

## Neuronal Excitability

# Lateralization of Autonomic Output in Response to Limb-Specific Threat

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## Abstract

In times of stress or danger, the autonomic nervous system (ANS) signals the fight or flight response. A canonical function of ANS activity is to globally mobilize metabolic resources, preparing the organism to respond to threat. Yet a body of research has demonstrated that, rather than displaying a homogenous pattern across the body, autonomic responses to arousing events, as measured through changes in electrodermal activity (EDA), can differ between right and left body locations. Surprisingly, an attempt to identify a function of ANS asymmetry consistent with its metabolic role has not been investigated. In the current study, we investigated whether asymmetric autonomic responses could be induced through limb-specific aversive stimulation. Participants were given mild electric stimulation to either the left or right arm while EDA was monitored bilaterally. In a group-level analyses, an ipsilateral EDA response bias was observed, with increased EDA response in the hand adjacent to the stimulation. This effect was observable in ~50% of individual participants. These results demonstrate that autonomic output is more complex than canonical interpretations suggest. We suggest that, in stressful situations, autonomic outputs can prepare either the whole-body fight or flight response, or a simply a limb-localized flick, which can effectively neutralize the threat while minimizing global resource consumption. These findings are consistent with recent theories proposing evolutionary leveraging of neural structures organized to mediate sensory responses for processing of cognitive emotional cues.

*Key words:* autonomic response; electrodermal activity; fight or flight; lateralization; threat response

## Significance Statement

The present study constitutes novel evidence for an autonomic nervous response specific to the side of the body exposed to direct threat. We identify a robust pattern of electrodermal response at the body location that directly receives aversive tactile stimulation. Thus, we demonstrate for the first time in contemporary research that the autonomic nervous system (ANS) is capable of location-specific outputs within single effector organs in response to small scale threat. This extends the canonical view of the role of ANS responses in stressful or dangerous stresses, that of provoking a “fight or flight” response, suggesting a further role of this system: preparation of targeted limb-specific action, i.e., a flick.

## Introduction

An organism’s ability to respond efficiently to threatening situations can mean the difference between survival and death. In the presence of an acute stressor, the autonomic nervous system (ANS), specifically, the sympathetic nervous system, signals the body to prepare for

action. Such ANS activation results in increases in cardiac and respiratory outputs, dilation of vasculature in skeletal muscles (in mammals), release of glucocorticoids into the bloodstream, and increased electrodermal activity (EDA; a measure of changes in electrical resistance across the

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skin because of modulation of the sweat glands; Critchley, 2002; Boucsein, 2012). This “fight or flight” response is highly conserved across vertebrate (Romero and Wingfield, 2016; Romero and Gormally, 2019) and some invertebrate (Shimizu and Okabe, 2007) species and its effective manifestation is critical to the deployment of specific survival behaviors (Blas et al., 2007; Lee and Wang, 2019; Romero and Gormally, 2019; Barrios et al., 2021).

The canonical role of the ANS is that of metabolic mobilization or conservation, demanded by situational cueing (Brener, 1987; Wehrwein et al., 2016; Gibbons, 2019). Emotional arousal in response to relevant events can trigger a sympathetic nervous response (for extended review, see Kreibig, 2010) including increases in sweat gland activity, as approximated through EDA (Vetruugo et al., 2003). Early theories proposed that such responses are homogenous across the entire body (Cannon, 1939). Although the field has moved on, current working assumptions still maintain generalized output to, and responses from, individual effector organs (Jänig and McLachlan, 1992; Folkow, 2000) mediated by a centralized autonomic network (Benarroch, 1993; Damasio, 1998; Valenza et al., 2019). Notably, with respect to the skin (the effector organ monitored during EDA recording), the contemporary division of ANS function still preserves the idea that the skin receives homogenous sympathetic output signaling the need for motor preparedness (Fredrikson et al., 1998; Blakemore and Vuilleumier, 2017; Le et al., 2019). Yet there is a substantial body of research (Richter, 1927; Freixa i Baqué et al., 1984; Picard et al., 2016) demonstrating that asymmetric ANS responses, as measured by changes in EDA, can differ between right and left body locations, albeit not always in a consistent manner (Bjorhei et al., 2019). One potential function of such asymmetry could be a limb-specific response to threat directed to one side of the body, challenging the assumption of global homogeneity. Surprisingly, the question of whether asymmetric ANS responses result from limb-specific threat has been almost wholly neglected.

Historical data from as early as the 1920s (Syz, 1926; Richter, 1927) provides evidence that ANS outputs, specifically, those monitored through EDA, are not always consistent across the body. Examination and explanation of these effects throughout the first half of the 20th century were minimal, relying predominantly on pathologic (Fisher, 1958; Fisher and Cleveland, 1959; Galbrecht et al., 1965) or structural (i.e., lesion dependent; Richter, 1927; Holloway and Parsons, 1969) justification for asymmetry,

albeit with some theories pairing EDA asymmetry to degrees of general arousal (Obrist, 1963). While interest in the area of lateralized EDA in both neuro-typical and atypical populations intensified in the 1970s (for review, see Freixa i Baqué et al., 1984), this was paired to the rise of theories evoking gross hemispheric specialization (i.e., right brain vs left brain rhetoric Sperry, 1968; Galaburda et al., 1978; Reeves, 1983), and overlooked what minimal evidence existed for a physiological basis for asymmetric ANS architecture (Fuhrer, 1971). As a consequence, much of this work fell into disrepute alongside the repudiation of the overarching frameworks in which they were nested.

Recently, incidental findings from the field of computer science have reinvigorated interest in EDA asymmetry. In data from wearable electrophysiological recording devices (Poh et al., 2010, 2012; Ayzenberg and Picard, 2014; Sano et al., 2014), collected for the purpose of training computer algorithms to sense, recognize, and respond to human emotional information (Picard, 2002; el Kaliouby et al., 2006; Picard, 2009), asymmetric EDA activity has been observed in response to specific types of emotional situation or arousal (Picard et al., 2016). This work has prompted a secondary resurgence of study on the lateralization of ANS outputs (Banks et al., 2012; Picard et al., 2016; Kasos et al., 2018; Bjorhei et al., 2019) primarily focused on understanding how data from wearable devices can be used to index biomarkers for mental health monitoring (Greene et al., 2016; Ghandeharioun et al., 2017; Mohr et al., 2017; Arza et al., 2019) and clinical impairment (addiction, Carreiro et al., 2015a, b; e.g., autism, Baker et al., 2018; dementia, Kourtis et al., 2019). Stemming from this line of research, the multiple sources of arousal theory (Picard et al., 2016) points to evidence that asymmetric EDA activation can result from ipsilateral signals from “limbic” regions, in particular the amygdalae, linked to stress or emotional arousal. It can also arise from contralateral signals from basal ganglia and pre-motor regions linked to motor preparedness.

In the context of canonical views of ANS functioning, however, ANS activation as a mechanism to mediate metabolic resource allocation, there is no clear reason why centrally-mediated arousal requiring whole body-responses would elicit greater EDA activity lateralized to one side versus another. Yet, the underlying architecture of the ANS is such that left-right signal variability undeniably occurs (Richter, 1927; Obrist, 1963; Freixa i Baqué et al., 1984; Banks et al., 2012; Picard et al., 2016; Bjorhei et al., 2019). Interestingly, however, almost all previous work displaying asymmetric EDA has involved stimuli that elicit generalized states of arousal not requiring body part-specific responding (Obrist, 1963; situational arousal, Freixa i Baqué and de Bonis, 1983; e.g., face perception, Banks et al., 2012; Picard et al., 2016; high vs low impact stressors, Bjorhei et al., 2019). However, it is unclear how asymmetric responding to generalized arousal could serve a functional purpose within the canonical role of the ANS, that of metabolic conservation; and thus, it is unlikely that these stimuli are the primary developmental motivators of the observed lateralized architecture. Rather, centrally mediated arousal processing is likely leveraging neural architecture based on physical responses to direct threat, where lateralization of

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response matters. Notably, there is almost no reference made to research conducted on direct tangible limb-specific tactile threat. Yet one largely forgotten historical assay provides preliminary support for the hypothesis that responses to limb-specific threat are lateralized (Fuhrer, 1971). Such preliminary evidence supports the hypothesis that a localized proximal threat to an organism may not require whole body action, but rather a targeted response in the threatened limb. Maximal conservation of metabolic resources would occur if sympathetic activation is evoked in the specific limbs required for the motion that will allow a return to safety, while the rest of the body maintains a state of rest.

The aim of the present study was to investigate lateralized changes in EDA in response to limb-specific aversive stimulation. Specifically, we aimed to identify whether increased sympathetic output is directed to a threatened limb, indicating a potential increase in resource mobilization limited to the site requiring subsequent motor response. To assess lateralization biases in EDA responses, we compared EDA activity from each arm during ipsilateral and contralateral stimulation. Consistent with theories of metabolic conservation in the ANS (Wehrwein et al., 2016; Gibbons, 2019), we predicted that EDA responses would be greater during ipsilateral stimulation, and that this bias would be observable when recording from both the left and right arm.

## Materials and Methods

### Participants

A total of 60 healthy participants (41 females, mean age = 20.45, SD = 2.6) were recruited from the University of British Columbia Psychology Human Subject Pool. Five of the participants indicated they are left-handed. This study was approved by the Behavioural Research Ethics Board (BREB) at the University of British Columbia. Five participants were removed because of insufficient data or incomplete tasks (i.e., <2 completed runs for each hand), and five more were removed because of excessive noise in the recording signal because of inadequate electrode contact or excessive participant motion (i.e., preprocessed data resulted in >50% of individual trials discarded because of noise). Thus, all analyses described below were conducted on the remaining 50 participants (33 females, mean age = 20.48, SD = 2.8).

### Stimulus and apparatus

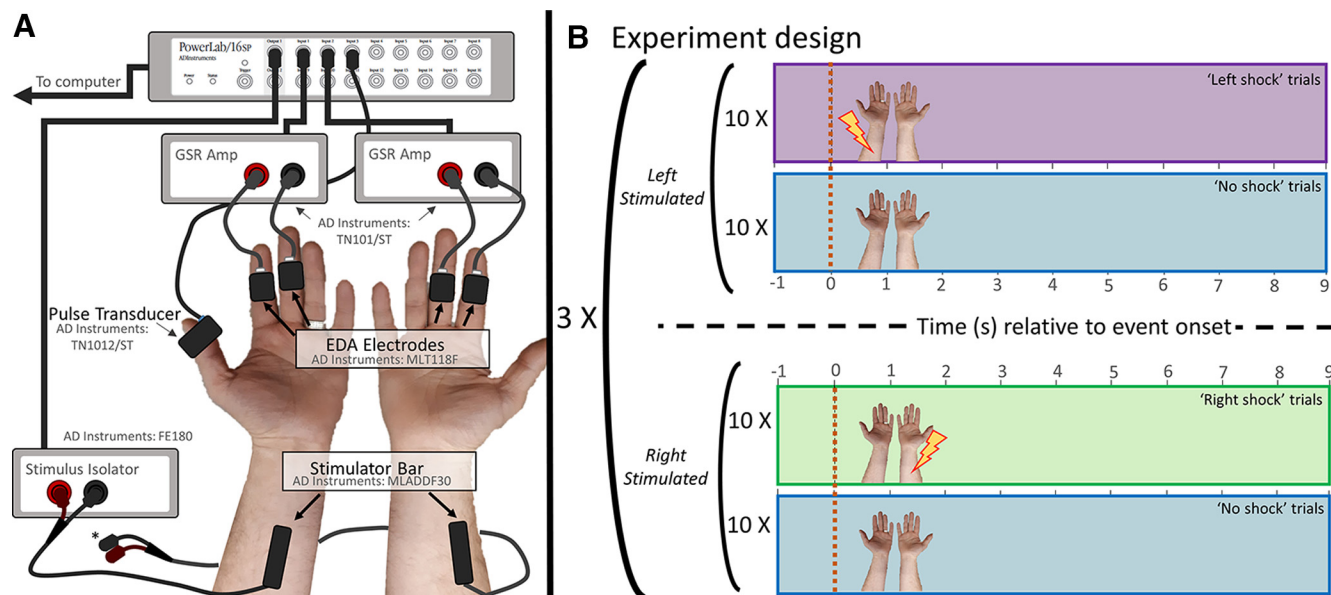
All psychophysiological recording and stimulation were conducted through an AD Instrument Powerlab 8/35 DAQ device (PL3508) and integrated with the experimental protocol through a custom Python-based program created in Psychopy. Tactile stimulation (max repeat rate = 500 Hz; and pulse width = 1 ms; titrated voltage for each participant) was administered via stimulating bar electrodes (AD Instruments, MLADDF30) connected to an AD Instruments-Stimulus Isolator (FE180). Bar electrodes with a conductive gel (SignaGel Electrode Gel) were placed bilaterally on the participant forearms ~15 cm distal to the elbow and fixed in place with medical

tape. Pretrial stimulation was performed to ensure minimal activation of motor units in the arm and hand by the bar electrode. All stimulation events were 50 ms (pulse width = 1 ms, pulse height = 5 V, repeats = 50, repeat rate = 1000 Hz) and administered with a rectangular waveform. Strength of stimulation was titrated independently for each arm until participants reported that it was aversive but not painful. Titration involved increasing stimulus amplitude, beginning at 0.5 mA until a maximum of 10 mA until stimulation elicited a consistent self-report rating of aversive but not painful. Increments varied from 1 to 0.1 mA depending on the previous response to stimulation. Following completion of the titration procedure, stimulation was held constant for the remainder of the experiment.

EDA was collected simultaneously from two bilateral EDA finger electrodes (AD Instruments, MLT118F), placed over the medial phalange of the middle and index fingers of each hand and amplified by an EDA-amp (AD Instruments, FE116). No conductive gel was used with the EDA electrodes, and they were secured in place with built-in hook-and-loop strapping. In addition, heart rate data were collected with a single finger pulse transducer (AD Instruments, TN1012/ST) connected to the left thumb. Electrode setup generally took less than 5 min before the start of data collection. An attentional visual task was run on PsychoPy v1.90.1, presented on a monitor (BenQ XL Series XL2420B 24 Widescreen; 60 hz) placed ~60 cm away from the participant. Initial EDA preprocessing was conducted with Labchart 8 (AD Instruments). All data were sampled at 1000 Hz. For a full schematic of the experimental setup, see Figure 1A.

### Procedure

Before data collection, participants were asked to sit upright and in a comfortable position, facing away from the experimenter, with their hands placed on a table, to minimize movement throughout the experiment. Participants completed six blocks of a task designed to monitor bilateral EDA response to aversive tactile stimulation, three blocks of shock events targeting each the left and right (e.g., block 1 = [10 shocks left + 10 no shock], randomly ordered; block 2 = [10 shocks right + 10 no shock], randomly ordered). The target of stimulation (left vs right forearm) alternated between blocks, with the initial location counterbalanced across participants. Stimulating electrodes were attached to both arms at the onset of the experiment, with only the electrode corresponding to the desired location of stimulation connected to the Stimulus Isolator for any given experimental block. Over the duration of each block, participants received ten electrical shock events to one arm (the one connected to the isolator), with each event comprised of  $50 \times 1$  ms pulses (see above, Stimulus and apparatus). Trial duration was 10,000 ms, with the shock stimulus administered 1000 ms into this window. "Shock" trials were randomly intermixed with an equivalent number of randomized "No Shock" trials of equal duration. Participants were instructed to remain still for the duration of the experiment and told that no response to the tactile stimuli was required at any point during the task. To minimize participant motion, and maintain engagement,



**Figure 1.** Experimental design. **A**, Bilateral electrodermal activity (EDA) data were collected from the medial part of the second and third digit on each hand. Stimulator bar electrodes were attached to the proximal half of both the left and right forearm. \* Stimulating bar electrodes were only attached to the Stimulus Isolator during experimental blocks in which they were to be used. **B**, Participants completed six experimental blocks, alternating between blocks targeting stimulation to the left and right forearm (3 blocks per side), respectively, with the starting order counterbalanced across participants. Within each block, participant completed 20 trials: 10 × “Shock” trials, and 10 × “No Shock” trials. “Shock” and “No Shock” trials were presented in random order within blocks and all individual trials had a total duration of 10 seconds. The time line of single trials related to the events of interest (right/left/no shock) is presented at the far right. The dashed line indicates placement of the shock stimulus (i.e.,  $t = 0$ ).

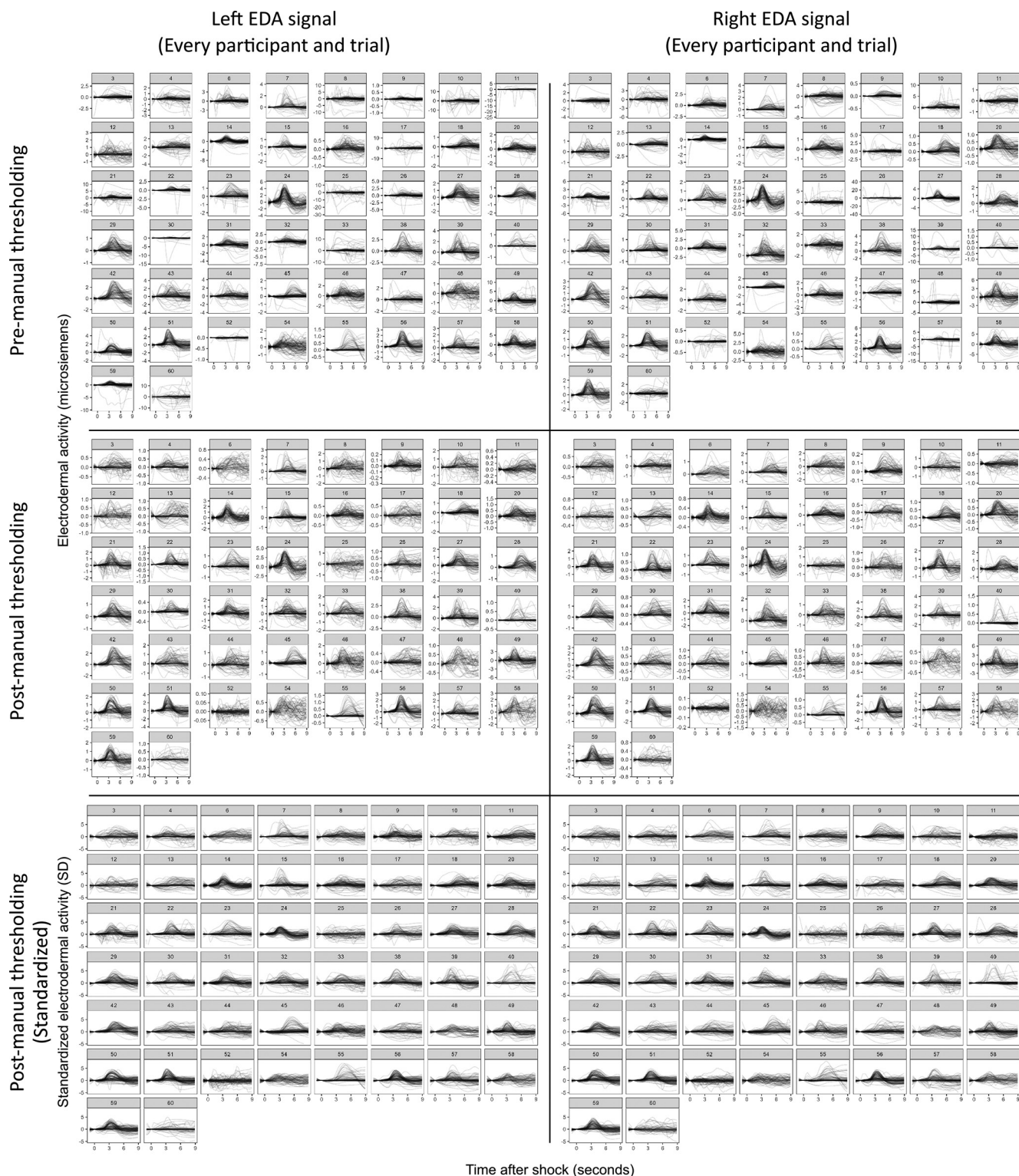
participants were instructed to track the number of color changes in a centrally-presented fixation cross and made a verbal report of this count to the experimenter following each block (range = 40–60 changes per block). Over the duration of the experiment, participants received a maximum of 60 shock events (30 to each arm), as well as 60 “No Shock” events (Fig. 1B). Bilateral EDA was collected over the duration of all events. The total duration for all experimental procedures was ~40 min.

### Preprocessing and analyses

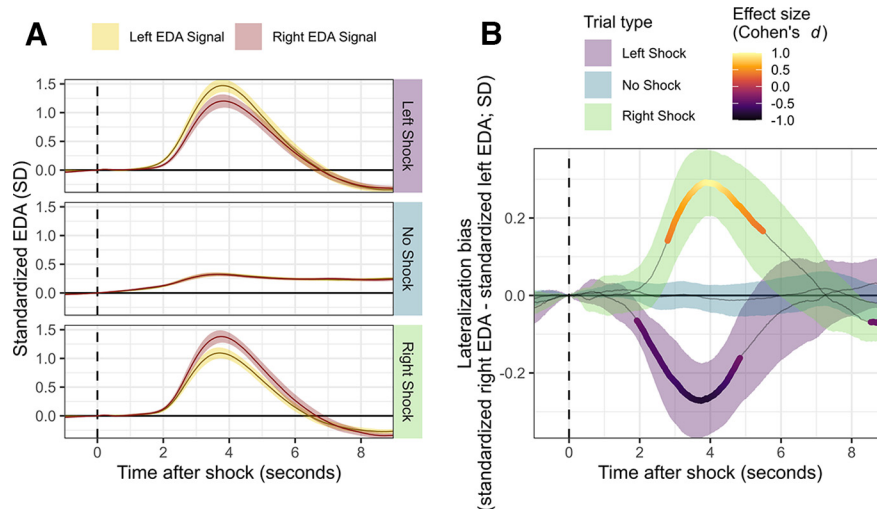
EDA data were exported from Labchart and down-sampled to 100 Hz (from 1000 Hz) to facilitate subsequent analyses. Down-sampling was performed through averaging of 10-ms sample windows (i.e., 10 samples). EDA from the electrode on each hand was subjected to second order Butterworth filter with a bandpass of 0.05–30 Hz. Data were separated into 10-s trial epochs ranging from 1 s before 9 s after each shock/no shock event. To further control for variation in baseline conductance between electrodes and signal drift, all EDA response curves were subject to a baseline correction which standardized EDA at stimulus onset ( $t = 0$ ) for each trial to zero. An additional manual filter of unlabeled trial-by-trial data were conducted to identify an EDA threshold for each electrode channel beyond which the data were most likely attributed to noise (e.g., motion-related artefacts, electrical noise, etc.) in the signal, with these trials to be excluded from further analyses. Manual data filtering eliminated an average of 16.1/117.5 individual trials (range = 0–47). EDA

response thresholds were identified independently by two members of the research team (referred to as raters), both blinded to the trial conditions. Interclass correlation estimates found excellent inter-rater reliability (Cronbach’s  $\alpha = 0.891$ ), and so thresholds identified by Rater 1 were used to filter data before all subsequent analyses (Fig. 2). The data retained after manual thresholding was subject to z score standardization for each signal channel (i.e., independently for both the left and right EDA electrodes) within each participant, centered to the signal mean across all trials. A second baseline correction was subsequently performed within each trial to again standardize EDA at stimulus onset ( $t = 0$ ) for each trial to zero (i.e., center the EDA response around signal baseline as opposed to participant mean). This process enabled direct comparison of signal changes across hands and participants, regardless of initial differences in mean amplitude and signal variance. A continuous “Lateralization Bias” index was calculated for each trial by contrasting the standardized right-hand and left-hand EDA (i.e., right hand EDA – left hand EDA) for all sampled time points. The resulting signal indicates the relative strength of EDA between electrode locations, with positive values indicating right-biased asymmetry, and negative values indicating left-biased asymmetry.

For group analyses, data from each participant was collapsed across trial type, resulting in three unique conditions (“Left Shock,” “Right Shock,” and “No Shock”). Three series of one-sample  $t$  tests were conducted comparing the Lateralization Bias for each condition against a test value of 0 (i.e., no bias) at each time point, with all



**Figure 2.** Manual data filtering. Before z score standardization, manual data filtering was performed to eliminate trials driven by probable noise in the electrodermal activity (EDA) signal (e.g., motion artifacts) independently for the right and left recording electrode. Top, Unlabeled EDA signal by trial; baseline corrected, unfiltered. Middle, Unlabeled EDA signal by trial, postmanual filtering. Bottom, Unlabeled EDA signal by trial, post z score normalization and an additional baseline correction. SD = standard deviation.



**Figure 3.** Group-wise contrast of Lateralization Bias in autonomic response. **A**, Electrodermal activity (EDA) response recorded from both right and left electrodes for each trial condition. For all conditions (“Right Shock,” “Left Shock,” and “No Shock”), the standardized signal is presented for both recording sites (right and left hand) averaged across all trials and participants. Light colored ribbons represent the standard error (SE) across participants at each time point. **B**, Lateralization biases were defined as [right-hand EDA – left-hand EDA] for each condition (Left Shock, Right Shock, and No Shock). A shift in Lateralization Bias toward either the left (down) or right (up) side indicated a stronger response measured from that location relative to the other side. Significant deviation of these bias scores from a test value of zero (i.e., no bias) are indicated by the highlighted area. Coloring of the highlighted area reflects the effect size (Cohen’s *d*) for contrasts between left-hand and right-hand biases. Light colored ribbons represent the uncorrected 95% confidence interval at each time point.

resultant *p* values subject to a false discovery rate correction (Benjamini and Hochberg, 1995). For single-participant analyses, trial events remained separate, and were used as independent repetitions in subsequent inferential tests. A series of one-sample *t* tests compared lateralization biases during left and right shock events to a test value of 0, replicating the analyses conducted at the group level. In addition, to account for the potential reduction in statistical power from group to within-participant analyses, a series of two-sample *t* tests compared lateralization biases between right and left shock conditions for each participant. As with group analyses, all resultant *p* values were subject to a false discovery rate correction.

## Results

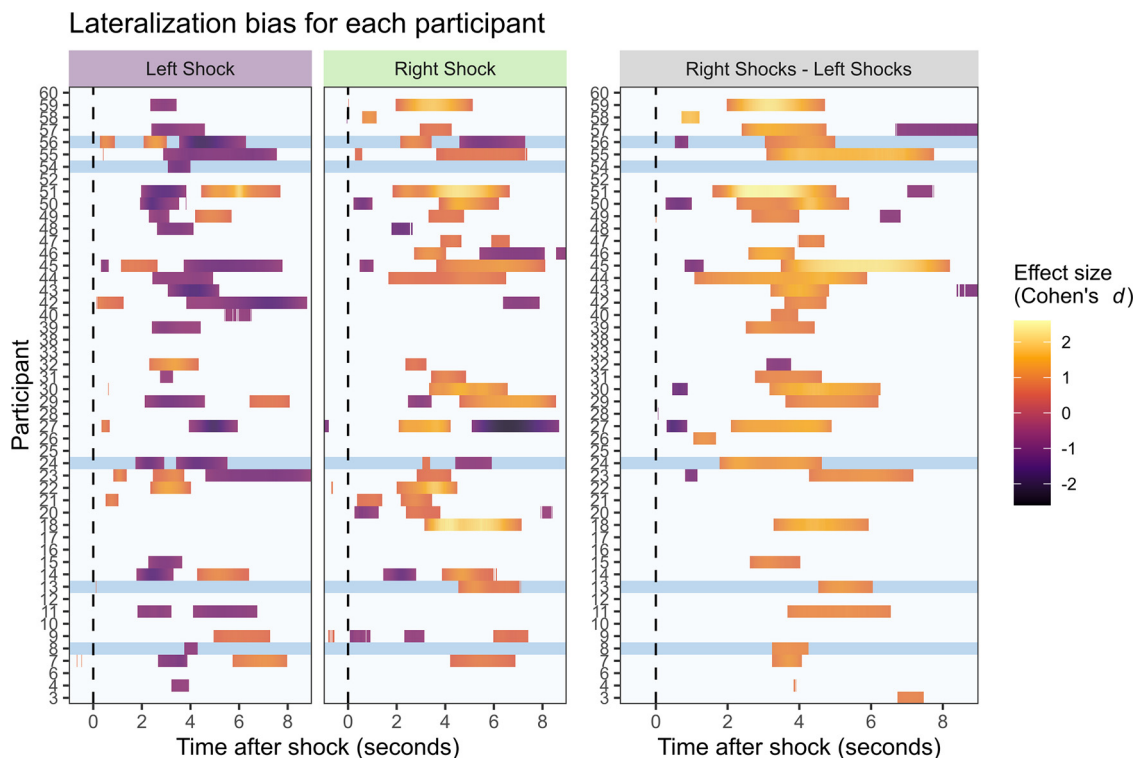
To assess lateralization biases, we contrasted EDA between the left and right hands in response to mild electric stimulation applied either ipsilaterally or contralaterally to the EDA electrodes (Fig. 3A; note that future studies could consider intermixing right and left shock events to minimize potential expectancy biases). To obtain an index of “Lateralization Bias,” *z* score standardized EDA data collected from the left hand was subtracted from that collected from the right hand. These data were then split into three distinct trial types: Left Shock, Right Shock, and No Shock. All reported *p* values have been subject to a false-detection rate correction through the statistical package R (RCoreTeam, 2013), corrected to  $p < 0.05$  (Benjamini and Hochberg, 1995).

### Across-participant analyses

To assess lateralization biases across all participants, a series of one-sample time-locked *t* tests were conducted

comparing the observed Lateralization Bias against a test value of zero (i.e., no difference in left vs right side EDA response) for each Left Shock, Right Shock, and No Shock condition averaged within participant. For ipsilateral stimulation, a clear lateralized response bias in both left and right recording sites emerged at ~2 s after stimulus onset and persisted for ~3 s (left bias during left shock: significance onset = 1920 ms after trial event, offset = 4840 ms after trial event,  $|t_{\text{range}(49)}| = 2.69\text{--}5.68$ , all  $p < 0.05$ ; right bias during right shock: significance onset = 2790 ms after trial event, significance offset = 5490 ms after trial event,  $|t_{\text{range}(49)}| = 2.68\text{--}6.93$ , all  $p < 0.05$ ; all times relative to the shock onset): greater EDA was observed at the recording site on the same side as the shock was administered relative to the contralateral recording site. By contrast, Lateralization Bias did not differ from zero at any time point during “No Shock” trials (Fig. 3B).

To test whether handedness acted as an independent confound, group-wise analyses were repeated separately for right-handed and left-handed populations in subpopulations. In right-handed participants ( $n = 45$ ), a near identical mirror of the full sample results emerged. Lateralized response bias was observed toward recording sites ipsilateral to tactile stimulation (left bias during left shock: significance onset = 2030 ms, offset = 4650 ms,  $|t_{\text{range}(49)}| = 2.74\text{--}4.88$ , all  $p < 0.05$ ; right bias during right shock: significance onset = 2860 ms, significance offset = 5630 ms,  $|t_{\text{range}(49)}| = 2.74\text{--}7.85$ , all  $p < 0.05$ ; all times relative to the shock onset). Lateralization Bias did not differ from zero at any time point during “No Shock” trials. In left-handed participants ( $n = 5$ ), Lateralization Bias did not differ from zero at any time point for any condition (all  $p > 0.05$ ). Because of the limited statistical power of these analyses associated with the reduction in sample size, however,



**Figure 4. A**, Lateralization Bias within shock conditions by participant. Lateralization Bias scores for each left and right shock events differing from no bias (i.e., Lateralization Bias = 0) are identified for each participant (row) by trial time course. Cohen's *d* (calculated with the statistical package R; [RCORETeam, 2013](#)) is presented for all time points with significant lateralization ( $p < 0.05$ , FDR corrected), and reflects the effect size for contrasts within each lateralized shock event in relation to a test-bias of zero. **B**, Lateralization Biases across shock conditions by participant. Differences in Lateralization Bias between left versus right shock events are identified for each participant (row) by trial time course. Cohen's *d* is indicated for all time points where differences are significant ( $p < 0.05$ , FDR corrected) and reflects the effect size for contrasts between left-hand and right-hand biases. Positive values indicate significant right-side bias. Blue banding on all plots indicates left-handed participants.

appropriate caution should be taken when interpreting results from left-handed participants.

### Within-participant analyses

If lateralized EDA to limb-specific threat is a foundational component of autonomic nervous architecture, this left versus right lateralization should be observable within individual participants as well as across-participant analyses. Accordingly, a similar set of analyses as conducted for group-wise comparisons was conducted at the single participant level. For each participant, a series of one-sided *t* tests compared the Lateralization Bias observed for each trial type to a null value of zero (i.e., no bias in response). Critically, these identified an overall pattern of results mirroring that observed at the group level (Fig. 4A). During right-administered shock events, 26 of 50 participants displayed a statistically significant lateralization bias in a direction that was consistent with those observed in the group-wise analyses (i.e., right-side bias). Of the remaining participants, four displayed a left side bias, while 20 displayed no significant bias in either direction. Similarly, during left-administered shock events, an overlapping (but not identical) group of 26 participants displayed a significant left lateralization bias, while of the remaining participants, two displayed a right-side bias

and 22 had no significant bias in either direction. Of note, there were a maximum of 30 possible trials for each condition, with an average of 22.5 left shock events and 22.9 right shock events analyzed following data cleaning. This resulted in lower statistical power for the within-participant analyses compared with the group-wise analyses.

To further reinforce the consistency of autonomic lateralization, an additional set of within-participant analyses was performed on trial-by-trial Lateralization Bias for each participant across experimental conditions. In a series of time-locked two-sample *t* tests, significant differences in Lateralization Bias in EDA responses to shock administered to the left versus right forearm were observed in 32 of 50 participants (with 31/32 significant results in the predicted direction; Fig. 4B). While the time course of significant differences ranged from as early as 500 ms after stimulus onset to as late as 8000 ms after stimulus onset, the most consistent range was 2000–5000 ms after onset. This is consistent with the range observed in the group analyses, and typical of expected EDA propagation latencies ([Boucsein, 2012](#)).

### Discussion

This study investigated whether lateralized EDA would be observed in response to limb-specific tactile stimulation.

For both left-administered and right-administered shock, EDA responses were larger at recording sites ipsilateral versus contralateral to the stimulation site. This pattern of results was observed, quite strikingly, in group-wise analyses, while in within-participant analyses, dissociable EDA responses between right and left stimulation were observed in 62% of participants. Together, these findings provide strong evidence that the ANS exhibits robust specificity in EDA, which prioritizes responding in threat adjacent limbs.

While lateralized EDA in response to centrally-mediated, or general, states of arousal (e.g., faces, emotionally salient situations) has been periodically observed throughout the past century (for review of pre-1985 examples, see Freixa i Baqué et al., 1984; also see Poh et al., 2010; Picard et al., 2016; Bjorhei et al., 2019), a potential functional role of this neuro-architectural quirk has remained elusive. Historical explanation of asymmetric autonomic response often evoked now-discredited theories of gross hemispheric lateralization (Sperry, 1968; Galaburda et al., 1978; Reeves, 1983), while recent work has made limited attempts to reconcile EDA lateralization within the canonical ANS function of metabolic conservation (Picard et al., 2016; Bjorhei et al., 2019). The current study demonstrates that lateralized EDA response is not only observed in response to centrally mediated arousal but can also be evoked by limb-specific aversive stimulation. This potentially provides a physiological rationale for the development of asymmetric architecture in the ANS consistent with its canonical role of metabolic resource management. Specifically, increased EDA was observed in both the left and right hands following ipsilateral (vs contralateral) electrical stimulation. This provides evidence for a functional role in threat response for lateralized changes in EDA. We suggest that the sympathetic output of our ANS, the driver of EDA (Vetrugno et al., 2003), prepares the body for a response option beyond the popular alliterative of “fight or flight”; it can ready us to flick.

### Heterogeneity of autonomic output

Evidence of hemisphere-specificity in autonomic responses is consistent with the increasingly prevalent view that ANS output, and particularly ANS output in response to emotional arousal, should not be interpreted as a single measure of balance between global activation/conservation of resources (for review, see Kreibig, 2010). Further, this work demonstrates that heterogeneity of ANS outputs extends beyond differential signaling to separate effector organs, as it also includes differential signaling across body-locations within a single effector organ (i.e., skin). This is consistent with the view that, when a limb-specific motor response is required in response to threat, limb-specific ANS outputs increase local action-preparedness while a state of rest across the rest of the body is preserved. Through this mechanism, the global loss of metabolic resources can be minimized while still ensuring resources are available for adequate behavioral responses to threatening objects or situations (Wehrwein et al., 2016; Gibbons, 2019).

The current work is the first contemporary study to identify threat-localized lateralization in ANS responding and the first to observe it at a single participant level. As early preliminary work in the area (Fuhrer, 1971) was initially overlooked, and later disregarded entirely, much remains to be learned about the specificity of the autonomic response to localized threat. While we provide evidence for local specificity of cutaneous responses to tactile stimulation, it is unclear whether similar spatial heterogeneity also occurs in response to localized threat in other ANS effector organs (e.g., muscle-specific vascular dilation), or in response to localized threats assessed by other modalities (e.g., visual threat). While some autonomic measures may best be regarded as homogenous outputs under heterogeneous control, e.g., it is unlikely that the right lung will have a greater response than the left, other responses likely manifest with more concurrent diversity to allow maximal metabolic conservation. For example, similar reasoning on the need to limit motor preparedness would suggest that vascular dilation should also be limited to the threat targeted limb, rather than across the entire body. While the neural architecture for limb-specific vascular responding is well established, localized patterns of dilation are well documented during motor activity and exercise (Wang, 2005; Green, 2009; Green et al., 2017), it is unclear whether this localized vascular responding can be used by the ANS preceding a threat-reduction response as well. It is also unclear whether limb-specific cutaneous activity is observed in response to limb-localized nontactile threats, such as the sight of a spider approaching the hand. Further investigation into modal specificity required to provoke body-localized changes in EDA would provide further insight into the functionality of such ANS responses, as well as highlight potential central structures involved in mediating these outputs. Additionally, subsequent studies that use threatening objects that do not depend on electrical stimulation, a signal also used as the dependent measure in EDA, may be able to tease apart the impact of induced electrical propagation through our peripheral nerves that could confound the current results.

While current results provide strong evidence of limb-localized sympathetic responding in group analyses, this effect was not observed for all individual participants. Indeed, significant unilateral bias toward the threatened limb was observed in just >50% of participants when analyzing data from a single shock location, and just greater than just >60% when analyzing data across shock locations. Furthermore, ~25% of participants displayed a lateralization bias at some point in the experimental time course that was opposite to that predicted (note: this does not imply a lack of bias in the predicted direction as analyses were conducted independently across time points; see Fig. 4). While we are hesitant to speculate on the route of these inconsistencies, as the number of trials and participants limit our ability to perform conclusive individual difference analyses, this is an avenue that would be of interest for future work.

### Development of cognitive arousal systems

A critical contribution of the current work is that we examined lateralized biases in electrodermal responding in



response to direct physical threat to a distal sensory target, rather than manipulating or examining circumstances triggering emotional arousal to examine a centrally-mediated cognitive state. The importance of this difference becomes apparent in the context of understanding the biological role and evolutionary development of heterogeneity in cutaneous ANS functioning. To date, contemporary work in the field has largely ignored these questions, focusing instead on either the applied uses of asymmetric electrodermal signaling, including monitoring health and wellness (Carreiro et al., 2015b; Greene et al., 2016; Ghandeharioun et al., 2017; Arza et al., 2019; Kourtis et al., 2019), or the cognitive states during which they manifest (Picard et al., 2016; Mohr et al., 2017). While these are important practical considerations when applying EDA signaling to health care concerns, neither provide any reasonable rationale for how the lateralized autonomic system they are describing may have developed.

By demonstrating greater EDA in body areas adjacent to versus distant from tactile threat, we have provided evidence that supports the proposal that the lateralized neural architecture observed in the cutaneous ANS serves a concrete function in efficient threat protection. Furthermore, we propose that the observation of lateralized EDA in response to centrally mediated arousal (situational arousal, Obrist, 1963; faces, Banks et al., 2012; e.g., high vs low impact stressors, Picard et al., 2016; Bjorhei et al., 2019) indicates that at some point during evolutionary development, central arousal systems likely co-opted pathways once dedicated to processing sensory arousal (Kryklywy et al., 2020). While the idea of building cognitive affect processing mechanisms on top of structures involved in sensory affect processing has been outlined for other specific sensory modalities (e.g., oral vs moral disgust; Chapman et al., 2009) and as a modality general evolutionary practice (Kryklywy et al., 2020), these proposals often rely on the interpretation of a shared central representation for these states, e.g., insular representations of disgust, rather than their common influences on peripheral autonomic outputs. The current work, however, highlights a specific example where the affective characteristic shared between general and tactile processes is peripheral in nature, yet only biologically sensible in its tactile manifestation. Autonomic lateralization observed during states of general arousal (Picard et al., 2016) does not have an obvious function related to metabolic management, yet when observed as a response to limb-localized threat, the metabolic benefits are apparent. Additional work investigating the neural underpinning of the ANS modulation to both sensation-provoked and centrally mediated arousals is still required to determine the extent to which these are overlapping processes within the CNS.

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