of dermatomes across the body elicited by the activation of the autonomous nervous system can be measured reliably using electrodermal sensors (Tronstad et al. 2022). Although there are still some uncertainties about both underlying mechanisms and biological function of "emotional sweating" linked to the elevated arousal state, it has been used in various aspects of emotion research. The rewarding aspects of listening to music, for example, were associated to prominent changes in emotional arousal (Salimpoor et al. 2009). Electrodermal activity (EDA) has been used extensively as a biomarker of emotions in both clinical and applied research. Electrodermal hyporeactivity proved to be a valid marker for both depression and suicidal risk (Sarchiapone et al. 2018; Thorell et al. 2013). Reduced skin conductance level in response to breathing manipulation suggests a loss of functionality of the autonomic nervous system in fibromyalgia syndrome (Reyes del Paso and de la Coba 2020). Rosalind Picard and her colleagues have identified autonomic footprints that could provide reliable biomarkers to identify patients with epilepsy who are at risk of sudden unexpected death (Poh et al. 2012). They developed a wearable EDA-based tool to detect possible convulsive seizures, alerting caregivers instantly (the Empatica, Embrace 2: https://www.empatica.com/en-int/embrace2/). Li et al. (2022) have identified the phasic component of electrodermal activity as a

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sensitive marker of driver state management and utilized this measure in takeover-safety predictions in applications for automated driving systems.

Bilateral asymmetry in the hemispheres, and in electrodermal activity

Our cerebral hemispheres are variously connected to optimistic and pessimistic behaviors. Both hemispheres are supposed to be involved in optimistic or pessimistic thinking, yet the right hemisphere is more arbitrated in pessimistic thinking, whereas the left hemisphere is more involved in optimistic thinking (Hecht 2013). However, it is not clear if electrodermal activity reflects hemispheric asymmetry or not.

Most of the literature states that the electrodermal responses are general, and thus, EDA activity measured on one single location represents the arousal state of the whole body. Opposing the traditional "One True EDA" Theory (Dawson et al. 2007), one of the central questions of current psychophysiological research is whether different body locations respond with a different degree of eccrine sweat gland activity. If yes, what is the pattern of electrodermal responses across different dermatomes? Are these differences systematic and psychologically meaningful? The "Multiple Arousal Theory" (Picard et al. 2016) argues that in emotionally aroused situations eccrine glands on the different body parts produce distinct amounts of "emotional sweating," and thus, different electrodermal activity can be detected on the different dermatomes. To prove this theory, Picard and colleagues recorded EDA from a single person throughout daily activities, with multiple stressful events. During these events, she reported asymmetry between EDA levels measured on the left and right side of the body.

Several other studies investigated results from bilateral and multilateral EDA measurements with contradictory results. Kasos et al. (2018) found that short, 7-s musical segments with various emotional categories resulted in measurable differences of lateral asymmetry on the two palmar areas. Fear, peacefulness, and sadness evoked right-hand laterality, while happiness elicited dominance of the left-hand EDA. In a more recent study, Kryklywy et al. (2022) stimulated either the right or the left hand of participants electrically in both ipsilateral and contralateral ways. They reported lateralized EDA response aroused by limb-specific stimulation, suggesting that the autonomic nervous system prepares the body to a side-specific action, not just to a general "fight or flight" response. On the other hand, Bjørhei et al. (2019) reported that although bilateral EDA levels might be asymmetric, they do not display significant difference in their pattern between two psychologically distinct conditions, as measured by tasks with high- and low-stake stressors.

Investigation of lateral EDA asymmetry is a novel direction in psychophysiological research as most studies to date use unilateral measurements (including the ones listed below).

Electrodermal activity and performance in sports

Due to recent technological improvements in EDA measurement, application in sport-related situations has become relevant. Posada-Quintero et al. (2018a, b) demonstrated that EDA is sensitive to cognitive stress underwater, by having participants do a Stroop task in a small pool. Their results are advocating that EDA can be used in mildly alternated situations, and might be potentially useable in such extreme sports as diving.

Here we present a study of EDA asymmetry during a darts competition. Among many other sports, darts was chosen to be the subject of our investigation for the following reasons: First, it is a widely known and popular sport, with clear rules and distinct subsequent competitive actions with a direct outcome that could be characterized as success or failure. Thus, this sport seemed to be ideal for measuring EDA responses. Moreover, throwing the darts involves brief but sudden movements. The latter is crucial, as it was hypothesized that continuous intensive physical activity might cause artifacts in EDA signals (Can et al. 2019; Taylor et al. 2015). And last, darts has been studied previously using unidirectional electrodermal activity measurements on the left fingers (Bertollo et al. 2013).

Bertollo et al. (2013) conducted an experiment with two national-level sports athletes to understand the emotional, physiological, and postural trends linked to the four performance categories proposed in the multi-action plan model (Bortoli et al. 2012). The model suggests four distinct performance categories based on two factors: performance level (optimal vs. suboptimal) and the degree of conscious action control (automatic vs. controlled). Athletes were instructed to pinpoint the fundamental elements of the action and then perform the actions (e.g., throwing a dart). A within-subjects multivariate analysis of variance (2×2, optimal/suboptimal $\times$ automated/controlled) indicated that psychophysiological and postural distinctions are apparent among the four performance categories of the MAP model. They showed better performance linked to controlled trials (with higher consciousness of the action) as compared to automatic trials (with lower consciousness of the action). They conclude that understanding the full range of psychophysiological and behavioral attributes associated with performance is crucial for the development and application of biofeedback and neurofeedback methods to assist athletes in recognizing their personal zones of optimal functioning, improving their performance, and effectively managing their emotions to prevent choking under competitive pressure.

Although EDA seems to be an important biomarker of physical training and competition, the role of bilateral or multilateral EDA markers of performance has not been investigated to date.

The role of attributional style in sports

Numerous studies investigated how the optimistic attributional style affects performance. Global negative attributional style was related to poorer performance of academics (Houston 2016). Many researchers claim that optimists outperform pessimists, but there are only a handful of studies which prove this assumption. The Attributional Style Questionnaire, or ASQ, developed by Peterson et al. (1982) is the most widely used measure of the optimist or pessimist attributional style. As an example, a university swimming team was assessed before a championship. They found that the optimistic swimmers had less bad results than expected (Seligman et al. 1990). Gordon and his team (2008) reinforced these findings with a study on soccer players, where a significant positive relationship was found between athletic performance and the ASQ measure of optimism. Interestingly, there was no significant performance difference between these two groups during a subsequent win; however, when loosing, optimistic soccer players demonstrated better performance as compared to losing pessimists.

It is obvious to investigate if there is any relation between attribution style and EDA lateral asymmetry in competitive situations, such as in sport competitions. Interestingly, no previous studies tested this research question.

Goal of our present study was to investigate if lateral electrodermal asymmetry could serve as a psychophysiological marker of optimistic or pessimistic attitude toward evaluating one's own performance during a darts competition.

Hypotheses

(1) Differences in bilateral skin conductance can be measured reliably on the wrists during darts competition.
(2) We expect to detect lateral asymmetry of electrodermal activity in the time frame of the competition.
(3) Laterality of EDA (right or left dominance) characterizes each throw and may be used to implicate psychological state (attributional style) of the players.

Methods

Materials and procedure

The study protocol was approved by the Institutional Ethical Board of the Eötvös Loránd University (approval number: 2018/330-3). Participants were recruited via convenience sampling.

After filling out informed consents, electrodes and EDA measuring devices were placed on their left and right wrists. We collected bilateral EDA during the entire session (presented in Figs. 1, 2, 3 and Online Resource Fig. 2). Handedness was determined by the Hungarian adaptation of the Edinburgh Handedness Questionnaire (Oldfield 1971, see shared software at: http://www.brainmapping.org/shared/Edinburgh.php).

Subjects threw darts in a predetermined order as instructed by the experimenters. Question and answers before and after each throw were sound recorded for later analysis (see: "Definition of attribution style" below).

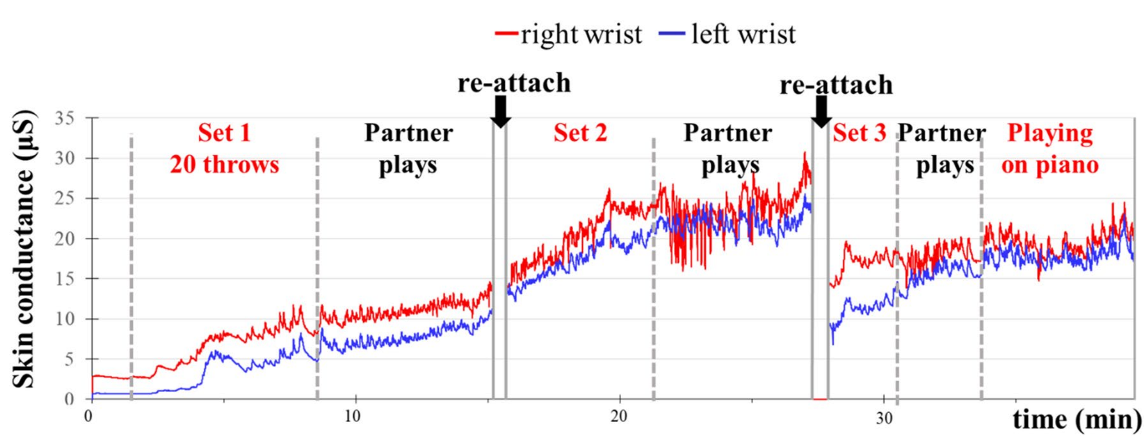


Fig. 1 Re-attachment of electrodes between sets during darts competition

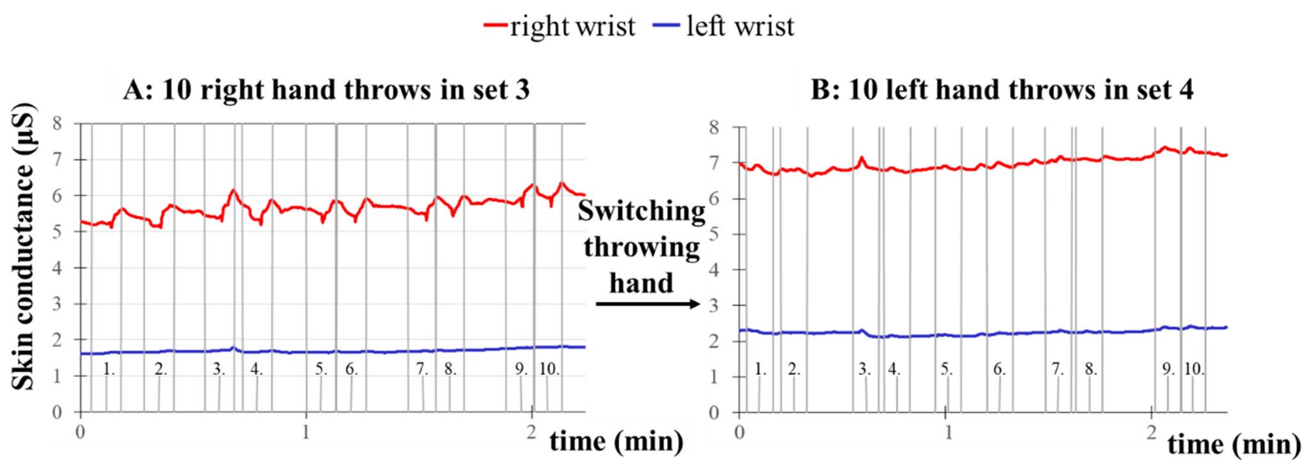
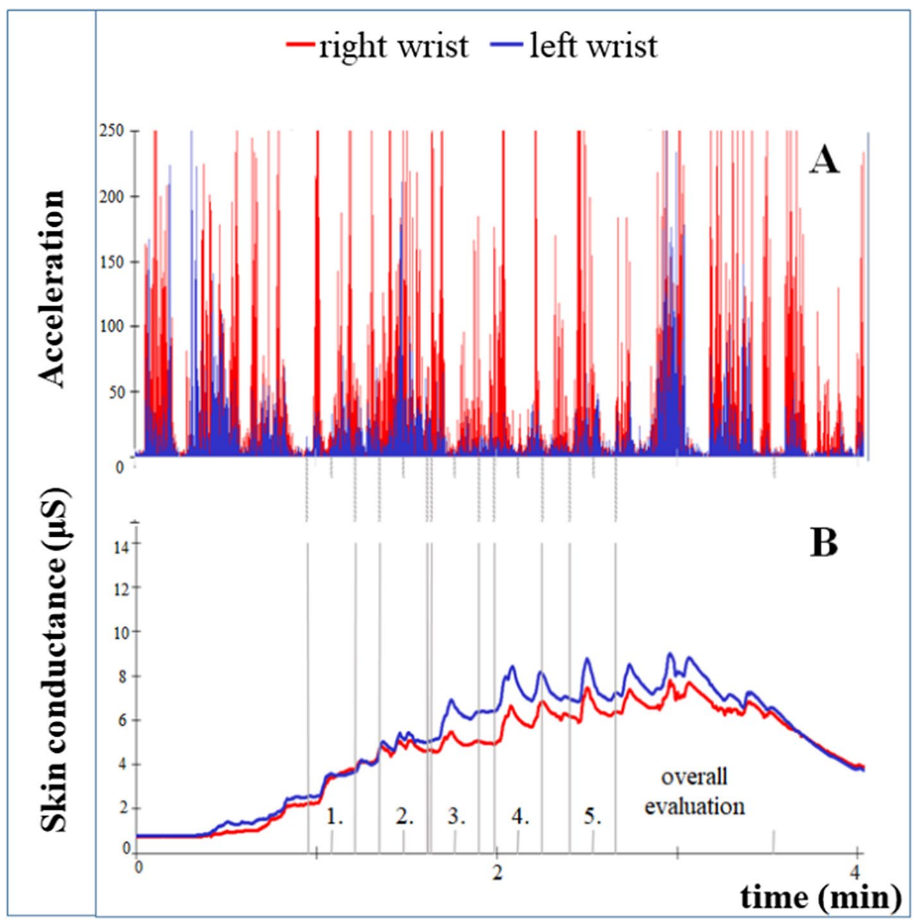


Fig. 2 Effect of switching the throwing hand during darts competition

Fig. 3 Bilateral EDA pattern of Subject 7 during the darts competition



We used a 40 cm diameter magnetic darts board, and 9 cm long darts. The board was divided to 20 equal sections worth different points each, and rings marked single, double, and triple areas along the center "bull" and "bull's eye" according to standard scoring (Wikipedia contributors 2021a, b, July 15, Darts). Electrodermal activity from both wrists was measured during throws with the open-source biomonitor (http://obimon.com, Kasos et al. 2019) device supplied also by accelerometer. EDA measuring devices and a sound recording were synchronized using Network Time Protocol (Wikipedia contributors 2021a, b, July 5, Network Time Protocol). Electrodes (Skintact FS-GR1; Leonhard Lang GmbH, Innsbruck, Austria) were placed on both wrists of participants, connected directly to the devices, secured by wristbands.

All of the studies were performed at room temperature, specifically: Study 1 at 22–24°C, Study 2 and 3 at 19–21°C, Study 4 at 20–22°C.

Definition of lateral asymmetry

Raw EDA values as measured on the right (red lines) and the left wrist (blue lines) are presented at each figure separately (see Figs. 1, 2, 3 and Online Resource Fig. 1 and Online Resource Fig. 2) A left-sided EDA dominance was present, if EDA values on the left wrist are higher throughout the darts session. A right-sided lateral dominance was present if on the contrary, the left wrist EDA data were lower. Laterality was not obvious only in 6 cases of the total of 230 throws. These ambiguous cases were the 1st throw of Subject 7 (see Fig. 3) and all the 5 throws of Subject 13 (see Online Resource Fig. 1).

Definition of attributional types

One of the three dimensions of Seligman's questionnaire (Peterson et al. 1982) was used to determine if the participant' s opinion of their own performance could be defined as an optimistic or a pessimistic attitude toward the specific throws. This dimension was based on whether the participants had external or internal reasoning about their performance. The participants were asked before each throw about their expectation, as well as after each throw to explain their better or worse performance than expected.

The attributional style was determined by two independent evaluators based on the recorded explanations of the throwers. The throw was regarded as "good" if the resulting point was higher or equal to expectations, while it was "bad" if the result was lower than expected. An internal explanation of a good throw or an external explanation of a bad one was classified as an *optimist attribution type* (see examples in Table 1). On the other hand, if a person had an external explanation when a good throw occurred or blamed themselves for a bad throw, they were classified as having a *pessimist attribution style.*

An overview of the four studies, participants, and throws

We chose to use throws as the units of measurement, since each throw action could be characterized by laterality real-time psychophysiological EDA measurement and changes in laterality could be expected. Moreover, each throw action could be characterized by its attributional style label provided by independent reviewers based on the self-reported account of failure or success of that specific throw action. Only right-handed participants were included in this study, as prior results on EDA laterality and handedness are scarce and since only 2 participants were left-handed.

Table 2 provides an overview of the studies, participants, and throws. Participants were recruited to take part in one-to-one or 4 subjects/group competitions. Data of three participants (see their numbers in brackets in Table 2) were excluded from the analyses, due the lack of valid EDA measurement (Subject 1) or being left-handed (Subjects 14 and 15).

Table 1 Characteristics of optimist or pessimist attribution type

Attribution type	Evaluation of throw	Type of explanation	Example
Optimist	Good	Internal	"I'm getting the hang of it!"
	Bad	External	"These magnetic darts are really bad to play with!"
Pessimist	Good	External	"I was just lucky"
	Bad	Internal	"I'm bad at darts"

Table 2 Main characteristics of the Studies 1–4 and participants

Study	Competition type & study No		Subject No.	Gender	Age	(Sets × throws)/person
Reliability study	One-to-one	Study 1	(1.), 2	Males	19, 49	3 × 10
		Study 2				6 × 10
Initial study		Study 3	2., 3	Male, female	49, 50	4 × 10
Replication studies	Group	Study 4	4., 5., 6., 7	2 males, 2 females	25, 24, 19, 25	1 × 5
			8., 9., 10., 11	2 males, 2 females	25, 31, 23, 21	
			12., 13., (14.), (15)	2 males, 2 females	24, 22, 24, 23	

In the reliability studies, 90 throws were analyzed from a single subject. In the initial study, a total of 80 throws were provided by the 2 participants of the duo, who played 4 sets with 10 throws, each. In the replication study, 50 throw actions were carried out, since each of the 10 participants played 1 set, with 5 throws per set. Out of the 130 narratives for causes of success or failures of throw actions, 84 contained sufficient self-report information to be unambiguously categorized as "optimistic" or "pessimistic" by independent raters.

The *reliability studies* were based on wrist measurements from Subject 2. In Study 1 the EDA electrodes were re-attached twice to see if laterality changes due to the replacement of electrodes (see Fig. 1). In Study 2 we asked this participant to throw with alternate hands to detect if there is any effect of the throwing hand movement (see Fig. 2).

In the *initial study* (Study 3), Subject 2 (male) and Subject 3 (female) engaged in a *one-to-one darts competition*. A single dart was thrown 10 times by one of the players, followed by 10 throws of the other player in each set. A total of 4 sets were accomplished by each player.

The *replication study* (Study 4) aimed to investigate shorter competition assays in a *group setting of 4–4 participants of 3 groups*. They were recruited as part of a university course requirement. Students were instructed to gather their own groups of four people, representing both sexes equally. Each participant performed 5 throws in a single set one after each other.

Throws were performed by the right hand of the players except in Study 2, where half of the sets were made by the right hand and the other half by the left hand of Subject 2. In all studies, participants had a chance to warm up before the darts game by a few minutes of practice throws.

The *initial sample* resulted in 80 responses of which 71 were judged identically by the two evaluators (88% consistence). In 9 cases where the two independent evaluators judged differently the explanations of the participants, they discussed their opinions, and a consensus was formed between them for each debated explanation. 30 cases were judged as uncategorizable by both evaluators as they were not informative enough to determine the attribution style. Therefore, 50 throws with unambiguous judgements and valid asymmetry were analyzed in the *initial sample* (Study 3).

In the *replication sample*, throws and answers of 10 participants have been analyzed for attribution type. Here evaluators showed 87% initial consistency, and similarly to the previously described procedure finalized a consensus for each of the cases (including 10 explanations that were not categorizable for attribution type). As noted before EDA data of 6 throws did not have a clear asymmetry, thus 34 throws with unambiguous judgements and valid asymmetry were analyzed in the *replication sample* (Study 4).

Data analyses and statistics

Raw acceleration and EDA data with automated time stamps based on the Network Time Protocol (NTP) were extracted from the memory of Obimon EDA devices. The start of the darts competition and the exact time of the throws were determined with the use of the sound recordings (also synchronized via NTP): The audio recordings provided an anchor for the exact moment when the dart hit the board. The time interval of each throws varied. They are labeled by gray vertical lines in Figs. 2 and 3, as well as Online Resource Fig. 1 and Online Resource Fig. 2.

The unit of statistical analysis was the throw interval. Two main variables characterizing each throw were used in the analyses: left or right dominance of EDA and the optimist or pessimist attribution type. Chi-square tests were performed separately for *initial study* (Study 3) and for *the replication study* (Study 4) to test the possible frequency differences of lateral electrodermal asymmetry dimensions and the attribution styles.

Results

Reliability considerations of lateral asymmetry during darts competition

Our first hypothesis aimed to attest reliable wrist EDA measurements during a darts competition, where hand movements might have hindered data collection. In studies 1 and 2, we investigated reliability of EDA measurements using data from two one-to-one dart competitions. We evaluated the effect of both electrode re-attachment and wrist movements on EDA patterns, focusing on lateral asymmetries.

Re-attachment of electrodes does not change EDA asymmetry

In study 1, Subject 2 was asked to play a 3-set competition with Subject 1. Bilateral EDA measurements were collected only from Subject 2 only. (The role of Subject 1 was to ensure the context of a competition.) In between sets both the Obimon devices and the electrodes were detached from both wrists of Subject 2 and then re-attached to approximately the same areas. We assessed if there were any laterality changes after re-attaching the electrodes.

Skin conductance values of Subject 2 are displayed for the three sets. The red line represents right wrist skin conductance in μS, and the blue line represents left wrist

EDA during the 40-min competition. Set 1, 2, and 3 labels highlight the time frame of a couple of minutes, when Subject 2 was throwing the darts. These periods are followed by waiting times for Subject 2, indicated by "partner plays" labels. After the darts game, Subject 2 played the piano. The "re-attach" labels signal the two short time periods (28 and 35 s), when devices and electrodes were taken off from both wrists, and then devices were re-attached using new electrodes.

Figure 1 shows an increase of skin conductance levels of both wrists with an apparent right-sided laterality throughout set 1 and in the first waiting period. After the first re-attachment, skin conductance level for both wrists started from approximately the same values as before the re-attachment. In set 2, skin conductance level continued to raise with a right wrist dominance throughout the 10 throws. While partner played after set 2, Subject 2 had large negative peaks on the right wrist presumably resulting from hand and body movements as walking around. For the end of the waiting period, a right-hand dominance appeared again.

After the second re-attachment of device and electrodes, there was a large, 22 µS drop in the skin conductance level of both wrists due to unknown reasons. The lateral asymmetry of EDA, however, remained the same: The right wrist EDA was higher than the left wrist EDA throughout set 3. In contrast to set 3, the bilateral EDA values were nearly equilibrated during the last waiting period. After the game, Subject 2 played the piano to attest emotional arousal in a more relaxed state of mind with active wrist movements. During this time (starting at about the 36th minute, see Fig. 1), asymmetry of laterality disappeared.

Switching throwing hands does not change EDA laterality

Since wrist movements are a clear obstacle of EDA measurements according to the literature, we tested in Study 2 whether switching the hand that the player throws with has any effect on lateral asymmetry. Subject 2 was playing another darts competition with Subject 1, but once again, only EDA data of Subject 2 was assessed. Both players threw 6 sets each, but Subject 2 was asked to switch throwing hands in between set 3 and set 4, and once again in between set 5 and 6. All sets lasted approximately 2-min, with a 4-min resting time interval in between.

Figure 2 shows EDA measurement results during throws of set 3 and set 4 as an example of EDA asymmetry in EDA measurements of the two wrists. Skin conductance values measured on the right wrist are presented by the red line, and left wrist measurements are highlighted with blue. One could notice that fast negative EDA peaks on the right wrist characterized each of the ten throws at the moment of throw when the throws were made by right hand (see: Fig. 2A). These EDA negative peaks, however, were not detectable if the left hand was used to throw (see Fig. 2B). Nevertheless, considerably higher right wrist EDA levels in both parts of Fig. 2 suggest that Subject 2 was lateralized to the right, regardless of the hand used for throwing. A similar, right dominant EDA pattern was detected in all the other sets (data not shown), independently from the throwing hand.

Skin conductance values of Subject 2 in Study 2 are displayed: right-hand throws in set 3 and left-hand throws in set 4. All sets involved 10 throws. The red line represents EDA measurements from the right wrist, and the blue line represents left wrist skin conductance in µS. Small vertical gray lines with numbers represent the moment of throws. Long vertical gray lines show the ± 4 s time interval of each throw.

Portraying lateral asymmetry during darts competition

According to our second hypothesis, we expected to detect lateral asymmetry of electrodermal activity during the darts competition. In the *initial sample* (see "Study 3" in Methods section), two, similar age, mixed gender participants (Subject 2 and Subject 3) competed in a one-to-one setup. Raw EDA data of Subject 2 during one of his games are shown in Fig. 1. The game consisted of 4 sets with 10 throws in each set, so a total of 80 throws were evaluated in this assay. In *the replication sample* (see "Study 4" in Methods section), 10 participants engaged in a darts competition in small groups and all of them played one set with 5 throws, resulting in a total of 50 throws. EDA values were detected continuously on both the right and left wrists of all participants during the whole session.

We chose to present a single subject's EDA patterns as an example (see Fig. 3) during a single set of the game with 5 throws. Similar figures for all participants of Study 4 (Subject 4–Subject 13) can be seen in Online Resource Fig. 1. Acceleration data of the right (red line) and left (blue line) wrists are shown on part A of Fig. 3, while the raw EDA data measured on the right (red line) and left (blue line) wrists in the same time period are presented in part B of Fig. 3.

Part A displays the physical movement of the right and left wrists of Subject 7 through accelerometer data as the function of time. Part B shows raw electrodermal activity values (right wrist in red, left wrist in blue) within the same timeframe. Acceleration and EDA data are presented with red line for the right wrist and with blue one for the left. The long gray lines border the ± 8 s time interval of each throw while the short gray lines with the number above them represent the exact time of each throw. The 5 dart throws are labeled by numbers from 1 to 5.

One can notice that Subject 7 showed no asymmetry at the beginning of the game but became more and more lateralized to the left wrist during the dart competition, which is apparent even throughout the overall evaluation part of the game but diminishes afterward (see Fig. 3B). It is important to note that during "Evaluation" darts throws did not occur; thus, there is much less movement as compared to throws. EDA level and asymmetry, however, remained the same as during the throws. This was not typical to just Subject 7 (see Fig. 3A) but characterized most competitors (see: Online Resource Fig. 1). In general, half of the subjects were lateralized to their left, the other half to their right wrist. In some cases, however, the direction of EDA laterality changed during the darts game (see Online Resource Fig. 1 Subject 12).

Visual analyses of individual patterns of raw EDA showed considerable individual variability (see Online Resource Fig. 1). At the same time, lateral asymmetry of participants (either to the left or to the right) was obvious and consistent throughout the games. There was only one person whose EDA values did not show characteristic asymmetry of electrodermal laterality during the dart game (see Online Resource Fig. 1, Subject 13).

As shown in Fig. 3B, the darts competition started about 1 min before the first throw. A short discussion with the instructor and several practice trials of dart throws were carried out within this timeframe. However, 1 min might be too short to catch the time frame when the players were relaxed. Therefore, the bilateral EDA values during the total time of the session (approx. 40 min) are also depicted (see: Online Resource Fig. 2). Regarding the EDA pattern collected during the whole session, most subjects have low EDA level without significant difference between the right and left wrists at a certain time period but not during their darts game (see Online Resource Fig. 2).

EDA laterality indicates players' attribution style toward their own performance

Out third hypothesis assumed that laterality of EDA (right or left dominance) will characterize each throw and will be linked to specific attribution of the success or failure of throw actions. To test this hypothesis, we collected verbal feedback about participants' opinion about each of their throw. They guessed their next performance (the points) right before the throw action, and after the throw, they reported about their performance as well as the cause of their result compared to their guess. Based on these data, we determined the attribution style as either optimistic or pessimistic toward participants' own performance in each throw action. This dimension was based on the participants' external or internal reasoning with regard to their performance (see details in Table 1). The results are summarized in Table 3, highlighting the lateral differences in the proportions of throws characterized by optimist and pessimist attribution style.

Table 3 Lateral electrodermal asymmetry and the attribution style

	Attribution style		
	Optimist (%)	Pessimist (%)	
Initial study—Study 3 (N = 50)			
Right wrist dominance	84	16	$\text{Chi}^2 = 11.61$
Left wrist dominance	37	63	$p = 0.001$
Replication study—Study4 (N = 34)			
Right wrist dominance	61	39	$\text{Chi}^2 = 4.480$
Left wrist dominance	25	75	$p = 0.034$

The outcomes of Table 3 show us outcomes of both the *initial* (Study 3) and *replication study* (Study 4). Throws that were lateralized toward the right wrist had more optimistic attributions (84% in *the initial study* and 61% in the *replication study)* as compared to the throws lateralized toward the left. Throws lateralized toward the left were more likely to have a pessimistic explanation (*initial study*: 63%, *replication study*: 75%). The Chi-square test revealed significant difference in both studies (*initial study*: Chi-square = 11.61, $p = 0.001$, $N = 50$; *replication study*: Chi-square = 4.480, $p = 0.034$, $N = 34$).

Discussion

Reliable measurement of EDA lateral asymmetry during a competition

There is a common belief that artifacts caused by physical movement invalidate EDA measurements. Even though there are multiple solutions around this problem in long-term measurements (Can et al. 2019; Taylor et al. 2015), researchers often choose not to measure at all during physical movements. The presented study is not the first attempt to measure EDA during a sport competition. Bertollo et al. (2013) reliably measured electrodermal activity of a sports shooter and a darts player during more than a hundred shots. Novelty of the presented findings are in relation to lateral asymmetry. We demonstrate here that the emotional state induced by a darts competition results in location-specific arousal. Consequently, EDA lateral asymmetry can be reliably detected on the wrists, despite excessive movement of the throwing hand.

The contact between electrodes and the skin is crucial for EDA measurements; thus, type and placement of electrodes require careful consideration (Boucsein 2012). The measurement procedure followed technical principals of Dawson's handbook (Dawson et al 2007). EDA was measured on the wrist as they are less prone to the physical activity required by the throws. Based on previous results, wrists are adequate for bilateral measurements. Picard and colleagues measured EDA from the wrist during sleep (Sano et al. 2014), and our research group measured bilateral electrodermal activity from five different sites of the body: fingers, feet, calves, shoulders, and wrists (Kasos et al. 2020). Most EDA studies require subjects to keep their hands still while EDA is being measured, since physical activity alters the EDA signal (Posada-Quintero et al. 2018a, b). On the other hand, ecological validity of EDA measurements requires wearable devices and the opportunity for measuring normal daily-life activities. We acknowledge that measuring valid EDA is a challenge during physical activity due to movement artifacts; thus, Study 1 and Study 2 investigated several aspects of measurement reliability.

One of the main issues is whether the direction of lateral asymmetry is affected by physical movement. To answer this question, we asked Subject 2 to change throwing hands across sets. Results displayed in Fig. 2 suggest that physical activity did not affect lateral asymmetry. Our results confirm that although physical activity does influence the EDA signal, lateral asymmetry is not an artifact of the throwing hand movement. Further investigation of re-attachment of electrodes (Fig. 1) showed that EDA asymmetry was not affected by these factors. Thus, we confirm our first hypothesis and conclude that raw skin conductance data from wrist locations with stable attachment of the electrodes are reliable sources of EDA lateral asymmetry measurements during specific psychological states, such as a darts competition.

We also hypothesized that emotional state induced by the competition will result in EDA lateral asymmetry, since the Multiple Arousal Theory (Picard et al. 2016) implicates that the increased arousal in a competition with "high stakes" should trigger different amounts of eccrine sweat gland activity on the different body parts, and thus, level of EDA will be different on distinct body locations. Underlying this theory, Picard and colleagues depicted EDA asymmetry between left and right side of the body throughout daily activities with multiple stressful events. At the same time, Bjørhei et al. (2019) did not report any significant EDA lateral asymmetry in two stress-tasks. We demonstrated here that out of 13 right-handed participants in the current study 12 showed lateral asymmetry during the competition (see Fig. 3 and Online Resource Fig. 1). We believe that the setting is crucial in inducing the assumption about stress and triggering the feeling in participants that the "stakes are high." Thus, real life stress situations can induce feelings that are very different from those set up in a laboratory, where participants might have prior beliefs about experimenters' intentions. On the other hand, lateralized EDA response was clearly demonstrated in a laboratory setting where arousal was induced by direct physiological triggers: electric stimulation (Kryklywy et al. 2022), instead pf psychological triggers. Moreover, the direction of lateral asymmetry of the EDA response was limb-specific, advocating a side-specific "fight or flight" response.

Individual differences are apparent in electrodermal activity. Some participants show EDA values as low as a few µSiemens, and some over ten µSiemens. Similarly, the degree of laterality can also vary. According to our results, lateral asymmetry characterizing players are mostly consistent throughout the competition; however, difference between wrist EDA measurements of a player may increase during the competition (see Subject 2 for example in Study 3). In addition, Subject 2 showed a right-sided lateral asymmetry not only in Study 3 but also in two other studies executed at another time using other Obimon devices (see Figs. 1 and 2). These results demonstrate that the lateral asymmetry of EDA in a high-stake game is likely to be linked to the emotional state of the participant and is not a consequence of external bias, such as re-attachment of electrodes or physical movement. It is also important to note that Subject 2 was characterized by an increasing EDA level and right-hand EDA dominance when throwing the darts in the competition. On the other hand, this right-sided asymmetry was less apparent in the time periods of the competition when he watched his partner play when he played the piano after the competition (see Fig. 1). Thus, we confirm our second hypothesis: We detected lateral asymmetry of electrodermal activity that specifically characterize the arousal state induced by the competition.

To summarize findings from our first three studies, we may conclude that while selection of measurement location and secure placement of electrodes is important, EDA lateral asymmetry is typical in a competition and can be measured reliably on the wrists despite hand movements. Re-attachment of electrodes in Study 1 did not change laterality, activity induced by the throwing hand did not have significant effect on the EDA signal, and switching throwing hands did not influence laterality. These results are in line with previous findings from long-term EDA measurements, where EDA asymmetry did not associate with physical activity (Picard et al. 2016). Thus, we infer that differences of bilateral skin conductance on the wrists characterize EDA lateral asymmetry reliably during a darts competition.

There is clear evidence that handedness affects brain asymmetry (Johnstone et al. 2021); however, effect of handedness on EDA laterality has not been studied yet in detail. It should be emphasized that it is not likely that EDA laterality is a consequence of left or right handedness, as both left- and right-sided EDA dominance was detected in the present study among right-handed individuals. In order to avoid unknown variations in EDA laterality between left-handed and right-handed individuals, the present study involved only right-handed participants.

EDA lateral asymmetry as a biomarker of attributional styles

We assumed that attribution of the performance regarding each throw might be linked to laterality of objective EDA measurement portraying their emotional arousal. We based our assumption on the Multiple Arousal Theory (Picard et al. 2016) highlighting that while two sides of the body typically provide synchronized measures, when EDA levels are different, the pattern can be informative.

According to our best knowledge, this is the first study exploring the possible link between laterality and optimistic/pessimistic attributional styles defined on the bases of Seligman's theory (Peterson et al 1982). We demonstrated that the right or left EDA dominance is associated to the explanation provided by the players about their success or failure. Optimistic or pessimistic attribution style was based on Seligman's model (Gillham et al. 2001), suggesting an optimistic attribution if a good throw performance (higher than estimated) was seen as achievement by oneself, and a bad throw performance (lower than estimated) was due to external factors. On the contrary, a pessimistic attribution style would imply that success is due to external factors, while failures have internal causes. Results presented in Table 3 show that EDA lateral asymmetry is linked to attributional styles. Optimistic attribution was significantly more frequent while measuring right-sided dominance of EDA (84% and 61% in the initial and in the replication sample). In comparison Pessimistic attitudes were linked to left-sided dominance (63% and 75%). We suggest that direction of EDA asymmetry may serve as a biomarker of the mental state of players in the competition, characterizing an optimistic or pessimistic self-evaluation related to their throw performance. Since this is a novel result, replication of our findings is necessary.

Hemispheric asymmetry is widely studied, and its relation to optimistic and pessimistic attitude is also investigated (for a review see: Hecht 2013). According to the general view, right amygdala activation is linked to pessimistic beliefs and attitudes, whereas activity in the left amygdala is linked to an optimistic attitude (Hecht 2013). However, it has not been stated to date if the above hemispheric laterality is apparent at the periphery as well, perhaps in the form of asymmetrical electrodermal activity. *According to our findings*, the right-sided EDA dominance was linked to the optimistic attitude, which seems to be in contrast with the classical view of hemispherical asymmetry. At the same time, we must note that electrodermal activity may originate either from both ipsilateral and contralateral pathways (Boucsein 2012). It is possible that in sport performance situations where significant physical movement is present, the majority of EDA signals have contralateral pathways. The other explanation implies that the optimists were involved in the game more than pessimist, and thus, they were experiencing a higher stress level which was shown to induce right-sided EDA dominance by previous studies (Picard et al 2016; Kasos et al 2018). This assumption is in agreement with the idea of "strategic optimism and defensive pessimism" (Gordon 2008).

It is important to emphasize that EDA laterality cannot be a consequence of left or right handedness, as both left of right-sided EDA dominance were found in the present study among right-handed individuals. Effect of handedness on EDA laterality has not been studied in details yet. There are, however, clear evidences that handedness affects brain asymmetry (e.g., Johnstone et al. 2021). In order to avoid unknown variations in EDA laterality between left-handed and right-handed individuals, the present study involved only right-handed participants.

Our data also demonstrated that the lateral asymmetry of the same body part of the same person may change over time. During the brief duration of throws (5–8 min) presented in most figures in the results section, it is relatively rare for EDA dominance to completely reverse, but it occurs for example in Participant 12 subject (see Online Source Fig. 1.). However, throughout the entire measurement period, where both competing and resting periods are presented, there are often extreme changes in EDA values measured on the right and left sides (see Online Source Fig. 2. which presents bilateral data measured during the entire data collection period for all subjects).

We also demonstrated in the validation tests that prolonged relaxation clearly reduces the difference in EDA levels between the two sides (see the last section of Fig. 1.: "playing on the piano").

To summarize findings from a one-to-one darts competition (Study3) as well as from a group setup (Study 4), we may conclude that lateral asymmetry of emotional arousal may serve as a reliable biomarker of attributional style in a competition. This is the first study to show a significant ($p = 0.001$) association of attributional style and right- or left-sided EDA dominance. Results clearly indicate that bilateral assessment of arousal is relevant. Our results indicate meaningful psychophysiological correlates of EDA measurements from distinct body locations—as proposed by the Multiple Arousal Theory (Picard et al. 2016).

Limitations and impact

The major limitation of the present study is small sample size, which should be expanded for greater generalizability. Also, our participants were amateur players and only right-handed individuals were included into the data evaluation due to the small number of left-handed participants. Another sport, where bilateral EDA measurements could be useful, is sports shooting i.e., where participant's movements are controlled and the scoring of the shooting target is less deviated. Regarding the determination of attribution style, one should consider that only one of the three dimensions of Seligman's questionnaire was applicable. Unfortunately, there was a large luck factor in the amateur player's throws in the presented study, resulting in a high standard deviations of individual performance. Thus, interrelations between performance and attributional styles could not be detected here.

Wearable EDA sensors are suitable to indicate the real-time emotional status and have potential implications for an applied setting. Direct feedback on emotional status has a potential benefit and often applied in performance optimization together with other psychophysiological measures (Fronso et al. 2017). These autonomic function assessments include various parameters, involving classical unilateral EDA measure. Based on the presented results, use of bilateral EDA setup instead of classical unilateral EDA could serve as an additional feature detection of the arousal state. Biofeedback techniques allow individuals to receive continuous feedback on their self-regulating skills. This could facilitate better sport performance (Blumenstein & Weinstein 2011), optimal exercise, and injury prevention (Düking et al. 2017).

Conclusions for future biology

Findings from this study suggest that lateral asymmetry of emotional arousal could be considered as a novel biomarker of attribution al style in competitive situations, such as a sport competition. We discuss the feasibility and reliability of measuring electrodermal activity on the right and the left wrists during a darts competition including excessive physical movement. Our analysis reveals that bilateral EDA may be characteristically different, and that lateral asymmetry can be linked to how players attribute their own successes and setbacks during the game. As future work we plan building AI models that can automatically extract bilateral biomarkers as AI features automatically and in real time. Such methodology could be utilized for the psychological training in various sports or various competitive settings in general.

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Declarations

Conflict of interest The authors have no conflict of interest to declare.

References

Bertollo M, Bortoli L, Gramaccioni G, Hanin Y, Comani S, Robazza C (2013) Behavioural and psychophysiological correlates of athletic performance: a test of the multi-action plan model. Appl Psychophysiol Biofeedback 38(2):91–99. https://doi.org/10.1007/s10484-013-9211-z

Bjørhei A, Pedersen FT, Muhammad S, Tronstad C, Kalvøy H, Wojniusz S, Pabst O, Sütterlin S (2019) An investigation on bilateral asymmetry in electrodermal activity. Front Behav Neurosci 13:88. https://doi.org/10.3389/fnbeh.2019.00088

Blumenstein B, Weinstein Y (2011) Biofeedback training: enhancing athletic performance. Biofeedback 39(3):101–104. https://doi.org/10.5298/1081-5937-39.3.07

Bortoli L, Bertollo M, Hanin YL, Robazza C (2012) Striving for excellence: a multi-action plan intervention model for shooters. Psychol Sport Exerc 13:693–701. https://doi.org/10.1016/j.psychsport.2012.04.006

Boucsein W (2012) Electrodermal activity. Springer, New York. https://doi.org/10.1007/978-1-4614-1126-0

Can YS, Chalabianloo N, Ekiz D, Ersoy C (2019) Continuous stress detection using wearable sensors in real life: algorithmic programming contest case study. Sensors 19(8):1849. https://doi.org/10.3390/s19081849

Dawson ME, Schell AM, Filion DL, Berntson GG (2007) The electrodermal system. In: Cacioppo JT, Tassinary LG, Berntson G (eds) Handbook of psychophysiology, 3rd edn. Cambridge University Press, Cambridge, pp 157–181. https://doi.org/10.1017/CBO9780511546396.007

Düking P, Holmberg H-C, Sperlich B (2017) Instant biofeedback provided by wearable sensor technology can help to optimize exercise and prevent injury and overuse. Front Physiol 8:256317. https://doi.org/10.3389/fphys.2017.00167

Empatica, Embrace 2. Retrieved 11:40, July 1, 2023, from: Embrace2 Seizure Monitoring | Smarter Epilepsy Management | Embrace Watch | Empatica

di Fronso S, Robazza C, Bortoli L, Bertollo M (2017) Performance optimization in sport: a psychophysiological approach. Motriz Revista De Educação Física 23(4):e1017138. https://doi.org/10.1590/s1980-6574201700040001

Gillham JE, Shatté AJ, Reivich KJ, Seligman MEP (2001) Optimism, pessimism, and explanatory style. Optimism & pessimism: implications for theory, research, and practice. American Psychological

Association, Washington, pp 53–75. https://doi.org/10.1037/10385-003
Gordon RA (2008) Attributional style and athletic performance: strategic optimism and defensive pessimism. Psychol Sport Exerc 9(3):336–350. https://doi.org/10.1016/j.psychsport.2007.04.007
Hecht D (2013) The neural basis of optimism and pessimism. Exp Neurobiol 22(3):173–199. https://doi.org/10.5607/en.2013.22.3.173
Houston DM (2016) Revisiting the relationship between attributional style and academic performance. J Appl Soc Psychol 46(3):192–200. https://doi.org/10.1111/jasp.12356
Johnstone LT, Karlsson EM, Carey DP (2021) Left-handers are less lateralized than right-handers for both left and right hemispheric functions. Cereb Cortex 31(8):3780–3787. https://doi.org/10.1093/cercor/bhab048
Kasos K, Kekecs Z, Kasos E, Szekely A, Varga K (2018) Bilateral electrodermal activity in the active-alert hypnotic induction. Int J Clin Exp Hypn 66(3):282–297. https://doi.org/10.1080/00207144.2018.1460551
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 56:e13374. https://doi.org/10.1111/psyp.13374
Kasos K, Kekecs Z, Csirmaz L, Zimonyi S, Vikor F, Kasos E, Veres A, Kotyuk E, Szekely A (2020) Bilateral comparison of traditional and alternate electrodermal measurement sites. Psychophysiology 57(11):e13645. https://doi.org/10.1111/psyp.13645
Kryklywy JH, Lu A, Roberts KH, Rowan M, Todd RM (2022) Lateralization of autonomic output in response to limb-specific threat. Eneuro. https://doi.org/10.1523/ENEURO.0011-22.2022
Li P, Li Y, Yao Y, Wu C, Nie B, Li SE (2022) Sensitivity of electrodermal activity features for driver arousal measurement in cognitive load: the application in automated driving systems. IEEE Trans Intell Transp Syst 23(9):14954–14967. https://doi.org/10.1109/TITS.2021.3135266
Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9(1):97–113. https://doi.org/10.1016/0028-3932(71)90067-4
Peterson C, Semmel A, von Baeyer C, Abramson LY, Metalsky GI, Seligman MEP (1982) The attributional style questionnaire. Cogn Ther Res 6(3):287–299. https://doi.org/10.1007/BF01173577
Picard RW, Fedor S, Ayzenberg Y (2016) Multiple arousal theory and daily-life electrodermal activity asymmetry. Emot Rev 8(1):62–75. https://doi.org/10.1177/1754073914565517
Poh M-Z, Loddenkemper T, Reinsberger C, Swenson NC, Goyal S, Madsen JR, Picard RW (2012) Autonomic changes with seizures correlate with postictal EEG suppression. Neurology 78(23):1868–1876. https://doi.org/10.1212/WNL.0b013e318258f7f1
Posada-Quintero HF, Reljin N, Mills C, Mills I, Florian JP, VanHeest JL, Chon KH (2018b) Time-varying analysis of electrodermal activity during exercise. PLoS ONE 13(6):e0198328. https://doi.org/10.1371/journal.pone.0198328
Posada-Quintero HF, Florian JP, Orjuela-Cañón AD, Chon KH (2018a) Electrodermal activity is sensitive to cognitive stress under water. Front Physiol 8:326478. https://doi.org/10.3389/fphys.2017.01128
Reyes del Paso GA, de la Coba P (2020) Correction: reduced activity, reactivity and functionality of the sympathetic nervous system in fibromyalgia: an electrodermal study. PLoS ONE 15(12):e0244830. https://doi.org/10.1371/journal.pone.0244830
Salimpoor VN, Benovoy M, Longo G, Cooperstock JR, Zatorre RJ (2009) The rewarding aspects of music listening are related to degree of emotional arousal. PLoS ONE 4(10):e7487. https://doi.org/10.1371/journal.pone.0007487
Sano A, Picard RW, Stickgold R (2014) Quantitative analysis of wrist electrodermal activity during sleep. Int J Psychophysiol 94(3):382–389. https://doi.org/10.1016/j.ijpsycho.2014.09.011
Sarchiapone M, Gramaglia C, Iosue M, Carli V, Mandelli L, Serretti A, Marangon D, Zeppegno P (2018) The association between electrodermal activity (EDA), depression and suicidal behaviour: a systematic review and narrative synthesis. BMC Psychiatry 18(1):22. https://doi.org/10.1186/s12888-017-1551-4
Seligman MEP, Nolen-Hoeksema S, Thornton N, Thornton KM (1990) Explanatory style as a mechanism of disappointing athletic performance. Psychol Sci 1(2):143–146. https://doi.org/10.1111/j.1467-9280.1990.tb00084.x
Taylor S, Jaques N, Chen W, Fedor S, Sano A, Picard R (2015) Automatic identification of artifacts in electrodermal activity data. In: 2015 37th annual international conference of the IEEE engineering in medicine and biology society (EMBC), pp 1934–1937. https://doi.org/10.1109/EMBC.2015.7318762
Thorell LH, Wolfersdorf M, Straub R, Steyer J, Hodgkinson S, Kaschka WP, Jandl M (2013) Electrodermal hyporeactivity as a trait marker for suicidal propensity in uni-and bipolar depression. J Psychiatr Res 47(12):1925–1931. https://doi.org/10.1016/j.jpsychires.2013.08.017
Tronstad C, Amini M, Bach DR, Martinsen ØG (2022) Current trends and opportunities in the methodology of electrodermal activity measurement. Physiol Meas 43(2):02TR01. https://doi.org/10.1088/1361-6579/ac5007
Wikipedia contributors (2021) Darts. In: Wikipedia, the free encyclopedia. Retrieved 11:40, July 18, 2021, from https://en.wikipedia.org/w/index.php?title=Darts&oldid=1033752494
Wikipedia contributors (2021) Network time protocol. In: Wikipedia, the free encyclopedia. Retrieved 11:41, July 18, 2021, from https://en.wikipedia.org/w/index.php?title=Network_Time_Protocol&oldid=1032183251