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Frontal electrocortical and cardiovascular reactivity during happiness and anger

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Abstract

The present study investigated electrocortical and cardiovascular reactivity during positive and negative emotion, and examined the relation of asymmetric frontal lobe activation to cardiovascular responses. Participants were 30 healthy, right-handed university students (mean age, 23.9; 60% female; 76% Caucasian). Electroencephalographic (EEG), blood pressure (BP), and heart rate (HR) responses were assessed while subjects engaged in laboratory tasks (personally-relevant recall tasks and film clips) designed to elicit happiness or anger. Happiness-inducing tasks evoked more prominent left than right frontal EEG activation, and greater left frontal EEG activation than anger-inducing tasks. However, anger-inducing tasks were, on average, associated with comparable left and right frontal EEG activation. Irrespective of emotional valence, cardiovascular activation was more pronounced during personally-relevant recall tasks than during the viewing of film clips.

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During anger recall, both greater left frontal EEG response ($r = -0.46$, $P < 0.02$) and greater right frontal EEG response ($r = -0.45$, $P < 0.02$) were correlated significantly with increased HR reactivity during the task. In addition, a right lateralized frontal EEG response during anger-inducing tasks was associated with greater concomitant systolic BP ($P < 0.03$) and diastolic BP ($P < 0.008$) reactivity. Exploratory analyses also indicated that men who displayed a left lateralized frontal EEG response during happiness-inducing tasks showed the greatest concomitant systolic BP and HR reactivity (P's < 0.03). These findings suggest that asymmetric frontal EEG responses to emotional arousal may elicit different patterns of cardiovascular reactivity in healthy adults.

Keywords: Electroencephalography; Lateralization; Frontal brain asymmetry; Cardiovascular reactivity; Blood pressure; Emotion

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Intense emotional arousal is posited to play a role in the onset of acute coronary events such as myocardial infarction and sudden cardiac death (Kamarck and Jennings, 1991; Lane and Jennings, 1995; Mittleman et al., 1995; Krantz et al., 1996). It is hypothesized that emotions activate regions of the brain that stimulate sympathetic outflow, thus promoting elevations in various cardiovascular parameters. Cardiovascular responses (reactivity) of sufficient magnitude may, in turn, elicit coronary events via myocardial ischemia and a lowered threshold for ventricular arrhythmias (Kamarck and Jennings, 1991). Repeated cardiovascular responses during emotional arousal have also been hypothesized as a link between dispositional psychological traits (e.g. anger, anxiety) and cardiovascular disease (Manuck, 1994; Rozanski et al., 1999).

Although numerous investigations have linked central nervous system (CNS) activation to emotional arousal, and others have related emotional arousal to cardiovascular reactivity (see below), actual brain–heart interconnections remain poorly understood (Armour and Ardell, 1994). Indeed, despite that CNS activation may partially mediate associations between emotion and cardiovascular reactivity, it is unusual for each of these parameters to be examined in conjunction in a single investigation. Yet, such studies are critical first steps in the identification of brain–heart linkages during emotional activation that may ultimately prove to have relevance to the development of cardiovascular disease or the elicitation of acute coronary events.

The primary goal of the present study was, therefore, to examine whether laboratory tasks designed to elicit happiness or anger, both of which are emotions that may play a role in eliciting cardiac arrhythmias or sudden cardiac death (Kamarck and Jennings, 1991), evoke concomitant increases in regional cerebral (particularly frontal lobe) and cardiovascular activation in healthy young adults. Evaluating the feasibility of such an investigation in a healthy sample was also deemed an important initial step prior to studying a more pertinent, yet biologically vulnerable, patient population that is prone to cardiac arrhythmias and sudden cardiac death (such as patients with implantable defibrillators).

Rationale pertinent to this study's hypotheses regarding patterns of cerebral and cardiovascular responses during positive (happiness) and negative (anger) emotion derives from several different bodies of literature that, to date, have been largely unintegrated (Lane and Schwartz, 1987). These investigations generally use fairly distinct paradigms and methodologies and include studies of emotions and CNS activation; emotions and cardiovascular reactivity; and CNS activation and cardiovascular reactivity.

The relation between acute emotional arousal and CNS activation has been examined using electroencephalography (EEG), and results of numerous studies indicate that positive and negative emotions are associated with different patterns of cortical activation. Most studies have demonstrated that left frontal lobe activation is associated with the expression and experience of positive emotions and approach behaviors, whereas activation of the right frontal lobe relates to the experience and expression of negative emotions and withdrawal behaviors (Davidson, 1992; Jones and Fox, 1992; Davidson, 1993, 1995; Hagemann et al., 1998). Happiness and anger were selected for the present investigation as target emotions that were representative of positive and negative valence, respectively, and that were high on the arousal dimension of emotion (Russell, 1997). In addition, as noted above, both emotions may be pertinent to the elicitation of cardiac arrhythmias (Kamarck and Jennings, 1991).

In studies of emotion and autonomic responses, it is less clear whether positive and negative emotions produce similar or different patterns of cardiovascular activation. Several investigations have noted differential blood pressure, heart rate (HR), and peripheral vascular resistance responses to positive emotions such as joy or happiness and negative emotions such as anger, fear, and sadness (Schwartz et al., 1981; Ekman et al., 1983; Sinha et al., 1992). However, other studies have shown similar cardiovascular responses during positive and negative emotion (Cacioppo et al., 1993; Warner and Strowman, 1994).

Although few investigations have directly examined relations between CNS measures and cardiovascular reactivity during emotional activation, several available theoretical models can be used to derive hypotheses regarding such associations. For example, Wittling (1990) has suggested that the right cerebral hemisphere is dominant for the elicitation of autonomic responses. In this regard, some research has shown that damage to the right hemisphere is more likely to result in autonomic dysregulation as compared with left hemisphere damage (Hachinski et al., 1992; Gainotti et al., 1993; Andersson and Finsett, 1998). However, other investigators have noted that sympathetic outflow can be elicited by activation of multiple cortical and subcortical regions of the brain (Lane and Jennings, 1995). Within cortical regions, activation of the frontal lobes is thought to be particularly important in eliciting sympathetic outflow, cardiovascular reactivity, myocardial instability, and cardiac arrhythmias (Skinner and Reed, 1981; Lane and Schwartz, 1987; Lane and Jennings, 1995).

Lane and Schwartz (1987) suggest that individuals who display the greatest lateralized frontal lobe activity during either positive or negative emotional arousal will experience lateralized sympathetic input to the heart via select stimulation of the stellate ganglion either contralateral or ipsilateral to the activated cerebral hemisphere (Lane and Schwartz, 1987; Lane and Jennings, 1995). Such an imbalance in sympathetic (particularly left) cardiac input has been shown, in animal models, to be arrhythmogenic (Schwartz, 1984). More directly pertinent to the present investigation, however, distinct patterns of cardiac activation may also result from asymmetric stimulation of the stellate ganglion due to differences in the topographical distribution of the right and left stellate cardiac nerves (Lane and Schwartz, 1987). In this regard, stimulation of the left stellate ganglion has been shown to increase cardiac inotropic activity as reflected in increased myocardial contractility, systolic and mean arterial blood pressure, in addition to increased AV conduction and prolongation of the QT interval; in contrast, stimulation of the right stellate ganglion tends to increase cardiac chronotropic activity as reflected in an increased HR (Lane and Schwartz, 1987; Wittling, 1995).

Although the biological underpinnings of Lane and Schwartz's model are not tested directly in the present investigation, the model suggests specific hypotheses regarding associations between asymmetric cerebral activation and cardiovascular response patterns. Accordingly, the present study examined the hypothesis that the negative emotion of anger asymmetrically activates the right frontal lobe and is associated with increased blood pressure reactivity. Conversely, asymmetric activation of the left frontal lobe during the positive emotion of happiness was expected to be associated with increased HR responses. The potential moderating influence of gender was also examined in exploratory analyses given previously identified gender differences in emotional expression (Brody and Hall, 1993) and cardiovascular reactivity (Stoney et al., 1987).

1. Methods

1.1. Participants

Participants were 30 healthy, right-handed university students (mean age, 23.9 years, S.D., 4.3). Sixty percent were female; 76% were Caucasian; 14% African-American; 7% Asian-American; 3% Hispanic. Exclusionary criteria were a self-reported history of hypertension, cardiovascular disease, diabetes mellitus, neurological or psychiatric disorder; history of head injury with loss of consciousness >10 min; use of medications affecting cardiovascular or cerebrovascular function (including oral contraceptives); and obesity ($>25\%$ overweight by Metropolitan Life Insurance Tables) (Metropolitan Life Insurance Company, 1983). All subjects provided written informed consent in accordance with the University of Maryland's Institutional Review Board guidelines, and were paid $20.00 for their participation.

2.2. Electroencephalographic recording

Brain electrical activity was recorded by EEG using a lycra stretch cap (Electro-Cap, Inc.). The cap electrodes were positioned according to the International 10/20 Electrode Placement System (Jasper, 1958). After gently abrading each electrode surface, the electrode sites were then filled with a small amount of electrolyte gel, which served as a conductor. Electrode impedances below 10 kΩ per site and within 500 Ω between homologous sites were considered acceptable.

The EEG was recorded at eight scalp locations: left and right mid-frontal (F3, F4), parietal (P3, P4), central (C3, C4) and occipital (O1, O2) regions. These sites represent the left and right hemispheres and anterior and posterior regions of the brain. All electrodes were referenced to the central vertex (Cz).

Electrooculographic (EOG) activity was recorded using two Beckman miniature electrodes, which were placed on the external canthus and the supra-orbital area of the right eye. The EOG signal was used to facilitate subsequent EEG artifact editing. A separate ground electrode was attached to the base of the subject's neck on the dorsal side.

The nine channels were amplified by individual Grass AC Bioamplifiers (Model 7p511). The filter settings for the nine channels were set at 1 Hz (high pass) and 100 Hz (low pass). A calibration signal (10 Hz/0.47 V rms sine wave) was input through each amplifier prior to each data collection. The output of this signal was 50 uV, with a gain of 10 000. The data from all nine channels were digitized on-line at a sampling rate of 512 Hz on a Gateway 486/33C PC in order to prevent aliasing of the EEG data (Pivik et al., 1993). EEG data were stored on optical laser disk for analysis.

1.3. Cardiovascular measures

Blood pressure and HR measurements were obtained oscillometrically using a Critikon Dinamap (Model #8100) automated vital signs monitor (Critikon, Tampa, FL).

1.4. Self-report items

Consistent with prior literature (Davidson et al., 1990; Wittling and Pfluger, 1990; Waldstein et al., 1997), subjects rated items reflecting their level of affective arousal (e.g. anxious, depressed, disgusted, happy, angry) and task engagement (e.g. interested, involved) on a Likert-type scale of 1–10.

1.5. Experimental tasks

Subjects engaged in a series of tasks chosen for their ability to elicit happiness or anger.[2] Positive tasks included a 1 min film clip shown previously to elicit happiness

[2] Subjects also viewed a film clip designed to elicit disgust and performed a computerized Stroop Color-Word Test. These data are excluded from the present report because this paper focuses on emotions previously associated with cardiovascular disease or sudden cardiac death.

(Jones and Fox, 1992), and verbally describing (3 min) and subsequently imagining (2 min) a personally-relevant, happy incident. For the negative tasks, a parallel procedure was used: a 1 min film clip previously shown to elicit anger (Jones and Fox, 1992), and verbally describing (3 min) and subsequently imagining (2 min) a personally-relevant, angry incident (Ironson et al., 1992). The specific film clips were chosen because they had previously elicited frontal EEG responses (Jones and Fox, 1992). The positive film clip depicted a scene from the movie 'On Golden Pond' involving a joyful mother–daughter interaction. The negative film clip derived from the movie 'Witness' and involved mistreatment of an Amish man by several local bullies.

Personally-relevant recall tasks were chosen because of their tendency to elicit relatively large cardiovascular responses, and both silent myocardial ischemia and cardiac electrical instability in cardiac patients (Rozanski et al., 1988; Ironson et al., 1992). Briefly, participants were asked to discuss an incident (preferably occurring within the past 6 months) that made them feel angry, frustrated, or irritated (and another that made them feel happy, glad, or cheerful). The participant was asked to recreate the incident from beginning to end relaying what was said and done and describing associated thoughts and feelings. During the imagery portion of the task, the participant was asked to continue to think about this situation, focusing on visualizing different aspects of the situation (e.g. location, persons involved) and concentrating on the associated feelings. They were also cued with signs periodically during the task to assist in focusing their attention (e.g. 'how did you feel?').

2. Procedure

Participants were seated in a comfortable chair in an experimental room. After providing written informed consent, participants completed a brief demographic questionnaire, and were instrumented for EEG and cardiovascular monitoring. A 10-min rest (baseline) period was followed by completion of the following tasks, each of which was followed by a 5–10 min intertask recovery period — happy film, happy recall and happy imagery, anger film, anger recall and anger imagery. Order of the positive (happy film, happy recall and imagery) and negative (anger film, anger recall and imagery) emotional stimuli was counterbalanced. Each film task was followed by a 5-min recovery period; recall tasks were followed by a 10-min recovery period.

EEG data were obtained during min 7–9 of the initial baseline period (to allow for habituation to the setting); continuously during each 1 min film clip; during min 3–4 of film recovery; continuously during the visualization (imagery) portion of the happy and anger recall tasks; and during min 8–9 of the post-recall recovery periods. EEG data were not collected during the verbalization portion of the recall tasks because of the well known effects of speaking on frontal lobe activation. Systolic blood pressure (SBP), diastolic blood pressure (DBP), and HR were obtained at 90-s intervals during each baseline and recovery period and at 60-s intervals during all task periods. Self-reported ratings of affect and task engagement were obtained at the end of each baseline and task period.

3. Data reduction

3.1. EEG measures

The EEG data were re-referenced to an average reference configuration and visually scored for artifact due to eyeblinks, eye movements, and other motor movements, using a software program developed by James Long Company (EEG Analysis Program, Caroga Lake, NY). This program removes data from all channels if artifact is present on any one channel. The amount of artifact edited EEG data was examined to exclude confounding by systematic within subject variation. All artifact-free EEG data were analyzed using a discrete Fourier transform (DFT), with a Hanning window of 1-s width and 50% overlap. Power (microvolts-squared) was computed in the 8–13 Hz (alpha) frequency band for each electrode site.

Change scores (mean log transformed task value minus mean log transformed values associated with the immediately preceding baseline) were calculated as an index of task-induced left and right frontal and parietal lobe responses. A negative change score indicated activation. A laterality difference score was also computed in order to examine hemispheric asymmetry in each region. This asymmetry score was calculated as follows (ln power (right hemisphere))–(ln power (left hemisphere)). Positive values on this metric represent greater relative left hemisphere activation and vice versa (Davidson and Tomarken, 1989).

3.2. Cardiovascular measures

Mean baseline values of SBP, DBP, and HR were computed using the three readings obtained during the final 5 min of each baseline or recovery period. Mean task values of SBP, DBP, and HR were computed from readings obtained during each task (one reading during film clips; three readings during the verbalization portion of the recall tasks; two readings during the imagery (visualization) portion of the recall tasks). Change scores (mean task value minus immediately preceding baseline value) were calculated as an index of task-induced SBP, DBP, and HR response to the tasks.

3.3. Self-report items

Change scores (task value minus immediately preceding baseline value) were computed to index task-induced affective and engagement responses for the following self-report items — happy, angry, anxious, depressed, disgusted, interested, involved.

4. Results

4.1. Regional EEG data

To examine task-induced changes in anterior and posterior EEG responses, repeated measures analyses of variance (ANOVAs) (Hemisphere$_{Right,Left}$ by Valence$_{Positive,Negative}$ by Task$_{Film,Recall-Visualize}$) of arithmetic change scores were performed. Separate analyses were conducted for frontal and parietal lobe activation (see Table 1). For frontal lobe activation there was a significant interaction of hemisphere and valence ($F(1,28) = 5.42$; $P < 0.03$). Simple effects analysis revealed that left frontal activation was significantly greater than right frontal activation during tasks designed to elicit happiness ($P < 0.05$). In addition, left frontal activation was significantly greater during happiness-inducing tasks than anger-inducing tasks ($P < 0.01$). However, right frontal activation did not differ as a function of valence or task.

Analysis of parietal lobe activation revealed a significant interaction between hemisphere and task ($F(1,28) = 12.72$; $P < 0.002$). Simple effects analysis revealed that right parietal activation was greater during the film clips than during the recall tasks ($P < 0.05$).

4.2. Cardiovascular data

Repeated measures ANOVAs (Valence$_{Positive,Negative}$ by Task$_{Film,Recall-Verbalize,Recall-Visualize}$) of task-induced SBP, DBP, and HR response revealed significant effects of task for SBP ($F(2,56) = 51.86$; $P < 0.00001$), DBP ($F(2,56) = 60.60$; $P < 0.00001$) and HR ($F(2,56) = 42.65$; $P < 0.00001$) (see Table 2). Tukey's post-hoc comparisons also indicated that SBP, DBP, and HR responses to the verbalization portion of the recall tasks were significantly greater than during the films or the visualization portion of the recall tasks (P's < 0.05). In addition, the SBP response to imagery was greater than SBP responses during the film ($P < 0.05$).

4.3. Self-report data

Repeated measures ANOVAs (Valence$_{Positive,Negative}$ by Task$_{Film,Recall}$) of task-induced affect and engagement revealed significant main effects of valence for

Table 1
Task-induced changes in frontal EEG alpha (8–13 Hz) power (microvolts squared)

	Mean (S.D.)			
	Happy film	Happy recall	Anger film	Anger recall
Left frontal	−0.39 (0.91)	−0.29 (0.45)	−0.11 (0.43)	−0.14 (0.50)
Right frontal	−0.16 (0.38)	−0.20 (0.45)	−0.11 (0.49)	−0.17 (0.54)

Table 2
Task-induced changes in blood pressure and heart rate

	Mean (S.D.)					
	Happy film	Happy recall-speak	Happy recall-visualize	Anger film	Anger recall-speak	Anger recall-visualize
SBP (mmHg)	−0.7 (5.3)	12.4 (8.8)	5.0 (6.1)	0.8 (4.1)	13.1 (8.3)	4.0 (5.7)
DBP (mmHg)	0.8 (6.0)	11.4 (7.4)	2.9 (6.2)	0.3 (4.2)	11.0 (8.2)	1.1 (5.3)
HR (bpm)	−2.5 (4.1)	6.5 (4.3)	0.3 (5.7)	−2.4 (4.1)	6.2 (7.5)	−2.3 (5.3)

Table 3
Self-Reported affect and engagement

	Mean (S.D.)							
	Happy film		Happy recall		Anger film		Anger recall	
	Baseline	Task	Baseline	Task	Baseline	Task	Baseline	Task
Happy	6.4 (2.4)	6.7 (2.1)	6.1 (2.5)	8.2 (1.8)	5.4 (2.3)	4.7 (2.6)	5.6 (2.4)	3.9 (2.4)
Angry	1.4 (1.1)	1.5 (1.2)	1.4 (1.1)	1.3 (0.9)	1.9 (2.0)	4.2 (3.2)	1.4 (1.1)	6.2 (3.0)
Anxious	2.4 (1.9)	2.0 (1.6)	2.2 (1.9)	2.1 (1.7)	2.5 (1.8)	2.8 (2.2)	2.1 (1.6)	3.8 (2.3)
Disgusted	1.5 (0.9)	1.6 (1.6)	1.4 (1.0)	1.2 (0.5)	1.6 (1.5)	3.1 (2.8)	1.4 (1.1)	4.8 (2.8)
Depressed	1.5 (0.9)	1.5 (1.2)	1.4 (0.9)	1.3 (0.8)	1.8 (1.9)	2.0 (1.5)	1.4 (1.0)	3.0 (2.6)
Involved	4.4 (2.9)	4.7 (2.5)	3.7 (2.5)	5.9 (2.2)	3.6 (2.5)	4.5 (2.5)	3.1 (2.3)	6.3 (2.1)
Interested	6.0 (2.5)	5.7 (2.3)	5.3 (2.8)	6.4 (2.2)	5.0 (2.6)	6.4 (2.3)	4.7 (2.4)	5.7 (2.6)

happiness ($F(1,28) = 48.85$; $P < .00001$), anger ($F(1,28) = 64.25$; $P < 0.00001$), anxiety ($F(1,28) = 21.58$; $P = 0.0002$), depression ($F(1,28) = 10.00$; $P < 0.004$), disgust ($F(1,28) = 26.89$; $P = 0.0001$), interest ($F(1,28) = 4.54$; $P < 0.05$), and involvement ($F(1,28) = 7.94$; $P < 0.009$) (see Table 3). Specifically, positive (happy film and recall) tasks elicited greater increases in happiness than did the negative tasks, whereas the negative (anger film and recall) tasks elicited greater increases in the items angry, anxious, depressed, disgusted, involved, and interested.

Significant main effects of film versus recall task were noted for anger ($F(1,28) = 9.76$; $P < 0.005$), anxiety ($F(1,28) = 8.91$; $P < 0.006$), and involvement ($F(1,28) = 41.84$; $P < 0.00001$) with a near-significant effect for interest ($F(1,28) = 4.04$; $P < 0.06$). The recall tasks elicited greater anger, anxiety, interest, and involvement than did the film tasks.

A significant interaction of valence and task was found for happiness ($F(1,28) = 16.82$; $P < 0.0004$), anger ($F(1,28) = 15.39$, $P < 0.0006$), anxiety ($F(1,28) = 15.38$; $P < 0.0006$), depression ($F(1,28) = 8.10$; $P < 0.009$), disgust ($F(1,28) = 9.58$; $P < 0.005$), and interest ($F(1,28) = 7.38$; $P < 0.02$). Post-hoc comparisons indicated that anger recall elicited significantly greater increases in all negative emotions than did the happy recall task or either film (P's < 0.05). The happy recall task induced greater increases in happiness than did the films or anger recall ($P < 0.05$).

Next, to examine whether the happy film and happy recall tasks were associated with greater self-reported happiness than all other emotions (i.e. anxiety, depression, disgust, anger), a series of paired t-tests were computed. Results indicated that the happy recall task elicited significantly greater changes in self-reported happiness than all other emotions (P's < 0.00001). Although changes in all emotions during the happy film were small and comparable, it is important to note that baseline levels of happiness were fairly high just prior to this task (see Table 3). However, task levels of happiness during the happy film were significantly greater than task levels of all other emotions (P's < 0.00001).

Finally, to examine whether the anger film and anger recall tasks were associated with greater self-reported anger than all other emotions (i.e. happiness, anxiety, depression, disgust) a series of paired t-tests were computed. Results indicated that the anger recall task elicited significantly greater self-reported anger responses than all other emotions (P's < 0.001). The anger film also elicited significantly greater self-reported anger than all other emotions except disgust (P's < 0.01).

4.4. Pearson (r) correlations between frontal EEG and cardiovascular measures

To explore the interrelations between frontal EEG and cardiovascular measures, Pearson (r) correlations were computed separately for responses to each task (happy film, happy recall, anger film, anger recall) using task-induced change scores on the following measures — left and right frontal EEG, SBP, DBP, and HR (see Table 4).

For the anger recall task, both greater left frontal EEG response[3] ($r = -0.46$; $P < 0.02$) and greater right frontal EEG response ($r = -0.45$; $P < 0.02$) were correlated significantly with increased HR reactivity during the task. No significant correlations between the frontal EEG and cardiovascular measures were noted for the happy film, happy recall, or anger film tasks.

Table 4
Correlations among frontal EEG and cardiovascular responses

	Left frontal EEG	Right frontal EEG
Happy film		
SBP	−0.09	0.08
DBP	−0.11	0.10
HR	0.20	0.05
Happy recall		
SBP	−0.16	−0.02
DBP	−0.02	0.03
HR	0.05	0.17
Anger film		
SBP	0.04	0.08
DBP	0.03	0.01
HR	−0.08	−0.12
Anger recall		
SBP	−0.02	−0.05
DBP	0.06	0.07
HR	−0.46*	−0.45*

[3] Negative change in EEG indicates greater arousal. Therefore, a negative correlation between EEG and cardiovascular response reflects a concordance between these measures.

4.5. Asymmetric left frontal EEG activity and cardiovascular response during happiness

To identify a subgroup of individuals who displayed lateralized left frontal EEG responses during the positive emotion tasks, participant's frontal EEG asymmetry scores during the happy film and happy recall tasks were averaged. Individuals having a positive value on this metric were classified as lateralized left frontal EEG responders during happiness-inducing tasks. Lateralized left frontal responders to positive tasks ($n = 14$) were compared with non-left lateralized (e.g. neutral or right frontal) responders ($n = 16$) to these tasks with respect to blood pressure, HR, and self-reported positive affect and task engagement responses to the positive tasks. Repeated measures ANOVAs (Frontal Lateralization$_{\text{Left, Non-Left}}$ by Valence$_{\text{Positive,Negative}}$ by Task$_{\text{Film,Recall-Verbalize,Recall-Visualize}}$) revealed no significant main or interactive effects of left frontal lateralization with respect to task-induced cardiovascular, positive affect, or engagement responses.

4.6. Asymmetric right frontal EEG activity and cardiovascular response during anger

To identify a subgroup of individuals who displayed lateralized right frontal EEG responses during the negative emotion tasks, participant's frontal EEG asymmetry scores during the anger film and anger recall tasks were averaged; individuals having a negative value on this metric were classified as lateralized right frontal EEG responders during anger-inducing tasks.

Right lateralized frontal EEG responders to the negative tasks ($n = 12$) were compared with non-right lateralized (i.e. neutral or left frontal) responders ($n = 18$) with respect to BP, HR, and negative affect and engagement response to the negative tasks. Repeated measures ANOVAs (Frontal Lateralization $_{\text{Right,Non-Right}}$ by Valence$_{\text{Positive,Negative}}$ by Task$_{\text{Film,Recall-Verbalize,Recall-Visualize}}$) revealed significant main effects of frontal asymmetry for SBP ($F(1,25) = 5.68$; $P < 0.03$), and a trend for DBP ($F(1,25) = 3.77$; $P = 0.06$). Subjects who displayed lateralized right frontal EEG responses during anger tasks showed greater SBP and DBP responses than non-right lateralized subjects (see Figs. 1 and 2). A significant interaction of frontal lateralization and task was also found for DBP ($F(2,50) = 5.33$; $P < 0.008$). Post-hoc comparisons indicated that subjects with right frontal lateralization showed greater DBP response to the verbalization and visualization portions of the anger recall task than did the other subjects ($P < 0.05$). There were no significant main or interaction effects of right frontal lateralization with respect to any of the negative affect or engagement items.

4.7. Exploratory analysis of gender interactions

To explore the potentially interactive influences of gender, the primary data analyses were repeated with gender as a between subjects factor. There were no interactive effects of gender with respect to task-induced EEG or cardiovascular

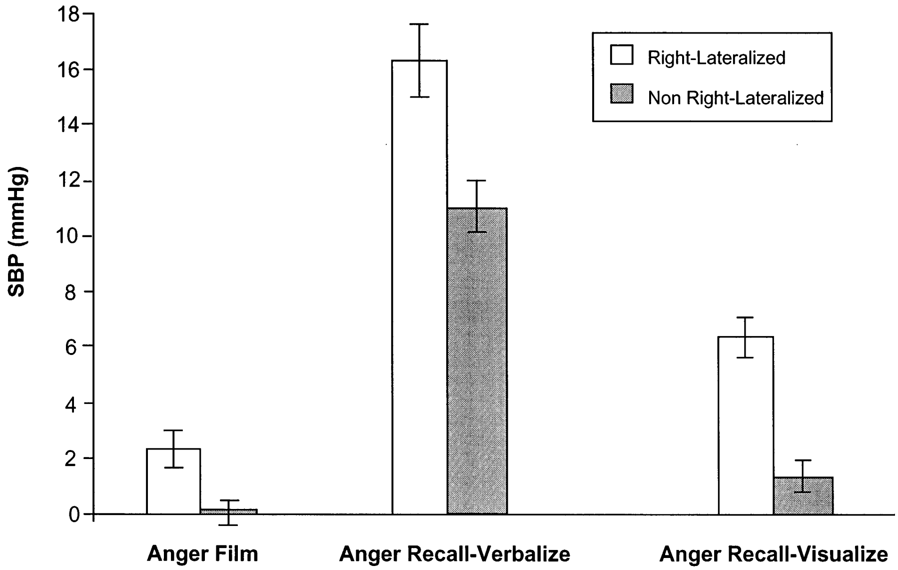

Fig. 1. Systolic blood pressure (SBP) response (mean and S.E. of arithmetic change scores) to anger-inducing tasks as a function of right-lateralized vs. non-right-lateralized frontal EEG response to those tasks.

responses. However, for self-reported affect measures, interactions of gender, valence, and task were observed for anxiety ($F(1,28) = 15.38$; $P < 0.0006$) and depression ($F(1,28) = 4.20$; $P < 0.05$). Post-hoc comparisons indicated that men showed greater increases in anxiety during the anger recall task than during all other tasks ($P < 0.05$). Men's responses were also significantly greater than women's anxiety responses to all tasks (P's < 0.05). In addition, men showed a greater increase in depression during anger recall as compared with all other tasks; the increase in depression was also greater than women's responses to the happy film and happy recall (P's < 0.05). Results also indicated an interaction of left frontal lateralization and gender for SBP ($F(1,26) = 5.75$; $P < 0.03$) and HR ($F(1,26) = 5.81$; $P < 0.03$) responses. As depicted in Figs. 3 and 4, simple effects analysis indicated that men who were lateralized left frontal responders showed greater SBP reactivity than all other subjects (P's < 0.05). Left lateralized men also showed a greater HR response than did left-lateralized women ($P < 0.05$). In addition, left-lateralized women showed less of a HR response than non-left lateralized women ($P < 0.05$).

5. Discussion

Using two neurobehavioral models as a theoretical framework (Lane and Schwartz, 1987; Davidson, 1992, 1993, 1995), we examined the association between electrocortical and cardiovascular measures in response to emotionally evocative stimuli that were presented across a variety of tasks.

5.1. Electrocortical findings

Consistent with theoretical models and a substantial empirical literature relating frontal EEG measures and emotion, we found that happiness inducing tasks evoked significant increases in frontal EEG activation, particularly in the left frontal region. Performance of the negative emotion-inducing (e.g. anger) tasks evoked negative affect, including anger, anxiety, and disgust; however, anger was the predominant emotion endorsed. The negative emotion-inducing tasks elicited comparable right and left frontal EEG activation.

The pattern of asymmetrical left frontal EEG activity during happiness is consistent with prior results indicating that asymmetric left frontal brain activity is related to the processing of positive emotions (e.g. Jones and Fox, 1992; Davidson, 1993). However, we found that the pattern of frontal EEG activity during the anger-invoking task was more symmetrical than would be predicted by theoretical models of emotion. That is, despite its frequent classification as an emotion with negative valence, anger was associated with activation of both right and left frontal regions, rather than with asymmetric right frontal activity. Other authors have also

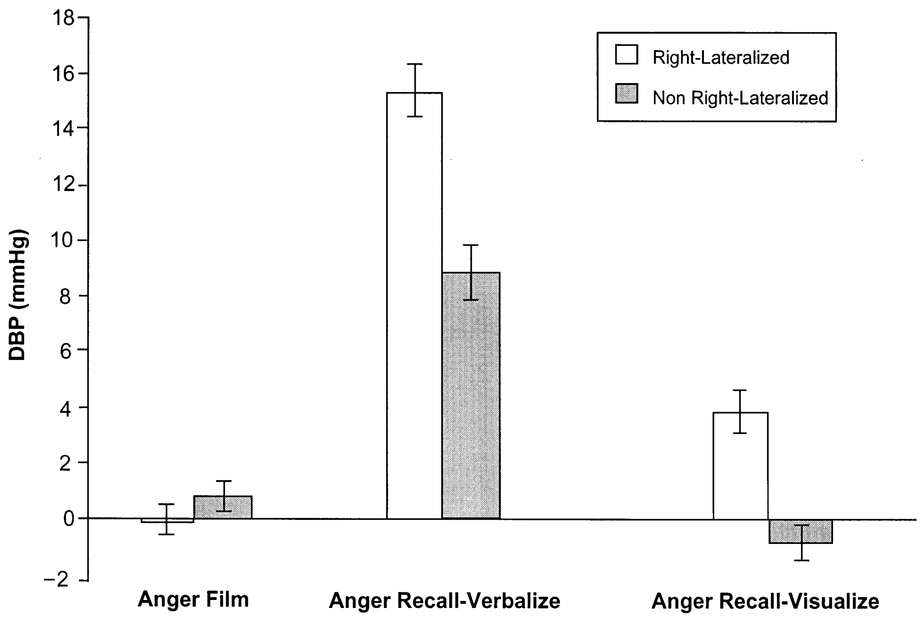

Fig. 2. Diastolic blood pressure (DBP) response (mean and S.E. of arithmetic change scores) to anger-inducing tasks as a function of right-lateralized vs. non-right-lateralized frontal EEG response to those tasks.

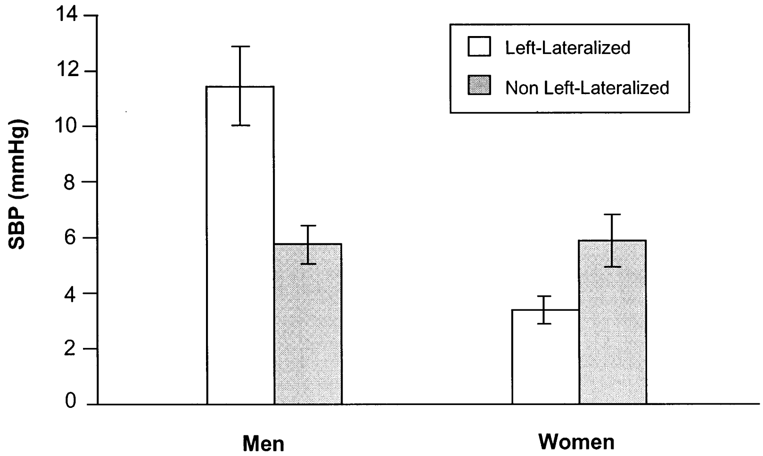

Fig. 3. Systolic blood pressure (SBP) response (mean and S.E. of arithmetic change scores), averaged across happiness-inducing tasks, in men and women as a function of left-lateralized vs. non left-lateralized frontal EEG response to those tasks.

noted an absence of right frontal EEG asymmetry during anger (Davidson, 1993). Further, it has been posited that anger may, theoretically, be associated with either approach or withdrawal and may thus elicit either asymmetric left or asymmetric right frontal activity (Davidson et al., 1990). This issue may be clarified in the future by examining individual's preferred mode of anger expression. It is conceivable that persons who tend to express their anger outwardly (anger-out style) may experience anger as an emotion associated with approach behavior, whereas individuals who tend to suppress their anger (anger-in style) may experience anger as an emotion associated with withdrawal behavior.

5.2. Cardiovascular findings

Although a number of studies have found that autonomic measures distinguish among emotions in humans (Schwartz et al., 1981; Ekman et al., 1983; Sinha et al., 1992), we found a similar pattern of autonomic activity across emotional valence. Consistent with some prior investigations, the similarity in cardiovascular responses to both positive and negative tasks may have reflected either a generalized emotional response to the affective stimuli or task-induced engagement or arousal (Cacioppo et al., 1993; Warner and Strowman, 1994; Nyklicek et al., 1997). The finding that different types of tasks (films vs. recall) elicit differential magnitude of cardiovascular responses is also consistent with prior work in which passive and non-social tasks (such as films) have been found to elicit a relatively small cardiovascular response whereas tasks involving personally-relevant material or social interaction evoke more pronounced responses (Krantz et al., 1986; Smith and Gerin, 1998).

5.3. Frontal EEG asymmetry and cardiovascular reactivity

Contrary to our theoretical models, we noted few significant linear relations between frontal EEG and cardiovascular responses. One of the few exceptions was a significant correlation between both right and left frontal EEG activation and greater HR reactivity during anger recall, the task that elicited the greatest emotional response. Overall, this relative absence of findings may suggest some degree of dissociation between EEG and cardiovascular indices. However, it possible that if directionally inconsistent patterns of association are apparent among subgroups of individuals (e.g. as a function of gender), the results may be cancelled out upon average.

Interestingly, however, results of asymmetry analyses revealed partial support for the predictions formulated on the basis of Lane and Schwartz's model (Lane and Schwartz, 1987). That is, as predicted, subjects who showed asymmetric right frontal EEG activation during anger-induction showed greater blood pressure (SBP and DBP) responses during those tasks. Similarly, Wittling (1990) found greater SBP and DBP responses during lateralized presentation of an emotion eliciting film to the right hemisphere as compared with the left hemisphere. This pattern of enhanced BP reactivity in the absence of a significant HR response suggests the possibility of an underlying increase in peripheral vascular resistance.

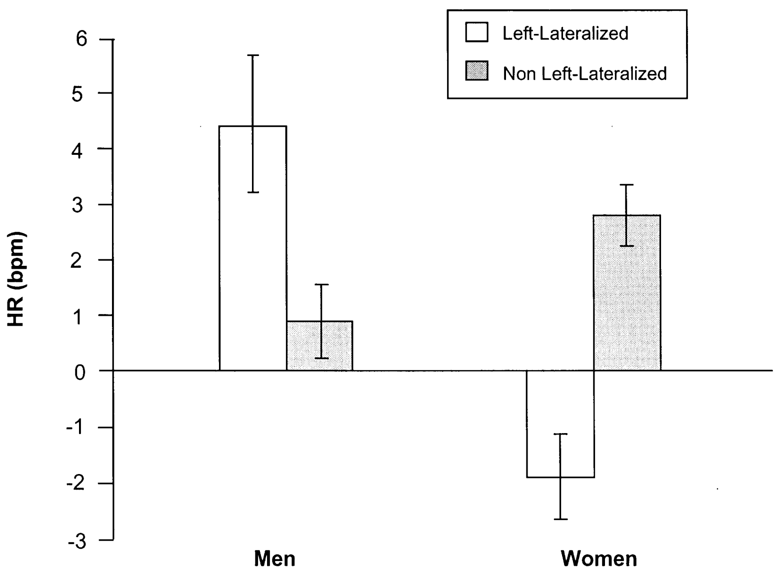

Fig. 4. Heart rate (HR) response (mean and S.E. of arithmetic change scores), averaged across happiness-inducing tasks in men and women as a function of left-lateralized vs. non left-lateralized frontal EEG response to those tasks.

Results of exploratory analyses also revealed that asymmetric left frontal EEG activity during happiness was associated with enhanced SBP and HR reactivity among men. This finding should be interpreted cautiously given limited statistical power; the findings are thus prone to both type 1 and type 2 errors. However, these results are also partially consistent with the study hypotheses (e.g. increased HR reactivity with asymmetric left frontal EEG activation). In addition, the overall cardiovascular response pattern (increased SBP and HR reactivity) suggests the possibility of an underlying myocardial activation. Further exploration of the hemodynamics underlying each of these patterns of cardiovascular response using a method such as impedance cardiography would be of interest in order to directly examine whether myocardial activation and peripheral vascular resistance are differentially affected by asymmetric frontal EEG activation. Examination of indices of parasympathetic function (e.g. HR variability) could also help to clarify these findings and, more generally, further an understanding of brain–heart interrelations (Thayer and Lane, in press).

5.4. Limitations and future directions

There were several limitations of the present study that warrant discussion and suggest future directions for research. First, as noted above, this investigation has limited statistical power due to a relatively small sample. It is thus critical to replicate these findings using larger samples.

Second, it is possible that EEG may not sufficiently identify or characterize the brain regions involved in autonomic responses to emotions. In this regard, Lane and colleagues have conducted a series of emotion-induction studies in healthy women using positron emission tomography to index cerebral correlates of emotion. In one study, activation of thalamus and medial prefrontal cortex was noted during the viewing of films or recall of personal experiences evoking happiness, sadness, or disgust (Lane et al., 1997a). In another investigation (Lane et al., 1997b), women viewed pleasant, unpleasant, or neutral pictures. Increased cerebral blood flow was noted in medial prefrontal cortex, thalamus, hypothalamus, and midbrain during both pleasant and unpleasant emotion conditions as compared with the neutral condition. Viewing pleasant pictures was also associated with activation of head of the left caudate nucleus, when compared with neutral pictures. Unpleasant picture viewing was associated with activation of the bilateral occipitotemporal cortex, cerebellum, left parahippocampal gyrus, hippocampus, and amygdala as compared with pleasant and neutral pictures. The authors concluded that although there are some unique dimensions of cortical and subcortical activation associated with pleasant and unpleasant emotions, these emotions also share a number of commonalities.

Gainotti et al. (1993) highlight the importance of subcortical processing in both emotional and autonomic activation. These authors suggest that cortical structures may be most important in inhibiting the subcortical structures involved in emotion and autonomic nervous system activity. Damage to the insula may be particularly critical in mediating sympathetic activity (Hachinski et al., 1992). Future research would benefit from the combination of methodologies that allow for the temporal resolution provided by EEG along with the spatial resolution of PET and functional magnetic resonance imaging in relation to central and autonomic processing of emotion.

Third, it has been suggested that it may be important to identify epochs of experience of discrete emotions and to examine those periods with respect to concomitant physiological activity (Davidson et al., 1990). Davidson et al. (1990) further suggest that the averaging of emotion and physiological response during emotion tasks may partially obscure relations. Pronounced individual differences in EEG, cardiovascular, and subjective responses were indeed noted here and may warrant examination of subgroups within a larger number of participants. It may also be necessary to elicit more intense emotional states in order to observe more pronounced interrelations between cardiovascular and electrocortical measures. Testing a broader range of positive and negative emotions would also be useful because the present findings may be specific to happiness and anger.

Fourth, the addition of further cardiovascular parameters in future research may assist in the differentiation of emotional states and in the linkage between cerebral and autonomic activity. Electrocardiographic indices of myocardial instability, such as QT prolongation or T-wave alternans, indices of HR variability, and assessment of hemodynamic response patterns (using impedance cardiography) may be useful in this regard, particularly in populations at high risk of cardiovascular morbidity and mortality. Inclusion of such indices is necessary to test more comprehensively Lane and Schwartz's model (Lane and Schwartz, 1987).

Fifth, it is important to note that identification of significant relations between cerebral and cardiovascular measures during emotional activation may require more careful examination among men and women separately. There are documented gender differences in emotional expression (Brody and Hall, 1993) and in patterns of cardiovascular reactivity (Stoney et al., 1987). In addition, cerebral representation of emotions has been suggested to differ between men and women (McGlone, 1980; Borod et al., 1986). Interactive effects of gender were indeed noted here with respect to self-reported emotion and frontal asymmetry findings, although these results must be viewed very cautiously due to limited statistical power.

Finally, it is critical to study a broader spectrum of individuals. Relevant to the Lane and Schwartz model (Lane and Schwartz, 1987), it may be particularly interesting to examine individuals who are vulnerable to myocardial instability such as persons with a family history of long QT syndrome or cardiac patients with implantable defibrillators.

6. Conclusion

The present data indicate that cerebral response patterns to emotionally challenging situations may play a role in the magnitude (and patterning) of cardiovascular reactivity. Future research should determine whether such central-autonomic linkages during emotional activation could play a role in eliciting myocardial instability or cardiac arrhythmias in vulnerable populations.

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