ARTICLE

emotion review

Emotion Review
1–14

ISSN 1754-0739
DOI: 10.1177/1754073914565517
er.sagepub.com

Multiple Arousal Theory and Daily-Life Electrodermal Activity Asymmetry

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Abstract

Using "big data" from sensors worn continuously outside the lab, researchers have observed patterns of objective physiology that challenge some of the long-standing theoretical concepts of emotion and its measurement. One challenge is that emotional arousal, when measured as sympathetic nervous system activation through electrodermal activity, can sometimes differ significantly across the two halves of the upper body. We show that traditional measures on only one side may lead to misjudgment of arousal. This article presents daily life and controlled study data, as well as existing evidence from neuroscience, supporting the influence of multiple emotional substrates in the brain causing innervation on different sides of the body. We describe how a theory of multiple arousals explains the asymmetric EDA findings.

Keywords
affective computing, ambulatory measurement, electrodermal activity (EDA), emotional arousal, idiographic research, sympathetic nervous system (SNS)

In all of its varieties of theories, including dimensional and continuous, categorical and discrete, appraisal-driven, consisting of action tendencies, socially constructed, or comprising core affect together with experience-driven influences, the concept of emotion has included some kind of capacity for physiological arousal. Over a century ago, Wundt (1897) identified excitement–calm and tension–relaxation as two of three dimensions forming the basis of feeling and emotion (the third being pleasant–unpleasant). Today, physiological arousal is typically conceived of as a single dimension, anchored on one end by "low arousal," an activation level which occurs in states such as calm relaxation or deactivating depression, and on the other end by "high arousal," which occurs in states such as hot anger or exuberant joy.

Importantly, emotional arousal is not the same theoretical construct as emotion "intensity," despite that the two are often confused. For example, low arousal may accompany a state of peaceful, quiet joy, while high arousal may accompany a state of fist-pumping joy. In that case, arousal is easily confused with intensity of the joy. However, emotion intensity is not the same as emotion arousal. The classic counterexample is depression: Intense depression, as when a person can hardly get out of bed, is low arousal. Thus, the "intensity" of depression acts in opposition to its "arousal," providing support that emotion intensity and arousal are independent concepts.

It sounds odd to propose having different arousal on one side of your body than on the other, or that you might somehow have both high and low arousal at the same time. After all, what would that "feel" like? Doesn't an experience of arousal apply to the whole body? The concept of arousal has classically been recognized as a unitary state, since emotional experience of arousal is generally a unified experience of overall activation. For example Bradley and Lang's self-assessment manikin (SAM; 1994) showed that you could ask people to directly self-report their arousal level with one question, and this led to a response that was highly correlated to a more complex semantic differential scale devised by Mehrabian and Russell (1974). While that work was shown in lab studies where participants viewed images,

Author note: We would like to thank all participants who shared their data. This work was funded by the Media Lab Consortium.
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many projects in affective computing have used SAM's single item responses for both arousal and valence outside the lab (Isomursu, Tähti, Väinämö, & Kuutti, 2007; Morris, Dontcheva, & Gerber, 2012; Väätäjä, Vainio, Sirkkunen, & Salo, 2011). The simplicity of a single dimension is appealing for quick labels, despite that dimensions relying on self-reported labels still contain ambiguities, as nicely described by Russell (2003).

This article is not the first to propose that a classically considered single dimension of emotion may need to be reconceptualized. Consider the classical emotion dimension of "valence," with endpoints typically labeled as positive or negative, usually associating positive with pleasing or attractive, and negative with displeasing or aversive (Schlosberg, 1954). While frequently acting in opposition, both positive and negative, and both attractive and aversive experiences may also be coactivated (Norman et al., 2011). For example, a person might experience a "disappointing win" feeling both pleased to win and displeased to obtain much less than expected. Norman et al. advocate that valence is better measured with two dimensions, one indicating low-to-high positivity, and another indicating low-to-high negativity.

The rationale to shift from a single dimension of valence to one that has separate dimensions for positive and negative drew upon increasing knowledge of how multiple levels of the nervous system engage in distinct and at least partially independent evaluative processes, which can simultaneously provide input. For example, a person may vacillate when encountering an aversive object or stimulus, approaching with cortical reflections, "it's good to get a vaccine" and withdrawing suddenly via spinal mediated neural activity when feeling the pain of the needle. The bivalent conception of valence measures two dimensions, making a plane that subsumes the traditional bipolar dimension. Thus, the expanded conception of valence allows both a positive dimension and a negative dimension to vary, without requiring that they always be in opposition.

We propose the usefulness of a similar theoretical conception for the arousal dimension, through the recognition of multiple arousals. Like Norman et al. (2011), we bring together a review of neuroscience findings that support multiple levels of the nervous system that contribute to emotional arousal. With affective computing's emphasis on objective measures, we suggest changing the classical electrodermal activity (EDA) measure of arousal from one that is usually measured on only one side and assumed to apply to the whole body, to one that separately reports the levels for different regions, such as the two wrists.

While the two sides of the body typically provide synchronized measures, just like positivity and negativity typically covary, we show that there are times when the two sides give different information. We show this in what follows with both case studies and a lab-based study. A theory of multiple arousals allows for a construct that does not require the two sides to be the same; indeed, when the sides differ, the pattern can be informative.

This article presents findings from physiological measurements made during affective computing experiments that open up a different theoretical conception for the arousal dimension of emotion: Arousal, when measured as core autonomic physiology, may occur in different ways around the body. Moreover, multiple arousals present in physiological expression can provide finer affective meaning than has been achieved with one single unitary concept of arousal.

Long-Term Measurement of Arousal Using EDA

Emotional changes have been observed in objective measurements of EDA for over 125 years (Fere, 1888; Vigoroux, 1879). EDA has been argued to be a great physiological correlate for representing emotional arousal using a variety of different ways of eliciting emotion (Bradley & Lang, 2000; Lang, Greenwald, Bradley, & Hamm, 1993). In particular, EDA is described by physiologists as produced purely by the sympathetic nervous system, thus allowing EDA to provide a sensitive measure of sympathetic nervous system arousal (Critchley, 2002).

Over the decades, a variety of methods to measure EDA have evolved, with an eventual standard developed over three decades ago for laboratory use. The standard recommends measuring skin conductance by applying a direct current (DC) current to the surface of the skin, using gelled electrodes attached snugly to either the palmar or plantar surfaces (Fowles et al., 1981). While this standard continues to be in use, gives sensitive measurements for lab studies, and has provided enormous value to the community making studies more comparable, neither of these measurement sites is practical for continuous daily long-term wear. Continuous wear is increasingly needed in affective computing and clinical studies where sensors are worn for weeks or months. Sensors on the palmar surface interfere with washing the hands, typing, and handling a variety of objects and tasks, while those on the plantar surface interfere with wearing shoes and an active lifestyle. Gels are also a problem: they degrade over hours of wear and interfere with the signal being measured.

An emerging alternative for ambulatory long-term measurement is to use dry electrodes, rely on natural skin hydration, and apply the current to the distal forearm, otherwise using the same technique as the standard. This method has been compared to the traditional palmar site and shown to give significantly correlated EDA responses on a study of 26 participants between the ages of 18 and 56 during three experimental stress conditions (physical, emotional, and cognitive tasks; Poh, Swenson, & Picard, 2010). Another independent validation study with 17 participants showed similar findings in emotionally induced sweating (van Dooren, de Vries, & Janssen, 2012), comparing 16 different body locations and finding that EDA measured at the wrist was positively correlated with EDA measured at the fingers. These findings make an EDA sensor worn on the wrist a practical alternative.

The value of monitoring long-term EDA from the wrist has been shown in multiple applications. Wrist-worn EDA sensors with dry electrodes have been worn for up to 7 days straight[1] by active children with drug-resistant epilepsy, reliably gathering

data that showed EDA improves the automated recognition of generalized tonic-clonic seizures (Poh, Loddenkemper, Reinsberger, Swenson, Goyal, Sabtala, et al., 2012). The children were free to get out of bed, play active games, wash their hands, and more. Moreover, long-term recordings enabled an exciting new medical discovery—a significant correlation between the amount of EDA and the duration of postseizure brain wave suppression (Poh, Loddenkemper, Reinsberger, Swenson, Goyal, Madsen, et al., 2012). The wrist location has been used successfully for measurement of autonomic stress in call centers (Hernandez, Morris, & Picard, 2011), for communication of emotional arousal in autism (Picard, 2009), for identifying emotional arousal in children eating in the absence of hunger (Pieper & Laugero, 2013), and for measurement of arousal during sleep (Sano & Picard, 2011).

Following the standard recommended over 30 years ago, most researchers have measured only the left palmar surface, usually from the medial or distal phalanges on two fingers or from the hypothenar and thenar eminences on the palm for a right-handed participant. In long-term measurement from the wrist, we approximated the standard by placing the sensor on the nondominant forearm near the palm. At MIT, because we were measuring particularly active children swinging from zip lines and jumping in ball pits, we asked participants to wear sensors on both left and right wrists and/or on both legs, on the lower calf just above the ankle. We initially believed that measuring multiple sites was helpful only to cancel signal noise due to motion artifacts. We expected the two sides would give similar data with wrists giving slightly higher responses than ankles; however, we found significant surprises.

First, there would often be a slight offset in amplitude between the two wrists or two ankles. We verified that the sensors were calibrated to be the same and that asymmetry happened even without motion artifacts. We surmised that the offset might be caused by one side of the person's body having a higher density or responsiveness of sweat glands than the other, or one side's sensor being tighter than the other, or one side having increased pressure applied due to position or motion. After all, most people are not perfectly symmetric, nor do they move with perfect symmetry—one leg is stronger than the other, one hand is larger, one side may sweat more. Small amounts of asymmetric physiological variation can be expected.

However, when we measured long-term within the same person (idiographic studies), we saw huge asymmetry come and go in a way not explained by the aforementioned sources of variation. Moreover, the asymmetry aligned in time with emotionally significant events. An example of such all-day data, measuring both wrists and both lower legs above the ankles is shown in Figure 1. This example shows 9 hours of data from an adult celebrating her teen's birthday by taking him and friends to Six Flags amusement park. Most of the day her two wrists are at essentially the same level (symmetric) and her two legs are symmetric, even though the legs usually have lower skin conductance level (SCL) than the wrists. However, this graph also shows two periods of strong asymmetry: before ~9:15 a.m., and from ~11:15 a.m. to ~12:15 p.m.

What explains this arousal asymmetry? While the following is just one case and does not constitute proof of general cause and effect, the data fit a pattern consistent with a converging set of neuroscience-based findings.

The participant, called "Chris," described the day as overall very positive. (Asymmetry does not map simply to "positive" or "negative" arousal.) Most of the day her SCL is symmetric: Her two wrists have nearly the same SCL, and her two legs have nearly the same SCL, albeit lower than the wrists. The first section of pronounced asymmetry corresponds exactly to the time period when there was a threat that the day's plans would be called off, an outcome that had happened before, which Chris worried was happening again. This segment can be described as filled with two kinds of arousal—anticipatory arousal of a fun day, and anxious arousal that the event may be called off. Around 9:20 a.m., she learned the event was on: Chris's emotions switched to relief and excitement. At this point, there is also a significant drop in right wrist SCL, and the left wrist SCL increases above the right SCL. This segment is followed by a relaxed lengthy highway drive, accompanied by lowered SCL with symmetry.

The other large asymmetric episode corresponds to the other main threatening experience of Chris's day, 11:15 a.m. to noon, and contains multiple peaks. The first peak occurred while standing in line worrying that their entry passes might be rejected. Importantly, this segment has little motion, in contrast with the early morning asymmetry that had a lot of motion. The next two huge asymmetric peaks are when they are standing in line and riding the ride that made Chris ill on her previous visit. We looked at the left and right motion during these asymmetries and the difference in the two sides' arousals cannot be attributed to motion. As with both positive and negative valence being capable at the same time, Chris described two kinds of arousal during the periods of asymmetric EDA: standing in line in "silent dread" of the ride, while also feeling proud and excited that the teens behaved positively during the long waits.

The Six Flags example shows periods of both high and low arousal that are symmetric—for example the huge symmetric peak around 14:15 as well as most of the valleys. Thus, asymmetry was not simply associated with a particular range of SCL. Also, the asymmetry is not generally associated with physical activity: Most of the afternoon had symmetry even though it contained the same physical activities (standing in line, walking, rides) as during the times of asymmetry.

There are two kinds of arousal common to Chris's experience during the right-dominant asymmetric EDA segments: (a) attentiveness to a kind of "threat" of something that matters to Chris, for example, ruining the teenagers' day if she gets sick on the ride, and (b) excitement to provide a thrilling new experience to special people, and sharing in their joy. It is important to notice that this is not simply "negative arousal" versus "positive arousal." The right-dominant wrist asymmetry for Chris was seen consistently with threat and was not found when she reported negative states such as disappointment, anger, or frustration.

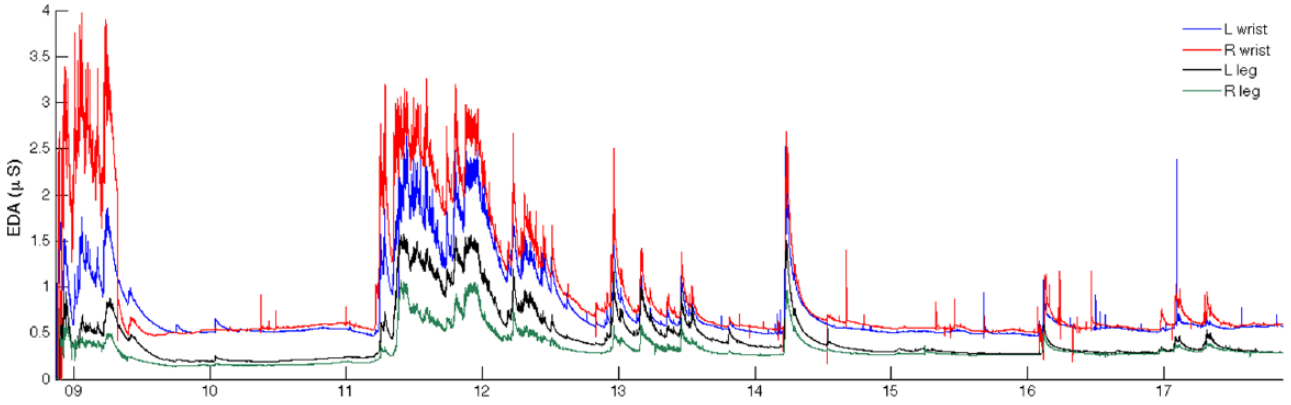

Figure 1. Four EDA signals. Amplitude is skin conductance level from the four limbs over 9 hours. For most of the morning, the amplitude of the right wrist (red) is largest, followed by the left wrist (blue), followed by the left leg (black) and the right leg (green). During the drive from ~9:30 to 11:10, and during the late afternoon and early evening, the two wrists are nearly symmetric, the two ankles are nearly symmetric, and all have fairly stable baselines. Significant right-dominant asymmetry happens before 9:15 a.m. when the event may be called off, as well as from 11:15 to noon while worried about getting into the park and dreading a ride that had induced sickness before.

The previous example was just 1 day. In order to see if an effect is strong and stable, we wish to test if it occurs long-term within a person, in a repeatable and reliable way. It was impractical for Chris to go back to Six Flags repeatedly during this study; however, when we looked at her daily two-sided measurements over multiple months, they showed an interesting pattern of events with consistent asymmetry, which we describe next.

Case Study: Long-Term Consistent Asymmetry

Chris gives presentations multiple times a week, and says she almost never gets nervous. However, she happened to be giving a special series of particularly high-stakes presentations on different days in front of potential partners and investors, and she described these meetings as especially important to her goals. We thus examined her long-term bilateral data, comparing all of her high-stakes presentations versus her other presentations that were "routine," such as presenting to her coworkers.

Figure 2 illustrates two contrasting meetings from the same afternoon. The first meeting is with her coworkers, and her EDA is relatively flat and symmetric, except for a pair of right-dominant peaks where she says she entered late, felt badly, and apologized, before launching her presentation. The second meeting she described as "exciting and exceptionally high stakes." We see that the high-stakes meeting has significantly more bilateral arousal, and more right-dominant asymmetry. Figure 2 shows for both wrists (red = right, blue = left): SCL, average activity score, and skin surface temperature. During the two meetings, the temperature and activity are fairly similar, and thus do not explain the huge differences in arousal that are seen.

Did we find this right over left asymmetry pattern to be consistent over time? Yes, in fact on days when Chris had an investor meeting, the right arousal during the investor meeting was her highest right arousal for the whole day. Eight out of nine investor presentations contained significant right-dominant asymmetry. The one exception had both significantly elevated right and left arousal, was slightly left-dominant and, interestingly, was the participant's overall favorite group to partner with. Figure 3 shows bilateral EDA from six of the high-stakes presentations, all with significant sections of right-dominant asymmetry. Each graph shows 90 minutes, including a little time before and after (the meetings lasted 55–80 minutes). The patterns of left and right arousal measured from the wrists thus showed consistency over time for Chris: high-stakes meetings almost always contained significant presence of right-dominant arousal, while routine meetings had mostly symmetric arousal.

A thorough investigation of the types of emotions involved in producing asymmetry is beyond the scope of this article; however, this idiographic study does show that long-term consistency can be found within an individual's asymmetry. In this case, it is not merely "face-to-face meetings" or "giving presentations" but it is specifically face-to-face presentations described as "high stakes" and "important" that tended toward right-dominant arousal. Other meetings tended to have low left and right arousal and little asymmetry except sometimes when things went wrong, as when our participant was late. Note that our participant described all her meetings as "positive" and "going well" despite that eight out of nine of the highest stakes meetings contained right-dominant asymmetry. While it does turn out to be true that her self-reported "best" investor meeting had the most left over right, and her "worst" investor meeting had the most right over left, these two instances do not prove a simple valence mapping. That said, the different EDA data on the two sides point to at least two sources of arousal.

Next we describe more examples from both case studies and controlled experiments, along with a review of the literature that grounds the theory for multiple arousals.

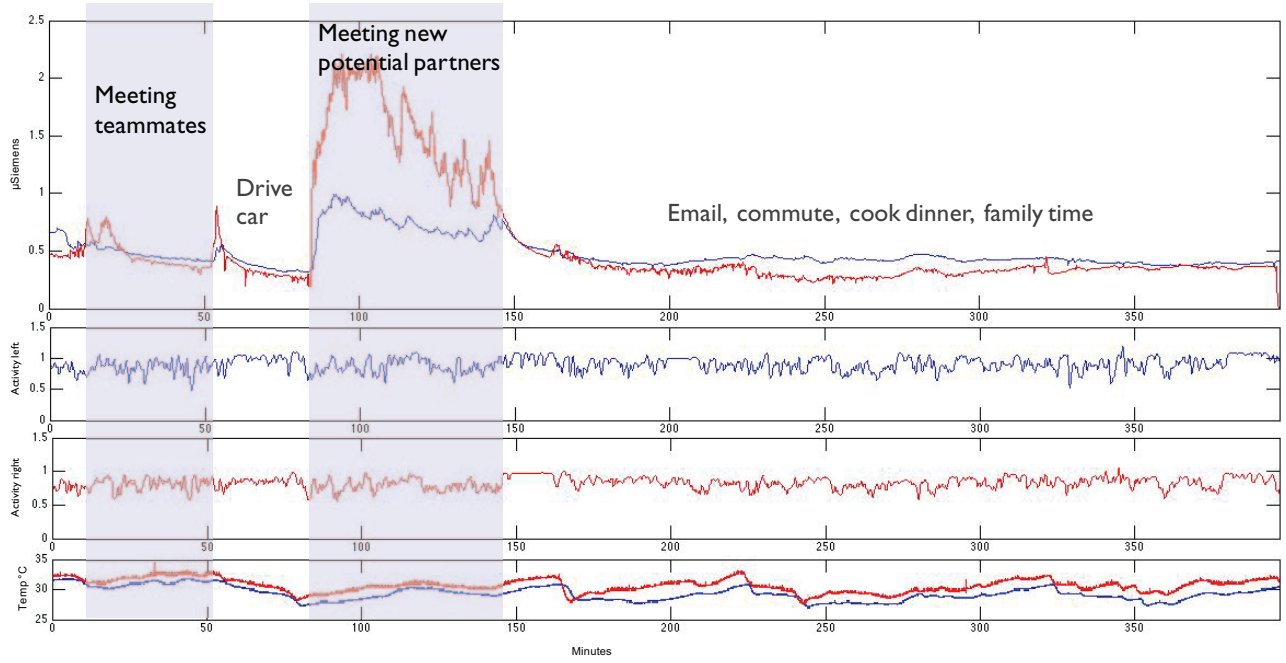

Figure 2. Five hours of bilateral data including two meetings (shaded). Red = right wrist, blue = left wrist. Top graph = SCL. Middle two graphs = activity level. Bottom graph = skin temperature. The team meeting has low and mostly symmetric EDA after the "sorry I'm late" entrance peaks. The high-stakes meeting with top potential partners has higher arousal on both left and right sides, with substantially more right arousal than left. Symmetry returns as soon as the high-stakes meeting ends.

Asymmetric EDA Examples From Ambulatory Field Measurements

First, we consider three sets of observations from long-term ambulatory recordings. In all the following cases sensors were worn on the wrists and recorded EDA using a DC current applied across dry 1cm diameter Ag-AgCL electrodes while measuring skin conductance.

Work threat: A bright young college-aged right-handed man had been working hard on a very important project for years. One day a major problem was discovered that threatened over a year of his accomplishments and had to be made public that day. He happened to be wearing an EDA sensor on his left wrist. He wore a sensor frequently, knew he felt stressed, and looked at the data expecting his skin conductance to be high. To his surprise, his left side was not high. He added a sensor on the right wrist. Later, he returned with the data, "The right side is high and the left side is not." The sensors worn on both sides were checked to confirm calibration within the same tolerance. He continued to wear two sensors and later confirmed that usually his two sides respond with similar levels.

Unexpected tragedy: A middle-aged right-handed woman was stunned and grieving with news of the unexpected death of a family member. She wore EDA sensors on both left and right wrists. Despite several tests (sounds, startles, pinches) to elicit arousal, her left side's skin conductance was almost nonresponsive and had a very low SCL while her right side showed a higher level and more skin conductance responses (SCRs) to the stimuli. This pattern held even after swapping her left and right sensors: her left side was still nonresponsive while her right side showed SCRs. The asymmetry held up during the next several nights of measurement of sleep as well, with the right side significantly higher than the left. After several days, the two sides went back to responding mostly symmetrically, which was normal for her.

Neurological threat: A young boy with limited verbal ability and diagnosed with autism was wearing sensors on both wrists as part of a home study to understand what causes him autonomic stress. At one point, one sensor had a signal that went up more than 5 times his daily maximum value, with a peak that was sustained for over 5 minutes. The signal went up on only one wrist. The sensor data was otherwise normal and symmetric on both wrists before and after the extreme asymmetry event, suggesting that both sensors were working fine. Later, it was learned that he had a generalized tonic-clonic seizure associated with the time period of asymmetric activation, including jerking movements on both sides of his body. The EDA asymmetry was not explained by motion as an observer confirmed that there was no interference (contact, change in pressure, etc.) applied to either sensor at the time of the seizure. An expert brain surgeon later explained that a seizure deep in the brain on one side could cause a sympathetic nervous system response on only that side of the body.

The previous examples show EDA asymmetry coming and going within the same person—suggesting that the arousal on the two sides of the body is under different mechanisms of control.

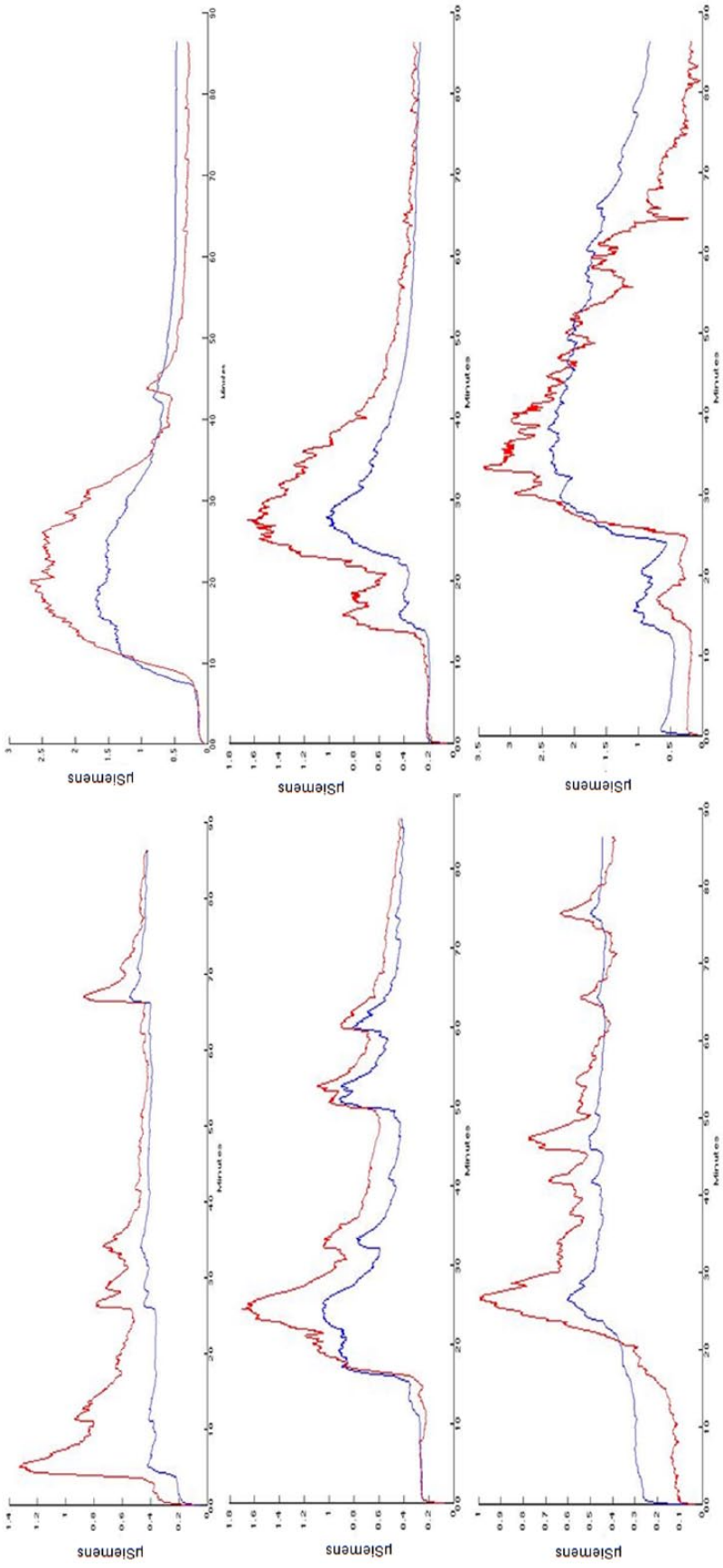

Figure 3. Left (blue) and right (red) skin conductance levels from a participant presenting in six "high-stakes" meetings to prospective investors. Each graph shows 90 minutes of data, and each contains a substantial amount of right-dominant asymmetry, which usually tapers off by the meeting's end.

Asymmetric EDA Examples in the Literature From Traditional Measures

We are not the first to find EDA asymmetry; many lab-based studies have measured the presence of EDA asymmetry on the left and right palms using traditional methods of EDA measurement, and several reviews of bilateral EDA studies have appeared (Boucsein, 2012; Miossec, Catteau, Freixa & Roy, 1985; Hugdahl, 1984; Kayser & Erdmann, 1991) These reviews mostly covered work during a time when hemispheric specialization was popular and researchers attempted to relate bilateral EDA measures to verbal/spatial, positive/negative, emotional/nonemotional specialization, with conflicting findings. Criticisms of the work at that time include methodological and conceptual problems such as asking participants to respond verbally (left brain) to spatial questions (right brain), not controlling for motor activation such as requiring a button push with one hand, not allowing for interhemispheric transfer times, not recognizing that many right-handers are not "pure" right-handers, assuming that an entire hemisphere is purely associated with all of emotion, assuming that valence neatly maps across the hemispheres, and more (Miossec, Catteau, Freixa i Baqué, & Roy, 1985).

We suggest another problem with the prior work on asymmetry given what we've seen increasingly with long-term data collection. The literature on EDA asymmetry made only short-term measurements and associated the short-term measures, for example, right > left (right signal higher than left), with long-term attributes of a person, for example, "normal" or "schizophrenic." Today we know that healthy adults having no known diagnoses can have EDA symmetry that changes with a variety of experiences. When measured for a long time the same healthy person will have periods of time where his or her EDA will have right > left, or left > right, and periods when the two sides are symmetric. Also, the same person may have periods of time with lots of SCRs, and periods with very flat nonresponsive EDA, a condition that would be interesting to examine in light of findings on stability and lability (Schell, Dawson, & Filion, 1988). Given the varied patterns seen in long-term measurements, we should be cautious of studies that rely on short-term "snapshot" measurements to explain long-term traits. On the other hand, if the measures do hold long-term for an individual, for example, if a person routinely has huge right > left EDA in social settings, then this measurable pattern may be powerful for diagnostics.

Finally, there is another significant problem with past bilateral EDA studies, which motivates the next section. Most of the early EDA studies assumed that "left brain activity" such as verbal activity should influence the right palmar EDA, while right-brained activity should influence the left palmar EDA. Thus, when researchers found that right EDA was lower than left EDA with a verbal stimulus, they concluded that the verbal stimulus was *inhibitory* toward EDA arousal on the right palm. This premise is likely to be flawed given other evidence about how the brain influences EDA. Next we review anatomical, brain imaging and direct brain stimulation studies that debunk the simple notion of contralateral EDA control and show that multiple sources of arousal influence bilateral EDA.

Evidence for a Theory of Multiple Arousals

Different fields of study have shown that multiple regions of the brain and body are involved in arousal, with influences descending from the brain to the skin as well as ascending from the viscera to the brain, especially to the amygdala and the basal forebrain in the processing of anxiety-related information (Berntson, Sarter, & Cacioppo, 2003). Drugs targeting different regions of the central nervous system evoke different kinds of arousal, as elucidated in studies of anesthesia (Brown, Purdon, & van Dort, 2011). Drugs can cause measurable changes to electrodermal response, for example, scopolamine may reduce EDA by blocking cholinergic responses (Patterson & Venables, 1981). The scopolamine effect was one of the earliest showing that cortical arousal and behavioral arousal were different (Longo, 1956). Drugs such as diazepam (an anxiolytic), clonidine (an antihypertensive), and haloperidol (an antiemetic) have such different effects that a unitary construct such as diminished arousal or "sedation" has been shown to be inadequate (Robbins et al., 1998). From a neural systems perspective, arousal processes are clearly not unitary; multiple sources of arousal interact in the brain, and have different kinds of effects on the mind and body, while details of their functioning continue to be elucidated.

In this article we ask specifically: Which regions of the brain give rise to significant EDA responses on which regions of the skin? In particular, which brain regions contribute to left and right palmar and dorsal forearm EDA? These are well-defined questions, and in the remainder of this section we review key findings pointing to multiple sources of arousal in the brain and their lateralized mappings.

Boucsein (2012) in his seminal book *Electrodermal Activity* gives an extensive overview of scientific beliefs regarding how the central nervous system (CNS) elicits EDA. He brings together anatomical studies, direct stimulation studies, and imaging studies showing that multiple brain structures contribute to producing EDA. Boucsein (2012, p. 41) summarizes three main pathways: two above the reticular formation and one part of the reticular formation:

> In summary the experimental as well as clinical evidence concerning the CNS elicitation of EDA points to the existence of two different origins above reticular level, which were already suggested by Edelberg (1972a): a limbic–hypothalamic source labeled EDA1, being thermoregulatory and also emotionally influenced, and a premotor-basal ganglia source labeled EDA2, eliciting electrodermal concomitants of the preparation of specific motor actions. In addition, there may be a reticular modulating system which mediates EDA changes that appear with variations of general arousal.

The so-called "EDA1" system arises from the limbic region, including structures known to play a strong role in emotion such as the amygdala, cingulate gyrus, anterior thalamus, fornix, hippocampus, and hypothalamus. This system is believed to be ipsilateral, drawing mainly on the early anatomical work of Schliack and Schiffter (1979). In short, activating several key emotion regions on the right side of the brain, such as the right amygdala, produces right palmar EDA activation. Similarly,

activating the left structures such as the left amygdala produces left palmar EDA activation.

The so-called EDA2 system, including the basal ganglia and premotor cortex, is contralateral in how it activates EDA. Thus, clicking a mouse button with the right hand should elicit EDA on the right palmar surface if the motion is generated from the left premotor cortex. Tasks that require the participant to move, even to click a button on a mouse, should take this contralateral influence into account.

The reticular modulation of EDA is believed to be "likely ipsilateral" in humans although this is not the case in cats, which have more cross-limbic pathways, where it has been shown to be contralateral (Boucsein, 2012).

Stimulating Brain Regions to Elicit Electrodermal Arousal

A particularly intriguing study is that of Mangina and Beuzeron-Mangina (1996) who were motivated to investigate bilateral EDA after finding striking asymmetries of EDA in children and adolescents with learning disabilities (Mangina, Beuzeron-Mangina, & Grizenko, 2000). They subsequently conducted the first study that directly stimulated regions of the human brain through intracerebral electrodes while simultaneously recording bilateral skin conductance on the palms, giving a relatively "pure" stimulus–response set of measurements. A limit of their study is that their five patients had implanted electrodes because of epilepsy. However, all were free of anticonvulsants and other medications for 1 week prior to and including the time of the recordings.

Stimulations that triggered epileptic discharge were discarded, as were stimulations that contained motion artifacts or nonspecific EDA responses directly prior to the stimulation. All patients were left-brain dominant for speech and right-handed as measured by the Sodium Amytal Test. For each patient, 48 stimulations were delivered to 12 different brain regions (four per region). The resulting mean values of the SCRs for the set of 240 stimulations are shown in Figure 4, which we reproduce from the table of numbers in their original paper (Mangina & Beuzeron-Mangina, 1996).

Figure 4 reveals three important findings: (a) Responses to direct stimulation of the eight limbic regions are strong and asymmetric: The left amygdala, left anterior hippocampus, left posterior hippocampus, and left anterior cingulate gyrus gave strong and statistically significant EDA responses on the left side of the body and almost no response on the right. Ipsilaterality also held when the limbic structures on the right side of the brain were directly stimulated. In particular, the amygdalae gave the strongest EDA responses. (b) Responses to direct stimulation of the four cortical regions were small and symmetric: left and right frontal cortical convexities and left and right mid cortical regions of the second temporal gyri contributed equally to the left and right palmar EDA. (c) The response from the limbic regions was significantly stronger than the cortical regions. In summary, strong and ipsilateral EDA responses were found with the stimulation of eight limbic brain regions involved in emotion. Meanwhile, weak and symmetric or absent EDA responses were found with stimulation of four cortical regions.

The Mangina & Beuzeron-Mangina (1996) findings provide strong support for multiple pathways of arousal, measured as EDA asymmetry in patients during medication-free and seizure-free times. While we have to be cautious not to overgeneralize from one patient population or from a small set of five individuals, the finding is a compelling one because of the direct procedure employed, the significant strength and specificity of the mappings, and their consistency with anatomical studies that identified limbic ipsilateral pathways many years earlier and by independent methods.

If you stimulate the left and right amygdala directly in humans, what happens to reported emotional experience? Another direct stimulation study (Lanteaume et al., 2007), tested this with eight epilepsy patients via intracerebral electrodes. The patients reported their emotions on Izard scales (Izard, 1977), rating each of nine emotions on a scale of 1 to 5, for a total of 4–9 stimulations per patient, totaling 69 stimulations across the study. Ratings were carried out just before the study to obtain a baseline, as well as after each stimulation to identify significant changes relative to baseline. Lanteaume et al. (2007) found that 100% of the electrical stimulations of the right amygdala evoked negative emotions. The negative emotions fear, anxiety, and sadness had scores significantly higher than those for anger, disdain, disgust, joy, and happiness ($p < .05$). Reported joy and happiness decreased after right amygdala stimulation. Moreover, the right amygdala stimulations evoked negative facial expressions as measured by facial electromyogram on the corrugator supercilii. The left amygdala stimulations led to mixed results, evoking either positive or negative emotions. Of left stimulations, 47% induced negative emotions, with increases in fear, anxiety, sadness, and decreases in happiness and joy, and these also induced corrugator supercilii activation. However, 53% of left amygdala stimulations evoked positive emotions with joy and happiness increasing after stimulation, and scores for sadness and anxiety diminished ($p < .05$ in all cases). Consistently, the left amygdala stimulations that evoked positive emotions did not evoke corrugator activity.

In summary, direct left amygdala stimulations contributed to increases in either positive or negative emotions, while right amygdala stimulations contributed to increases in three negative emotions, namely fear, anxiety, and sadness. Again, we do not suggest that the "right side is negative" which would be overgeneralizing: Lanteaume et al.'s (2007) study did not find support for the negative emotions of anger, disdain, or disgust with the right amygdala stimulation; the support was specific to anxiety, fear, and sadness.

The participants in Lanteaume et al.'s (2007) study were not asked to report arousal; however, SCRs were measured on the palmar surface of the side being stimulated, following the findings of Mangina and Beuzeron-Mangina (1996), and showed that 100% of the stimulations with emotional modifications induced SCRs on the ipsilateral palm. Additionally, the amplitudes of the SCRs were significantly larger when stimulations

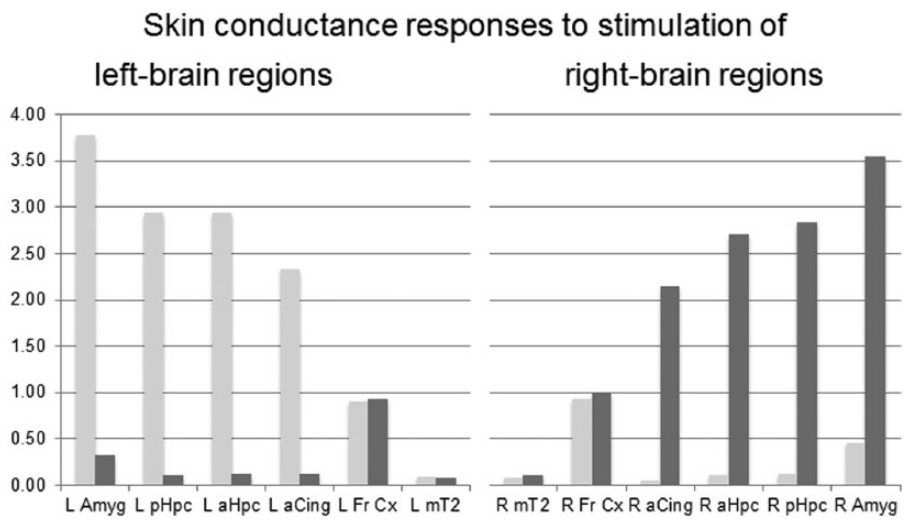

Figure 4. Mangina and Beuzeron-Mangina (1996) obtained these skin conductance responses to stimulation of left and right brain regions.
Mangina and Beuzeron-Mangina (1996) obtained these skin conductance responses to stimulation of left and right brain regions. Dark and light bars represent skin conductance measured on the right and left palm respectively.

induced emotional changes, whether pleasant for the left amygdala stimulation ($U = 6$, $p < .0001$) or unpleasant for both right ($U = 38.5$, $p < .0001$) and left amygdala stimulations ($U = 17$, $P < 0.0001$), compared to when they did not induce emotional changes. Unfortunately, Lanteaume et al. (2007) only measured the EDA on the same side being stimulated, so we do not know if emotions such as fear, anxiety, and sadness contributed symmetrically or asymmetrically to EDA. We hypothesize that they should contribute asymmetrically, provided that the emotions are genuinely experienced and their sources of arousal in the brain are lateralized.

A caveat when reviewing the literature is that most of the laterality results were derived from EDA measurements made on the palmar surface, but some were derived from measurements made on the plantar surface. As we saw in Figure 1 the direction of asymmetry in the lower limbs can differ from the upper limbs. Thus, it is not safe to assume that brain regions "that influence the right side" will equally influence both the right arm and the right leg. Our data suggest that we should no longer think of the left plantar and the left palmar surfaces as receiving the identical source of electrodermal activation. It is quite possible that signals cross once they carry to the lower limbs, and that other factors affect the dermatome mappings as well. We recommend that until the mappings have been fully characterized, laterality studies on humans measure all four limbs and *not* assume that the upper limbs will have the same asymmetry as the lower limbs.

Asymmetry observed when imaging brain regions related to arousal. Many brain imaging findings, while providing less specific correlations than direct brain stimulation, provide findings consistent with the significant influences found by Mangina and Beuzeron-Mangina (1996). Critchley (2002) provides a broad overview covering many interacting brain systems that contribute to EDA including both ipsilateral limbic structures and various cortical systems that influence them. We review a few key ones below showing new EDA-based evidence for multiple arousals.

Tranel (2000), as part of studies looking at the role of the ventromedial prefrontal cortex (VMPFC) in eliciting EDA during decision making, found that patients with extensive damage of the anterior cingulate gyrus also had significant impairments in skin conductance responses to stimuli that included affect-laden slides as well as loud noises and taking a deep breath. This is consistent with the direct stimulation findings showing the anterior cingulate gyrus is a strong source of the EDA response (Mangina & Beuzeron-Mangina, 1996).

Bechara, Damasio, Damasio, and Lee (1999) measured EDA on five patients with bilateral amygdala lesions and no VMPFC lesions; these five were unable to develop anticipatory SCRs during decision making, and were unable to produce SCRs as a consequence of reward or punishment. However, the same patients did have working EDA, as it responded to loud noises. This is consistent with the direct stimulation findings that the amygdala is a strong source of EDA and yet it is not the only source; multiple brain structures contribute to multiple kinds of arousal.

Raine, Reynolds, and Sheard (1991) claim to have made the first study with MRI of normal humans while eliciting skin conductance orienting responses using auditory stimuli while measuring both left and right EDA, but their stimuli are only auditory prompts designed to elicit orienting responses. With 17 normals, they did find EDA responses significantly correlated with activity in the right and left prefrontal areas, area of the pons, and left but not right temporal/amygdala area, and they confirmed no relationships with areas thought to be unrelated to skin conductance (cerebellum, nonfrontal cortical, medial prefrontal, and third ventricle). However, they only give averages of left and right EDA responses across the group so it is unclear if their study contained participants who experienced asymmetries.

Because the way they elicited activation was with startle, and not with threat, fear, anxiety, or sadness, we would not expect to see significant asymmetry unless some subjects felt anxious just to be in the scanner or in the study.

Raine et al. (1991) separately made seven different EDA measures—including SCLs, orienting responses, and nonspecific skin conductance fluctuations, for different auditory stimuli, and on both the right and left palms. They found that in all cases the right skin conductance measures had significantly higher correlations to the right prefrontal activation than did the left skin conductance measures. Their data lend further evidence that the right and left palms can receive different sources of arousal.

A variety of studies involving brain imaging have shown associations between right amygdala activation and anxiety. For example, a study with 42 children who met criteria for autism spectrum disorder found a significant association of anxious/depressed symptoms with right amygdala volume ($r = .469$, $p = .002$) but not with left amygdala volume ($r = .249$, $p = .112$). Also, the Child Behavior Checklist anxious/depressed scores were a significant predictor of right amygdala volume ($p = .002$; Juranek et al., 2006). These findings did not measure bilateral EDA, but with our theory we can make predictions such as, all other factors constant, the larger right amygdala activation would contribute to larger right EDA in a right-hander experiencing significant anxiety or depression. Moreover, studies that measure only left arousal might miss this effect.

Studies of generalized anxiety disorder (GAD) in 17 youth volunteers and 12 controls with no psychiatric diagnosis have shown larger right amygdala activation when youth viewed masked angry faces (and not masked neutral faces). The amount of right amygdala activation also correlated positively with GAD severity (Monk et al., 2008). Vigilance to threat is common in GAD. In multiple healthy right-handed adults we have seen consistency of right-sided "threat-related" EDA responses, which would be expected with greater right amygdala activation.

The presence of an experimenter watching a participant may be an important consideration in bilateral studies. While most studies ignore this effect when there is "no explicit interaction" the fact is that the presence of an experimenter can lead to a response in some participants who may have social anxiety. Social anxiety disorder is a condition that has exaggerated right amygdala responsiveness when participants are presented with angry "schematic faces" (line drawings) versus neutral schematic faces (Evans et al., 2008). Such an effect would also be hypothesized to contribute to greater right EDA, again controlling for other influences on EDA.

What do all of these findings suggest about multiple arousals contributing to asymmetric EDA? If an affective state such as anxiety were to activate more right brain structures that elicit ipsilateral EDA than left, then all other things controlled, we should expect to see EDA go up more on the right palmar region than on the left palmar region. Furthermore, we expect that the same ipsilateral responses apply to the forearm or wrist because their innervation pathways overlap those of the palm. That said, this effect could be diminished or flipped if there are contralateral motor influences or if there is greater activation of a brain structure that elicits more EDA on the left. We recommend that study designers consider the multiple sources of arousal. We anticipate that measuring both right and left responses could affect published findings even in classic paradigms. We illustrate this in the next section with a controlled study.

Asymmetry of EDA measures of arousal in a controlled study. Recently, our lab reproduced a classic experiment eliciting autonomic arousal. We measured EDA on both wrists and on both legs just above the ankle, using beta versions of the Q sensors made by Affectiva. These sensors used 1cm Ag-AgCl dry electrodes while measuring skin conductance, 3-axis accelerometer, and skin-surface temperature. Participants put on the sensors then (after an initial 10-minute rest) walked up and down a set of stairs and through an air-conditioned office building. Then they rested for a 10-minute baseline period. Then they rested for a 10-minute baseline period. Then, each participant was asked to follow instructions on a computer screen to perform serial subtractions in intervals of seven starting from 4,000 and counting down, speaking the numbers out loud until a visible countdown timer reached zero. An experimenter sat behind the participant and sounded a buzzer with mistakes. The participant had to correct the mistake out loud before continuing.

We measured EDA on the wrists of 25 healthy adults (10 male, 15 female), aged 19–30, all but one who said they were right-handed (#23 was left-handed). Median values of skin conductance level (SCL), shown in Figure 5, showed similar asymmetry per person as the mean values. The data show that 19 of the 25 participants have higher right than left wrist arousal. Striking is the distribution of the asymmetry: while most people are only slightly asymmetric, the seven who had the highest right EDA also have huge asymmetry (participants 24, 16, 22, 12, 5, 18, and 13). These right-dominant responders include both genders and a broad distribution of ages. If the asymmetry were a random effect, then we would expect to see it show up also on the left side of Figure 5, which does not happen. The data show only one of the participants has significantly higher left than right activation, and this participant has the lowest right activation. Overall during this task, there is significantly more right than left arousal ($t = 3.0607$, $df = 24$, $p < .01$).

While many more experiments are needed with multiple groups and situations in order to prove a cause for arousal asymmetry, one reasonable hypothesis is that some participants felt slightly more "threat" or "higher stakes" to perform well in this experiment, or felt more social anxiety, while not experiencing equivalently large positive arousal. The only motor effort required in this study was speech and all participants were seated and relatively still during the task. We did measure wrist accelerometer activity for all the participants and while some did move during the task, the movement does not account for the asymmetry seen in their EDA arousal.

This study shows that very different conclusions may be obtained when autonomic arousal is measured on both sides than

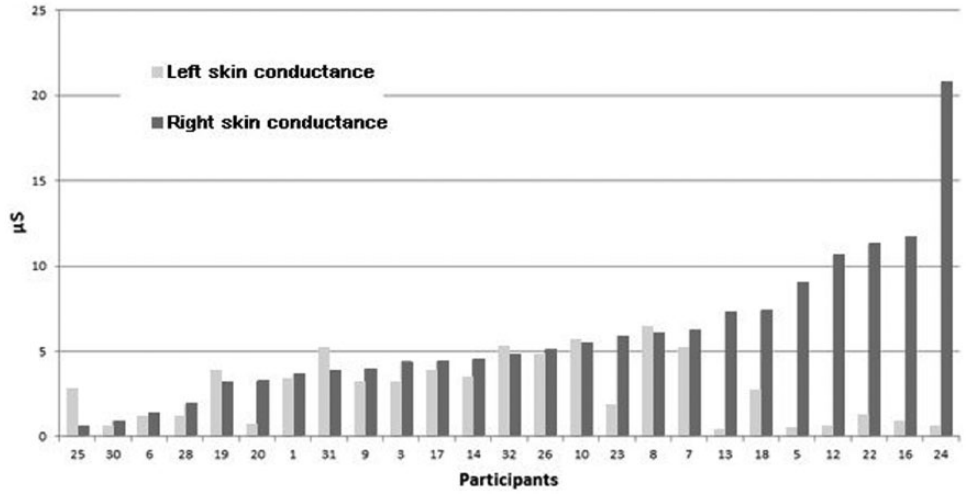

Figure 5. Median values of left (blue) and right (red) skin conductance level of 25 participants during a stressful counting-backwards-by-7s task. The participants are ordered by increasing right-sided arousal. Those with the largest right arousal also have the largest asymmetry.

on only the standard nondominant side. The standard methodology, measuring only the left side, would have concluded that six of the right-most participants in Figure 5 were not aroused. The bilateral measure shows they had huge right arousal.

Our multiple-arousal theory suggests another explanation for the mixed findings in so many of the bilateral EDA reviews done decades ago. Most of them focused on tasks with *cortical* left–right hemispheric differences, and assumed contralateral mappings of each half of the brain. Now that we have both anatomical studies and direct brain manipulation studies showing ipsilateral mappings for multiple limbic-EDA pathways, we can make more specific predictions about asymmetry of EDA under different emotions. We can plausibly suggest that underlying emotions such as fear or anxiety could contribute to greater right amygdala activation, and to right EDA, in a right-hander. Moreover, mouse movement with the right hand could potentially contribute to right EDA because of contralateral premotor influences on EDA. In short, we see that it is not enough to think about "right brain" or "left brain," but we need to think about which cortical or limbic regions of the right or left brain are activated, and which sides of the body they map to when eliciting autonomic arousal. Finally, since wrist measures can today be made long-term, we can also assess whether any asymmetry in arousal is a short-term "experiment-only" event or a long-term characteristic.

Summary and Discussion

Affective computing's emphasis on measuring emotion outside the lab has provided sensors that are comfortably wearable day and night for months, collecting unprecedented hours of real-life emotional arousal data. The data indicate that sympathetic nervous system arousal, traditionally measured on only one side of the body via EDA, can have very different responses when measured on both sides. We showed examples from days where asymmetric right and left EDA was present during certain events, where symmetry was present before and after the event, and where the asymmetry is not explained by motion, temperature, or other observables. While asymmetry is amplified more in the presence of high arousal, we showed that it is not a consequence of high arousal—as we see high arousal with both symmetry and asymmetry in different Six Flags rides. For one participant, measured over many days and experiences, the high arousal episodes containing strong right-dominant asymmetry were associated with face-to-face "high stakes" situations of personal significance.

We also showed evidence of strong asymmetry in a controlled lab study with a classical stressor that found right-dominant arousal in 19 out of 25 individuals. Importantly, the participants with the highest right arousal also had the lowest left arousal: They would have been misclassified as "low arousal" had the 30-year-old standard measure been used. Clearly, some kind of arousal is happening on the right, and it can be very different from the left. The multiple sources of arousal that we see when measuring both right and left data should cause us to rethink the vast literature on "emotional arousal," which has assumed that measurement at one point on the body represents one whole body arousal experience.

The finding of significant left and right arousal differences needs to be explained. While many more experiments are needed for a full theoretical explanation, this article sets forth the first steps of a "multiple arousal theory" by providing objective EDA data from both ambulatory and controlled laboratory studies, and a review of anatomical studies, direct stimulation, and imaging studies of brain regions involved in elicitation of arousal that influences EDA. The multiple-arousal theory suggests that different regions of the brain map their activation onto different positions on the body; thus, emotional experiences that differentially activate those brain regions may show up as different patterns of EDA across the body. While exploring those mappings remains as future work, this article argues that measuring both sides is an important first step.

In reviewing brain imaging and direct brain stimulation studies, we find evidence of multiple arousal eliciting mechanisms, some of which (primarily limbic regions) elicit EDA on the same side of the body, while others (primarily premotor cortex) elicit EDA on the opposite side of the body. Meanwhile, some cortical regions contribute symmetrically to the two sides. We suggest that the classic self-report notion of "arousal" in emotion research is a cognitive attempt to synthesize the multiple physiological arousals into one percept.

Our theory offers a different way to interpret findings on arousal that were based on lesion studies. Suppose it was concluded that, "a particular brain region X is not associated with arousal" since "a skin conductance response still occurred despite a lesion in X." Suppose further that this claim was made based on the standard one-sided measurement. An alternative explanation is that region X might contribute to arousal only on the side of the body not measured. There are also other possibilities, but the main point is that given the brain evidence for multiple sources of arousal, and several strong ipsilateral mappings, some of the prior conclusions in the literature may need reconsideration.

Direct brain stimulation studies showing strong ipsilateral EDA mappings may help resolve ambiguities in the left-brain versus right-brain studies of arousal in the literature. Those studies largely assumed EDA elicitation with contralateral cortical activation, despite that the main contributors to arousal were likely limbic and ipsilateral, or premotor and contralateral. While both right and left cortical activity can contribute to right-palmar EDA, the bigger and far dominant contribution is likely from right amygdala activity, right anterior or posterior hippocampus activity, or activation of the right anterior cingulate gyrus (Mangina & Beuzeron-Mangina, 1996).

We now know that it is possible that the right forearm EDA might show significant arousal while the left forearm EDA lies relatively flat. We have seen this occur within male and female participants, children and adults, under multiple case study conditions including anxiety, high-stakes threats, and seizures. The long-term data from one participant, discussed before, showed that a pattern of greater right-EDA activation during high-stakes meetings was consistent over time, while a pattern of symmetric EDA activation was consistent for routine meetings.

One of the areas that may be very important to consider moving forward in future bilateral studies is the role of background affect, such as produced by anxiety, depression, or pain. This type of affect is usually ignored in a study, but may arise in nonrandom ways that can influence the results. Emotions are about "what matters most" to a participant, and some participants can be more concerned with their performance in a study, or with some outside anxiety-producing situation, than with the distinction between two stimuli being presented. Unmeasured emotions are usually assumed to be random and to wash out with a large-enough group of participants; however, the fact is that some protocols may elicit emotional experiences among many participants. Protocols that foster social interaction or anxiety can significantly affect EDA; in some people these influences may provide a consistently asymmetric pattern. This bias should be considered when designing studies, as it may not simply "average out."

EDA is scientifically recognized as an objective measure of sympathetic nervous system arousal, and widely used as a practical measure of emotional arousal (Critchley, 2002). As a core dimension of "emotion," how can it happen in just one part of the body and not all of it? While the multiple arousal theory has not yet addressed the "experience" of arousal, which may remain unitary perhaps from integration across different regions of the body, we have found that different spatial patterns of physiological arousal can occur as measured by EDA. A promising area of future work is to look for which kinds of experience are consistently associated with patterns of arousal measured across the body. Multiple arousals may be activated in the brain and body and perhaps some of these may have different kinds of experiences associated with them.

An analogy to facial expressions may be appropriate: There are smiles that are symmetric, which arise both in true happiness and in true frustration (Hoque, McDuff, & Picard, 2012), and there are smiles that are asymmetric, or smirks, which tend to arise with contempt, doubt, and defiance (Senechal, Turcot, & el Kaliouby, 2013). Smiles do not equate to "happy," but as we measure their symmetry and dynamics, we start to uncover more of the affective qualities with which they do arise. Different parts of the brain tug on the two sides of the face, lending meaning to the different measurable outcomes. This article has argued that different parts of the brain also elicit arousal in different spatial patterns around the body. Measuring these patterns can help us better understand and interpret the multiple sources of arousal—perhaps even if one pattern may contain more anxiety or fear than another pattern.

Our recent work has focused on measurements of autonomic arousal on the wrists and ankles, while the traditional standard has measured palms and soles. Asymmetry has been found across both traditional sites as well as wrist/ankle sites, while the latter allow for much more data to be collected in real-world settings. We think there are patterns to be found across multiple dermatomes. From the moment each of us was an embryo we had three kinds of tissue: ectoderm, endoderm, and mesoderm. The ectoderm forms the nervous system and skin, and can explain why activation deep in the brain, such as in the right amygdala, can show up on the right palm or wrist, even when it does not show on a scalp EEG. Skin and neural tissue have been closely intertwined from embryonic form to our present adult form. The mappings from brain regions to skin regions are likely to contain a variety of valuable patterns.

While much remains to be learned, we know that multiple brain regions contribute to autonomic arousal. We have suggested that measurement of multiple points of EDA arousal is more informative than measuring only the traditional single nondominant palm. With a theory of multiple arousals, scientists can now begin to look for a more systematic mapping between the space of emotional experiences and measurable patterns of emotional arousal.

Note

1. Standard practice in the epilepsy monitoring unit involves no showering for the duration of the visit, while the child wears EEG and ECG (and our study added EDA).

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