

Electrodermal Responses: What Happens in the Brain

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Electrodermal activity (EDA) is now the preferred term for changes in electrical conductance of the skin, including phasic changes that have been referred to as galvanic skin responses (GSR), that result from sympathetic neuronal activity. EDA is a sensitive psychophysiological index of changes in autonomic sympathetic arousal that are integrated with emotional and cognitive states. Until recently there was little direct knowledge of brain mechanisms governing generation and control of EDA in humans. However, studies of patients with discrete brain lesions and, more recently, functional imaging techniques have clarified the contribution of brain regions implicated in emotion, attention, and cognition to peripheral EDA responses. Moreover, such studies enable an understanding of mechanisms by which states of bodily arousal, indexed by EDA, influence cognition and bias motivational behavior. *NEUROSCIENTIST* 8(2):132–142, 2002

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Background

Autonomic Responses

The skin is the largest bodily organ and the principal interface between organism and environment. It is an important component to processes as diverse as the immune system, sensory-motor exploration, thermoregulation, vitamin production, and emotional communication. Consistent with this complexity of function, the skin is densely innervated. In particular, autonomic innervation of sweat glands is reflected in measurable changes in skin conductance at the surface, termed electrodermal activity (EDA). Afferent neurons from the sympathetic axis of the autonomic nervous system innervate eccrine sweat (sudomotor) glands, and their activity modulates conductance of an applied current. EDA incorporates both slow shifts in basal skin conductance level (SCL) and more rapid transient events, that is, skin conductance responses (SCRs), which have also been referred to as galvanic skin responses (GSR) (Venables and Christie 1980; Fowles and others 1981; Boussein 1992; Dawson and others 2000) (Fig. 1). EDA reflects activity within the sympathetic axis of the auto-

nomous nervous system, and it is noticeable that there is no parasympathetic innervation of eccrine sweat glands.

The regulation of sweating is encompassed within the general principles of autonomic control. The autonomic nervous system, first, governs vegetative autoregulatory processes, for example, body temperature, heart rate, blood pressure, and gut motility. These maintain homeostasis of the internal milieu. Second, it dynamically modulates these homeostatic functions to meet behavioral demands, for example, in preparation and execution of energetic movements. In most instances, regulation of bodily states of arousal is achieved by balance of activity within sympathetic and parasympathetic autonomic subdivisions. The sympathetic nervous system is geared to facilitate motor action, whereas parasympathetic functions are more “vegetative.” Thus, increased sympathetic drive is associated with increases in heart rate, blood pressure and sweating, and diversion of blood from gut toward limb musculature, that is, “autonomic arousal.” Such arousal is particularly characteristic of particular stereotyped behavioral repertoires (e.g., fight and flight responses). Motor preparation, movements, and skeletomotor effort are accompanied by increases in EDA that parallel cardiovascular arousal (increases in heart rate and blood pressure). These motor-related autonomic responses are mediated in part by “central command,” which induces sympathetic arousal (reflected in both cardiovascular and EDA measures) necessary to support motor behavior (Vissing and others 1991).

Sweat gland activity contributes to mechanical friction and thermoregulation. In many animals, including humans, autonomic responses in the skin (sweating, piloerection, vasomotor changes) also serve as emotional expressions and social signals that help mould interindividual interactions (Darwin 1998). In humans,

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Electrodermal arousal during cognitive effort: Serial subtractions of 7

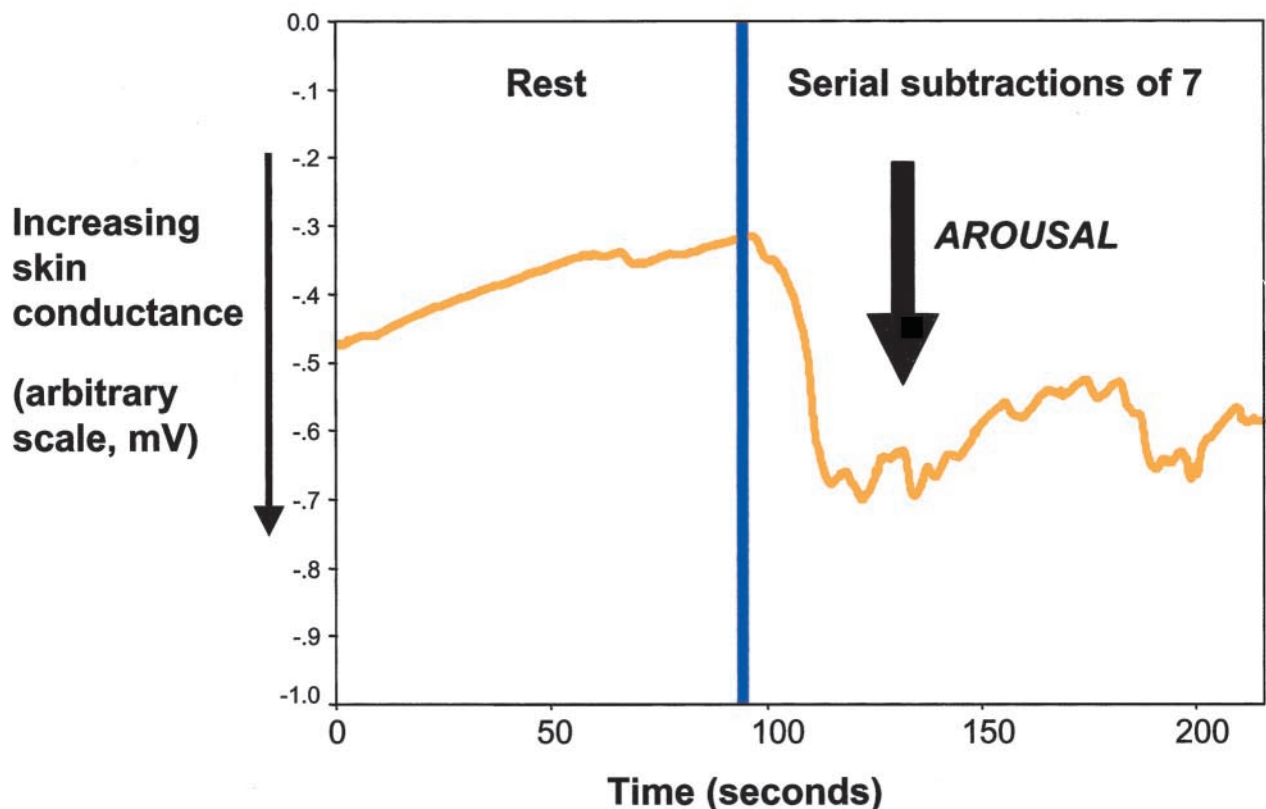


Fig. 1. Diagram of electrodermal responses to cognitive effort. The electrodermal responses of a subject at rest (to left of green line) and during performance of a cognitive stress test in which the subject had to overtly subtract serially the number 7, beginning at 400, and continuing as quickly as possible. The red line shows the subject's electrodermal activity during performance of the task. Decreases in the trace indicate increased sympathetic activity. The scale is an arbitrary mV scale, representing a linear function of conductance. Both slow baseline shifts and phasic responses can be observed.

subjective feelings of autonomic bodily changes also are important influences on individual emotional experience (James 1894; Damasio 1994, 1999). Sympathetic activity is closely linked to emotion, and EDA is a widely used and sensitive index of emotion-related sympathetic activity (Venables and Christie 1980; Fowles and others 1981; Bouscain 1992; Dawson and others 2000). This coupling enables EDA to be used as an objective index of emotional behavior as, for example, in its use as an indicator of conditioning in humans. Conditioning describes a rapid learning of an association between a stimulus and motivationally important “reinforcer.” In fear conditioning, when a previously neutral stimulus (conditioned stimulus, CS) is temporally paired with an aversive stimulus (unconditioned stimulus, US) such as a loud noise or mild electric shock, the CS quickly becomes predictive of the US and will elicit arousal responses previously associated with the US. This can be measured as increased EDA responses to the CS (now CS+), whether or not it is paired with the US. The neuroanatomical pathways supporting fear conditioning

have been well established and critically involve structures within the amygdala complex (LeDoux 1992) that project to brain stem autonomic output nuclei. Fear conditioning may occur without conscious awareness, as indicated by differential EDA responses to *masked* conditioned and unconditioned CS stimuli (e.g., Ohman and Soares 1993; Morris and others 1998). EDA is also used more generally to index implicit emotional responses that may occur without conscious awareness or beyond cognitive intent (e.g., Bechara and others 1995).

EDA responses are easily elicited by threatening stimuli, such as a loud noise or angry face, but are also sensitive to a range of stimuli that differ in motivational significance and degree of cognitive abstraction. These include novelty and familiarity, potential threat or reward, wins and losses, love and hate, anticipation and outcome, memory recall and cognitive work (Fig. 1). It would appear that a common factor that elicits EDA responses is subjective salience, a concept closely related to motivational importance. EDA is also a useful indicator of attention, and it is widely recognized that atten-

Diagram of pathway involved in thermoregulatory control of eccrine sweat glands

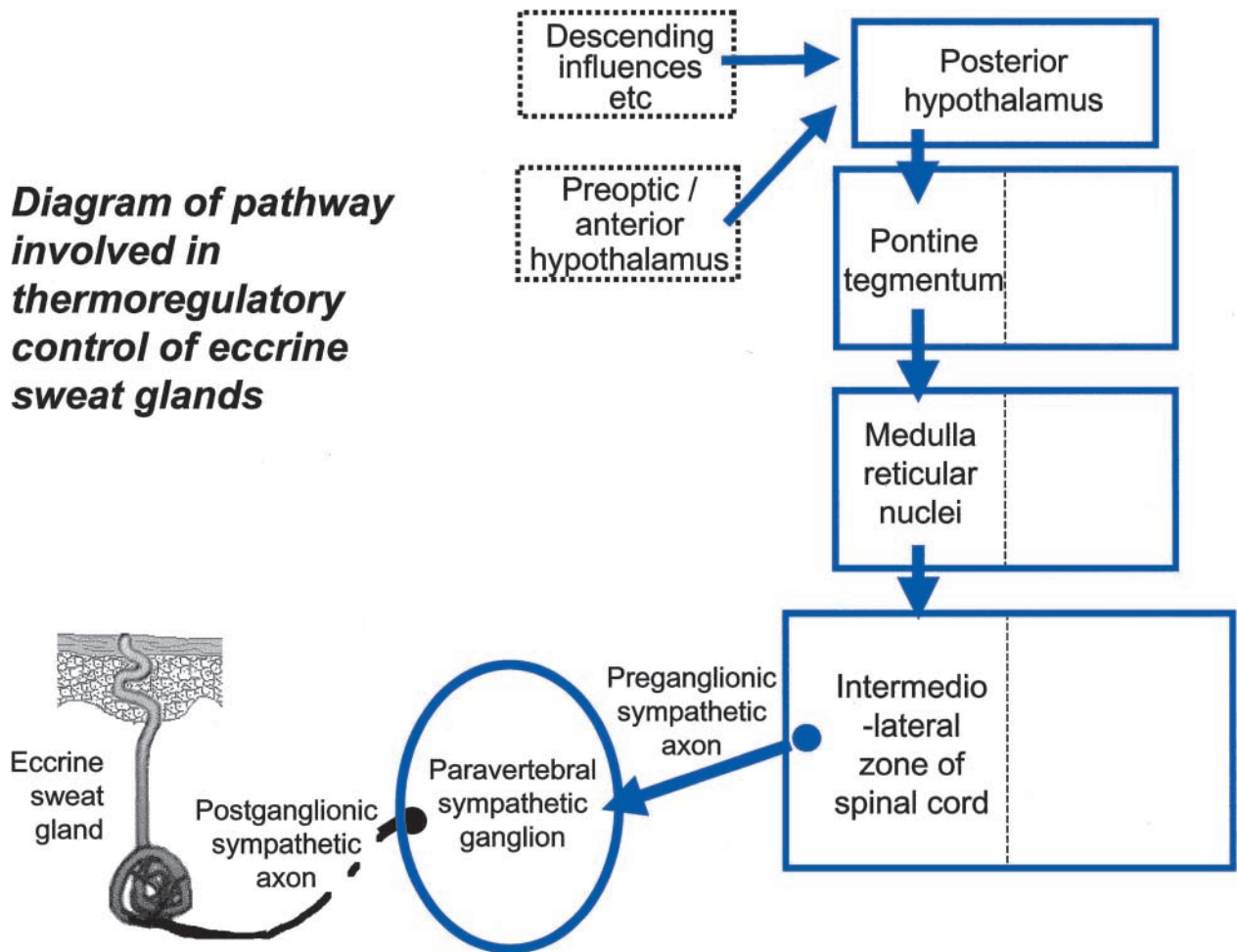


Fig. 2. Thermoregulatory pathways underlying sudomotor function. Diagrammatic representation of pathways involved in thermoregulatory control of eccrine sweat glands, which contribute to sympathetic modulation of electrodermal activity. Within the brainstem and spinal cord, thermoregulatory control is predominantly ipsilateral.

tion-grabbing stimuli and attentionally demanding tasks evoke increased EDA responses.

What Happens in the Periphery

Unmyelinated postganglionic sympathetic axons surround individual eccrine sweat (sudomotor) glands (Fig. 2). These glands are coiled, tubular structures that extend from epidermis to lower dermis and secrete water, electrolytes, and mucin (Sato 1977). They are found over the whole skin and are at highest density in palmar and plantar regions (approximately 400/mm²). The sympathetic sudomotor fibers ascend in the same fascicles as neurons supporting vasomotor control of the skin. Unlike other postganglionic sympathetic neurons, sudomotor synapses are cholinergic and thus are not modulated by peripheral catecholaminergic manipulations. Nevertheless, coactivation of vasomotor and sudomotor sympathetic neurons often occurs, producing familiar subjective phenomena such as “cold sweats.” As with other sympathetic neurons, postganglionic sudomotor neurons originate from the paravertebral chain of sympathetic

ganglia. Each ganglion acts as a relay between ipsilateral preganglionic neurons from the spinal cord and postganglionic neurons. An individual ganglion may receive inputs from up to six spinal levels, and sudomotor innervation retains a crude dermatome-like topography. Within the thoracolumbar spinal cord, preganglionic sympathetic neurons have cell bodies in the intermediate zone, with the majority in the intermediolateral region (Anderson and others 1989). These preganglionic sympathetic neurons are controlled by descending projections from neurons located in specific brainstem, hypothalamic, and forebrain regions (Pyner and Coote 1999).

What Happens in the Brain

Efferent thermoregulatory pathways, associated with sudomotor control, originate in the posterior hypothalamus, with many fibers relaying in pontine tegmentum and medullary (reticular) nuclei, and descend to preganglionic sympathetic neurons (Collins 1999) (Fig. 2). These sudomotor projections are ipsilateral. Increases in EDA may be elicited by electrical stimulation of sites

from the posterior hypothalamus, ventrolateral pons, medulla, and intermediolateral spinal cord (Davison and Koss 1975). Brainstem-evoked EDA responses are robust even in decerebrate animals. There is, however, a paucity of information specifically relating to brain pathways controlling EDA, but insights can be gained from studies of central autonomic control of the cardiovascular system (reviewed in Cechetto and Saper 1990; Bennarroch 1997). Experiments mostly in nonprimate animals have helped define mechanisms underlying the homeostatic regulation of cardiovascular function at the level of hypothalamus and brainstem nuclei, mediated via sympathetic and parasympathetic outflows. Additionally, a wider central autonomic network has been described, based on neuronal stimulation studies and anatomical connectivity, involving central amygdaloid nucleus, paraventricular and lateral hypothalamus, bed nucleus of the stria terminalis, and locus coeruleus. These regions project directly to autonomic nuclei such as parabrachial nucleus, nucleus of the solitary tract, dorsal vagal nucleus, and intermediolateral spinal cord, which in turn control efferent autonomic responses.

Sympathetic autonomic activity is also influenced by “higher” subcortical and cortical brain areas. Electrical or chemical stimulation of a number of discrete brain regions elicits sympathetic cardiovascular responses (there is less direct evidence concerning evoked EDA responses that would accompany such cardiovascular sympathetic arousal). These brain regions include areas implicated in 1) attention, motivation, decision-making, and episodic memory; that is, the anterior cingulate, dorsolateral, and ventromedial prefrontal cortices and hippocampus (Kaada 1951; Neafsey 1990); 2) representation of aversive emotions, that is, amygdaloid complex (Kaada 1951; Gelsema and others 1989); 3) initiation and control of limb movements, that is, motor cortex, nigrostriatal tract, neostriatum, cerebellum (Kaada 1951; Bradley and others 1991; Angyan 1994); and 4) representation of internal sensory, somatic, and endocrine states, that is, insula, dorsomedial and lateral hypothalamus, nucleus tractus solitarius (e.g., Oppenheimer and Cechetto 1990; Spyer 1999). Electrophysiological recordings indicate that the majority of these putative *efferent* autonomic centers also receive afferent information concerning peripheral autonomic states (e.g., Cechetto and Saper 1987; reviewed Cechetto and Saper 1990). Distinct components of EDA responses may themselves be mediated by more than one central pathway. Thus, damage to dorsolateral prefrontal cortices in monkeys may diminish *orienting* EDA responses, but not those associated with motor behavior (Kimble and others 1965). In cats, medullary transection, sparing only pyramidal tracts (conveying corticospinal motor efferents), abolishes EDA responses evoked by parietal stimulation, but not EDA responses evoked by prefrontal stimulation (Sequeira and others 1995). These observations suggest that corticospinal pathways controlling sympathetic arousal and (EDA) via motor “central command” may bypass brainstem nuclei classically involved in autonomic regulation.

In humans, stimulation and lesion studies have helped identify higher brain centers controlling sympathetic function. Direct stimulation of insula (Oppenheimer and others 1992), medial prefrontal cortex, anterior cingulate (Pool and Ransohoff 1949), and medial temporal lobe (Fish and others 1993) elicits cardiovascular changes. Right-sided stimulation of insula increases heart rate and blood pressure, consistent with a lateralization of sympathetic control (Oppenheimer and others 1992). EDA responses may be elicited by direct electrical stimulation of cingulate, lateral prefrontal cortex, medial temporal lobe (amygdala and hippocampus), and middle temporal gyrus. Stimulation of “limbic” areas (i.e., amygdala, hippocampus, and cingulate) produces strong ipsilateral EDA responses (Mangina and Beuzeron-Mangina 1996). In humans, discrete lesions to the lateral prefrontal cortex, ventral and medial prefrontal cortices, anterior cingulate, and right parietal lobe reduce the magnitude of EDA responses (Tranel and Damasio 1994; Zahn and others 1999; Tranel 2000). Moreover, damage to the right hemisphere appears to have the greatest effect on EDA (Oscar-Berman and Gade 1979; Zoccolotti and others 1982; Zahn and others 1999). The frequency of EDA responses is reported to correlate with the size of the prefrontal lobe (Raine and others 1991), and in psychiatric patients, reduced EDA is associated with either decreased frontal volume or ventricular enlargement (Lencz and others 1996). Together, these anatomical studies in humans suggest that higher control of sympathetic arousal and EDA is subserved by a neural matrix involving prefrontal and parietal cortices, and limbic structures including cingulate and medial temporal lobe with a degree of lateralization to the right hemisphere.

EDA, Arousal, Cognition, and Emotion

Discrete brain regions contribute differentially to cognitive and sensory processes, and therefore may influence EDA in a behavioral or context-specific manner. Thus, lesions to some brain regions affect EDA in some circumstances but not others. Observations of these differential effects of localized brain lesions underlie important theoretical models concerning how states of bodily arousal interact with emotion and behavior (Damasio 1994). The ventromedial prefrontal cortex and amygdala in the medial temporal lobe are implicated in both autonomic control (see above) and emotion. Damage to these regions may result in disturbed social and emotional behavior, associated with abnormalities in strategic decision-making (Damasio and others 1990; Shallice and Burgess 1991; Bechara and others 1997; Adolphs and others 1998). In the case of patients with ventromedial prefrontal damage, these deficits are characterized by a failure to change maladaptive behavioral patterns. Whereas normal subjects will alter their behavior to avoid punishment, patients with ventromedial prefrontal damage persist with the same pattern of behavior, even if it is repeatedly associated with punishing outcomes (Bechara and others 1997, 1999). This has been illus-

trated experimentally using decision-making tasks (Damasio and others 1990; Bechara and others 1996). Ventromedial prefrontal lesion patients have abnormalities in generating EDA responses that are more apparent during decision making (Tranel and Damasio 1994; Zahn and others 1999) that manifests as a reduction in anticipatory arousal. Thus, before making a risky decision (i.e., associated with a high likelihood of punishment), normal subjects show increased anticipatory EDA (Bechara and others 1997). Patients with ventromedial prefrontal damage do not show this anticipatory arousal but retain EDA arousal responses to “physical” stimuli such as loud noises (Bechara and others 1996; Zahn and others 1999; Tranel 2000).

The “Somatic Marker Hypothesis” has been proposed based on this conjunction between absent anticipatory arousal and maladaptive behavior (Damasio and others 1990, 1991; Damasio 1994). Somatic markers describe states of bodily arousal (as indexed by EDA) that may bias emotional behavior and guide strategic decision-making. In this hypothesis, particular emphasis is placed on the role of the ventromedial prefrontal cortex in generation and representation of these bodily states. More specifically, this brain region contributes to generating EDA (and other bodily arousal responses) that relates concurrent with past experience and hence the likely consequences of a particular behavior.

Damage to the amygdala, which is anatomically and functionally interconnected with the ventromedial prefrontal cortex, is also associated with reduced EDA responses during anticipation. EDA responses to the feedback of reward and punishment, and during aversive (fear) conditioning are also impaired after amygdala lesions (Bechara and others 1999). Nevertheless, EDA responses are preserved to physical stimuli, such as loud noises (Tranel and Damasio 1989; Zahn and others 1999; Tranel 2000). Together, these findings suggest that the amygdala is involved in EDA response to motivationally important stimuli, particularly where these stimuli acquire meaning through learning. The amygdala is also proposed to be a crucial neuroanatomical component of mechanisms involved in the emotional enhancement of declarative memory. Events and stimuli that are strongly emotional in content or context are remembered better than unemotional material. It has been proposed that emotional enhancement of memory is mediated by sympathetic arousal, via the effects of stress hormones on amygdala. The amygdala in turn is proposed to modulate memory consolidation within the hippocampus (Cahill 1997; Cahill and McGaugh 1998). Thus, the amygdala may contribute to generation of EDA responses to salient stimuli that have gained emotional meaning through experiential learning or conditioning.

Functional Neuroimaging Investigations

Functional neuroimaging is now a major neuroscientific technique for examining *in vivo* human brain functions. So far, however, there have been relatively few functional imaging studies examining EDA-related activity

and central autonomic control. Some neuroimaging studies have used EDA as an objective indicator of automatic emotional processing, for example, fear conditioning, and the role of specific brain areas such as amygdala (Buchel and others 1998; Morris and others 1998). Understanding how sympathetic bodily arousal, reflected in both EDA and cardiovascular measures, relates to regional brain activity is important for the interpretation of many neuroimaging experiments. Emotional, cognitive, and motor behaviors may induce different degrees of sympathetic arousal depending on the specific task demands (Fig. 1). Many neuroimaging studies have compared brain activity during performance of a difficult (cognitive or motor) task with an easier-to-perform “control” condition, or contrasted two different emotional states. In such comparisons, the two conditions are likely to be associated with different states of autonomic bodily arousal. Thus, some of the differential activity observed may reflect autonomic, rather than cognitive, motor, or emotional, processes. For example, activation in anterior cingulate and insula cortices (putative centers of autonomic control) is frequently observed in neuroimaging experiments (e.g., Paus and others 1998).

To relate peripheral autonomic responses to regional brain activity, some studies have scanned subjects performing specific tasks (used clinically as “autonomic function tests”) that engender arousal responses, for example, increases in heart rate and blood pressure. These tasks include the Valsalva maneuver (breathing against a closed glottis), isometric handgrip exercise, deep inspiration, mental stress (arithmetic), and cold pressor tests. These procedures modulate EDA as well as cardiovascular arousal. In one such functional magnetic resonance imaging (fMRI) study, King and others (1999) reported increased activity in anterior and posterior insula, medial prefrontal cortex, and ventroposterior thalamus during respiratory, Valsalva, and exercise challenge. Similarly, a further fMRI study (Harper and others 2000) described activity increases in the ventral and medial prefrontal cortices, anterior cingulate, insula, medial temporal lobe, medial thalamus, cerebellum mid-brain, and pons during cold pressor challenge and performance of Valsalva maneuvers. Critchley and others (2000a) used positron emission tomography (PET) to examine commonalities in activity induced by mental and exercise challenges compared to low-grade control tasks. Increased activity was observed in the right anterior cingulate, dorsal pons, and midline cerebellum during effortful mental and physical tasks (accompanied by sympathetic cardiovascular arousal) compared to performance of control tasks. Activity in the right anterior cingulate, right insula, and pons covaried with increases in blood pressure and heart rate independently of task modality. This study suggested that regions such as the anterior cingulate cortex are important for integrating cognitive and volitional behaviors with sympathetic arousal and supported the notion of laterality of sympathetic responses to right hemisphere (Oppenheimer and others 1992).

Although these imaging studies examined cerebral activity during sympathetic arousal, they did not relate brain responses to EDA. The first neuroimaging study that explored directly the relationship between EDA and brain activity was that of Fredrikson and others (1998) who used PET neuroimaging and continuous electrodermal recording to identify changes in brain activity relating to EDA arousal. Subjects were scanned while presented with intrinsically emotive stimuli, including skin shocks and videos of snakes. Activity in the motor cortex, anterior and posterior cingulate, right insula, right inferior parietal lobe, and extrastriate visual cortex was modulated in association with the presence of strong electrodermal responses. In fact, positive correlations were observed between EDA and activity in cingulate and motor cortices, and decreased correlations in the insula, parietal, and visual cortices. This study suggested a distributed neural system governing electrodermal arousal within the human brain and highlighted involvement of regions such as the anterior cingulate cortex in EDA responses.

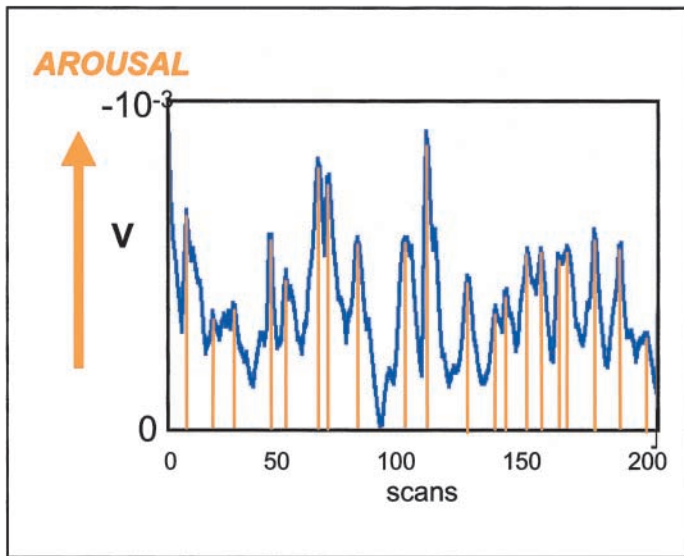
In an fMRI experiment, Critchley and others (2000b) examined brain activity relating to EDA fluctuations evoked naturalistically by performance of a cognitive “gambling” task (Fig. 3). This was motivated by the use of EDA as an index of autonomic arousal in many behavioral experiments, especially the gambling/decision-making tasks that underlie Damasio’s influential “Somatic Marker Hypothesis.” Subjects performed a gambling task during scanning while EDA was continuously monitored. On each trial of the task, the subject saw a pair of playing cards and had to make a two-choice button press decision to win (or lose) money. Visual feedback of overall winnings and whether the decision was “right” was given after each response (Elliott and others 2000). Task performance evoked subject-specific EDA fluctuations that were used in two sets of analyses. First, the EDA trace over the course of the experiment was used as a regressor of interest to examine brain activity covarying with this peripheral measure of arousal. Second, distinct peaks in the EDA trace were used to identify activity related to generation and feedback representation of discrete EDA responses (Fig. 3A). Task-specific variability was excluded by entering regressors derived from the feedback given to the subject into the analysis. EDA fluctuation over the course of the experiment was associated with increased activity in the bilateral ventromedial prefrontal cortex, right insula/orbitofrontal cortex, right inferior parietal cortex, and extrastriate visual cortex. Decreased activity was observed in premotor regions and the posterior parietal cortex. The study also found greater activity in the left ventromedial prefrontal cortex, extrastriate cortex, and cerebellum before discrete EDA responses, suggesting these regions preferentially contribute to EDA generation. Conversely, there was greater activity in the right medial prefrontal cortex after EDA responses, suggesting importance of this region in representing peripheral EDA arousal. These observations suggest a partial segregation, even within the ventromedial prefrontal cortex,

of regional brain activity supporting generation and representation of EDA.

This study therefore confirmed contribution of ventral and medial prefrontal regions in EDA responses during gambling task performance. These observations are consistent both with the reported effects of prefrontal lesions on generation of EDA responses (Tranel and Damasio 1994; Bechara and others 1996; Zahn and others 1999) and with proposed modulation of these areas during motivational decision-making by EDA-related arousal (Damasio 1994; Bechara and others 1996, 1997). Also the study showed activity in regions such as the inferior parietal lobule, and the extrastriate visual cortex also reflected EDA-indexed arousal. Because these areas are key to directing visual attention, these findings suggest that arousal and attention may share a common neural substrate. However, the study only partly addressed the mechanisms by which cognitive or emotional responses are integrated with EDA arousal and, interestingly, did not report anterior cingulate activity in association with EDA, in contrast to other observations (Tranel and Damasio 1994; Fredrikson and others 1998).

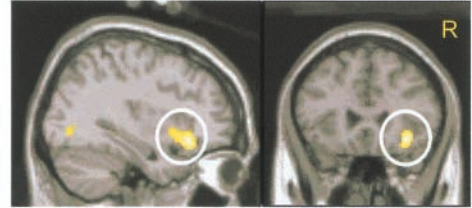
Some of these issues were addressed in a further fMRI study that examined how arousal, indexed by EDA, may influence regional brain activity during anticipation of a rewarding or punishing outcome (Critchley and others 2001a). Each subject was scanned while performing a gambling task wherein the subject had to guess, when he or she saw one playing card (face value between 1 and 10), if the next card seen would be higher or lower. Correct decisions were associated with financial gain and wrong decisions with financial loss. These decisions were therefore associated with different but predictable risks that were a function of the face value of the cue card. Although the subjects responded as soon as they saw the first card, the second card (indicating if the subject had won or lost) was presented after a fixed delay period. The question addressed by the subject was how sympathetic arousal (indexed by EDA) and the risk-value of each decision modulated brain activity during anticipation of outcome. During the anticipatory delay period, anterior cingulate and dorsolateral prefrontal cortex activity varied parametrically with the degree of anticipatory EDA response. Activity in the anterior cingulate and insula cortices was influenced by risk, and a conjunction analysis confirmed that the anterior cingulate cortex was the only area to be modulated by both risk and arousal (Fig. 4). These findings are consistent with the imaging studies of Fredrikson and others (1998) and Critchley and others (2000a) implicating anterior cingulate arousal responses. More specifically, the findings strongly suggest that the anterior cingulate cortex is involved in the integration cognitive processes (for example, processing risk and expectancy) with EDA and other bodily states of arousal. The role of the dorsolateral prefrontal activation appears yet more selective. Damage to both dorsolateral prefrontal and anterior cingulate cortices diminishes EDA response magnitude (Zahn and others 1999; Tranel 2000). However, it is likely that the observed association between dorsolateral

(A) Individualized fluctuations in EDA during performance of a gambling task

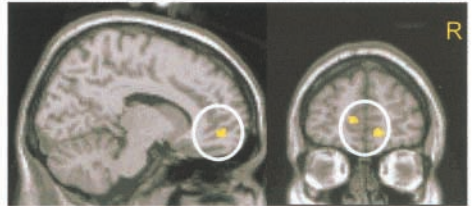


(B) Activity covarying with EDA

Right anterior insula / orbitofrontal cortex



Bilateral ventromedial prefrontal



Inferior parietal lobe and extrastriate cortex

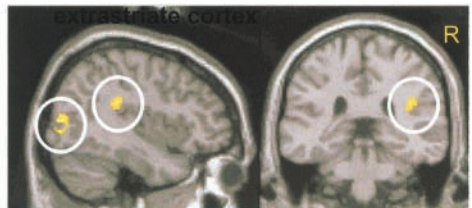


Fig. 3. Study examining brain activity relating to electrodermal activity (EDA) during performance of a gambling task. The figure illustrates regions covarying with EDA as described in Critchley and others (2000b). *A*, Performance of a reward-related decision (gambling) task produced individualized fluctuations in EDA recorded throughout the task (black line). In a covariance analysis, these continuous data were used to examine activity covarying with EDA. Also, peaks in EDA responses were identified (illustrated in red) and used in an event-related analysis. *B*, Brain regions covarying with EDA. Significant group activity is mapped on parasagittal and coronal sections of a template brain and is observed in anterior insula and ventromedial prefrontal cortices, extrastriate visual cortex, and right parietal lobe.

prefrontal activity and anticipatory EDA responses relate to the contextual control of bodily arousal during cognitive processing of information about expectation, response-selection, and experience.

A recent neuroimaging study examined directly the functional neuroanatomy by which intentional cognitive processes may influence EDA (Critchley and others 2001b). Although autonomic processes such as EDA are generally beyond conscious influence, biofeedback relaxation techniques can be used to enable subjects to gain control over involuntary autonomic responses. Prior to PET scanning, subjects were trained in performance of a biofeedback relaxation task in which EDA was used as an index of the level of sympathetic arousal. This was displayed visually in the form of a “thermometer.” As a subject relaxed and decreased the level of EDA arousal, this was reflected in a decrease in the column height of the thermometer, eventually reaching the “bulb” (which served as a fixed end point). Subjects were trained to relax rapidly and effectively using EDA biofeedback. During PET scanning, subjects performed repetitions of four different tasks: 1) the biofeedback relaxation, where the subjects aimed to relax and decrease the column

height while receiving accurate EDA-feedback; 2) attempted relaxation with false feedback, where the display column fluctuated randomly; 3) no relaxation with EDA biofeedback, where subjects attempted to stem any downward drift in their EDA level; and 4) attempting no relaxation while watching a false, randomly fluctuating display. EDA was recorded during all experimental tasks, whether or not it contributed to the visual feedback. The main effect of subjects attempting to relax and reduce EDA arousal was associated with increased activity in the anterior cingulate, inferior parietal cortex, and globus pallidus. Integration of the intention to relax with feedback of the subject’s EDA level (i.e., the interaction between true versus false EDA-biofeedback and relaxation versus no relaxation) was associated with increased activity in the ventromedial prefrontal cortex, anterior cingulate, and cerebellar vermis. Last, a medial temporal region, just anterior to the amygdala, reflected the rate of decrease in EDA-indexed arousal across all experimental tasks (Fig. 5). Together these observations provide further evidence implicating brain regions such as the ventromedial prefrontal cortex and anterior cingulate in integration of bodily arousal with cognitive

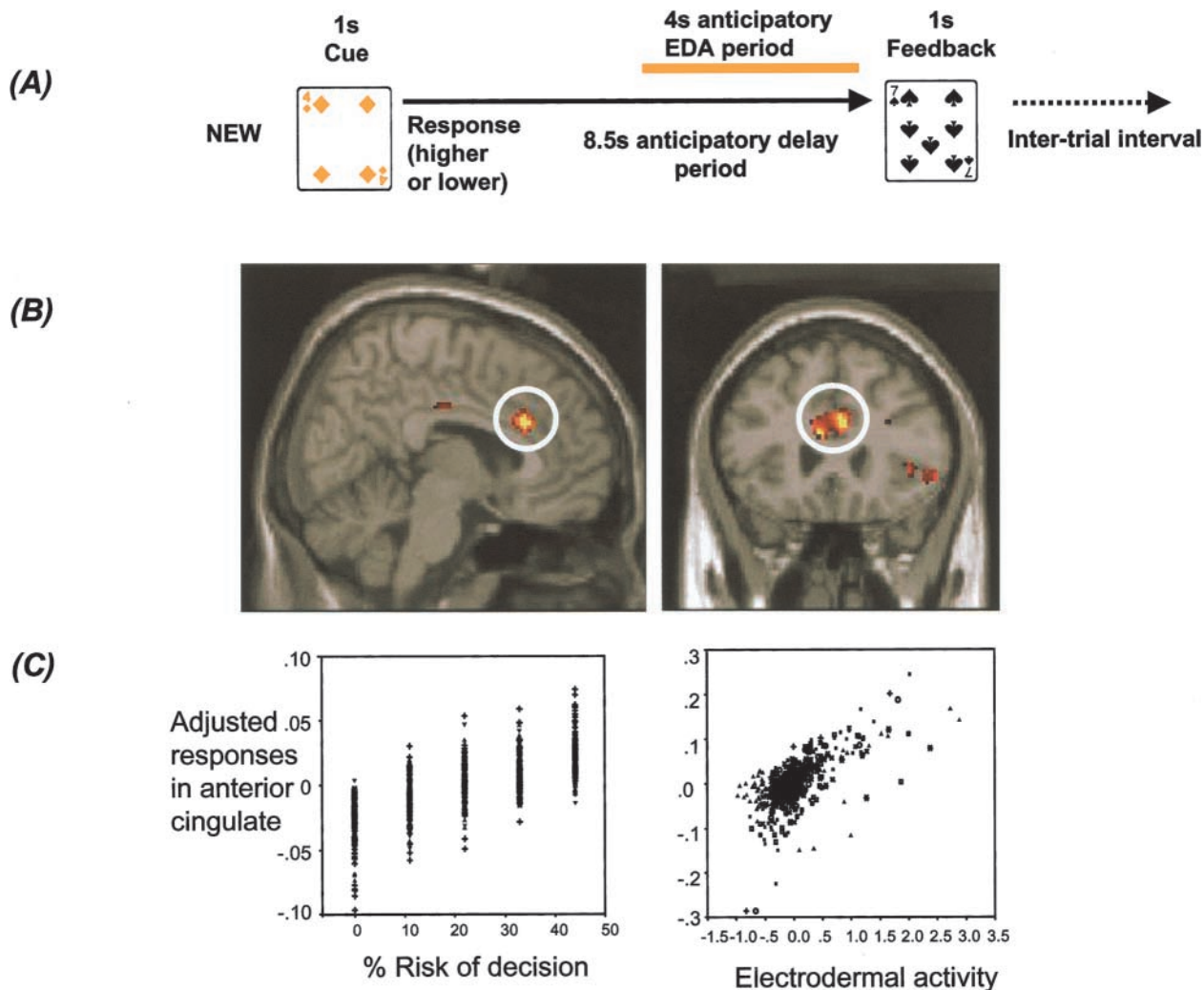


Fig. 4. Modulation of delay-period activity by risk and anticipatory arousal. The figure summarizes aspects of a study by Critchley and others (2001a). *A*, Diagram of individual trial. Subjects made a response to a cue card, judging if next (feedback) card would be higher or lower. Activity during the delay period before outcome was examined for modulation by riskiness of decision and by anticipatory electrodermal activity (EDA) response (mean EDA in 4 seconds prior to outcome feedback). *B* and *C*, Activity within anterior cingulate was modulated as a function of both risk and EDA.

processes (intention to relax). Interestingly, in contrast to studies of sympathetic arousal (Critchley and others 2000a, 2000b), activity during performance of relaxation tasks was greater in the left hemisphere than the right. Also, the observation that activity in a medial temporal lobe region is associated with sympathetic relaxation suggests a mechanism by which relaxation strategies may therapeutically influence brain regions mediating fear and stress responses, such as the adjacent amygdala.

Conclusions

Electrodermal activity remains a sensitive and convenient measure of indexing changes in sympathetic arousal associated with emotion, cognition, and attention. Within the hypothalamus and brainstem, there exists a discrete set of brain regions involved in homeostatic control of sympathetic arousal that controls peripheral

EDA via ipsilateral descending connections to the spinal cord. The autoregulatory functions of these brain regions are dynamically modulated to adapt bodily arousal to meet the demands of behavior. It is this second-order modulation, manifest in discrete peaks of electrodermal activity (SCR, GSR), that has been the basis of the application of EDA to psychophysiological research. "Higher" brain regions that influence EDA include the ventromedial prefrontal cortex, anterior cingulate, parietal lobe, insula, amygdala, and dorsolateral prefrontal cortex. There are distinct anatomical contributions to the contextual control of EDA: The ventromedial prefrontal cortex and amygdala are associated with EDA responses during motivational behavior, but they differ in their specific roles. Thus, the ventromedial prefrontal cortex is involved in anticipatory EDA responses, whereas the amygdala is implicated in EDA responses to learned associations between stimuli and reinforcement (e.g.,

Activity in right medial temporal lobe covarying with rate of decrease in EDA in all tasks

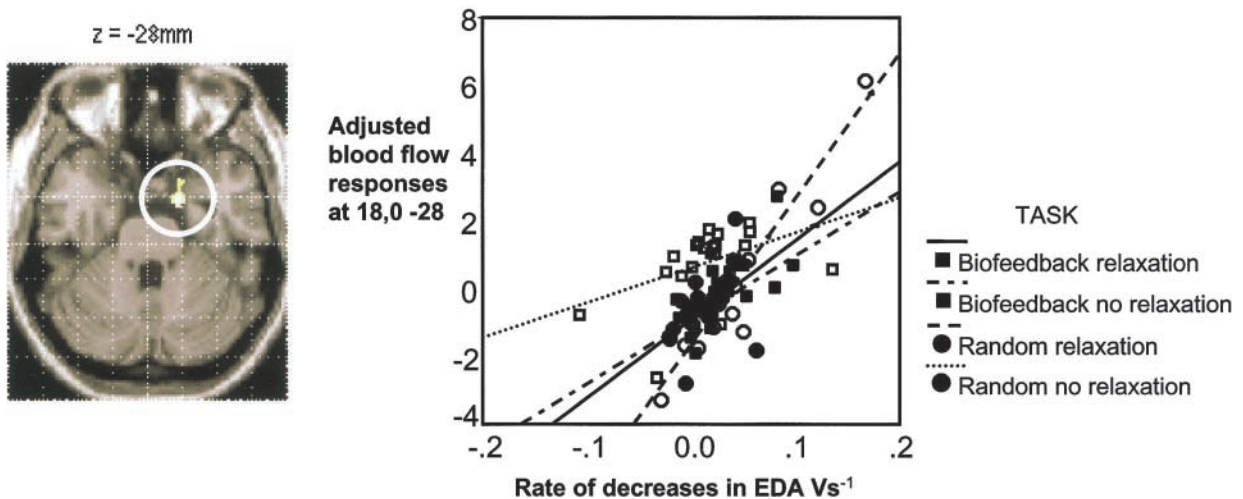


Fig. 5. Activity relating to electrodermal activity (EDA) relaxation. Right anteromedial temporal lobe increased in activity the faster subjects relaxed their sympathetic arousal (indexed by EDA). The experiment examined brain mechanisms underlying biofeedback relaxation. Anterior cingulate activity was associated both with trying to relax and, more specifically, with the interaction between intention to relax and biofeedback of EDA (i.e., including “biofeedback relaxation”). In addition to these observations, a specific region of the right anterior medial temporal lobe, adjacent to the amygdala, was found to increase activity the faster subjects were able to reduce their EDA level, across all tasks. This figure shows the anatomical location of this activity (group data from eight male subjects, mapped onto a horizontal section of a template brain) and plots of the adjusted response within this region for all subjects, with regression lines representing each experimental task.

during fear conditioning). There is also evidence suggesting that a primary role for the anterior cingulate cortex is to integrate autonomic bodily states with behavior (Critchley and others 2000a, 2001a, 2001b). Thus, anterior cingulate activity varies with EDA responses to emotive stimuli (Fredrikson and others 1998), and anticipatory EDA in the context of risk (Critchley and others 2001a), and is also associated with volitional modulation of EDA responses (Critchley and others 2001b). The interaction between EDA-indexed arousal and attention is perhaps of more general importance. A critical area for visual attention is the right parietal cortex. Lesions here not only impair attention but also diminish EDA responses (Tranel and Damasio 1994; Zahn and others 1999; Tranel 2000), and right parietal cortex activity covaries with EDA (Critchley and others 2000b). These findings suggest commonality in the neuroanatomy supporting both attention and bodily arousal, consistent with the use of EDA as an index of attention and the observation that attention is directed toward stimuli that evoke arousal (e.g., Lane and others 1999).

Overall, there is increasing knowledge about how bodily arousal, particularly sympathetic responses indexed by EDA, interfaces with cognitive and emotional processes. The use of human lesion-deficit models and functional neuroimaging is enabling a clearer defini-

tion of neural substrates and behavioral purpose such as body/brain interactions. However, there is still much that remains uncertain, and a mechanistic understanding of these processes governing autonomic arousal and its influence on behavior is an important goal for future study.

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