Journal of Affective Disorders 320 (2023) 725–734

Contents lists available at ScienceDirect

Journal of Affective Disorders

journal homepage: www.elsevier.com/locate/jad

Research paper

Resting respiratory sinus arrhythmia is related to emotion reactivity to social-evaluative stress

Danny Rahal[a,*], Julienne E. Bower[b,c,d], Michael R. Irwin[c,d], Andrew J. Fuligni[b,c,d], Jessica J. Chiang[e]

[a] Pennsylvania State University, Edna Bennett Pierce Prevention Research Center, State College, PA 16802, USA
[b] University of California, Los Angeles, Department of Psychology, Los Angeles, CA 90095, USA
[c] University of California, Los Angeles, Department of Psychiatry and Biobehavioral Sciences, Los Angeles, CA 90095, USA
[d] University of California, Los Angeles, Norman Cousins Center for Psychoneuroimmunology, Los Angeles, CA 90095, USA
[e] Georgetown University, Department of Psychology, Washington, DC 20005, USA

ARTICLE INFO

Keywords:
Emotional reactivity
Affective response
Late adolescent
Parasympathetic nervous system
Respiratory sinus arrhythmia
Young adult

ABSTRACT

Background: Higher resting parasympathetic nervous system activity, as indexed by respiratory sinus arrhythmia (RSA), has been considered a marker of emotion regulatory capacity and is consistently related to better mental health. However, it remains unclear how resting RSA relates to emotion reactivity to acute social-evaluative stress, a potent predictor of depression and other negative outcomes.
Method: A sample of 89 participants (M_{age} = 18.36, SD = 0.51; 58.43 % female) provided measures of RSA at rest and then completed the Trier Social Stress Test, a standardized laboratory-based social-evaluative stress task that involves public speaking and mental arithmetic while being evaluated by two confederate judges. Participants reported a variety of emotions (e.g., negative emotion, positive emotion) at baseline and immediately after the stress task.
Results: Participants with higher resting RSA showed greater increases in negative emotion, guilt, depressive emotion, and anger, as well as greater decreases in positive emotion after the task.
Limitation: Data were limited to a relatively small sample of late adolescents, who may be particularly responsive to social-evaluative stress compared to adults.
Conclusions: Findings suggest that higher resting RSA may enhance emotion responses to social-evaluative stress in adolescents, potentially due to active engagement and responding to rather than passively viewing stimuli. Higher resting RSA may promote flexible emotion responses to the social environment, which may account for associations between higher RSA and better mental health.

1. Introduction

Greater emotion reactivity—or responding to negative stimuli (e.g., negative social interactions) with more intense fluctuations in emotion (i.e., increases in negative emotion or decreases in positive emotion; Herres et al., 2016; Mroczek et al., 2015)—has been consistently related to poorer health outcomes, including depression and mortality (e.g., Chiang et al., 2018; Ha et al., 2019; Herres et al., 2016; Mroczek et al., 2015; O'Neill et al., 2004; Parrish et al., 2011). One physiological system that has been posited to support expressive and receptive emotion processing is the parasympathetic nervous system (PNS), one of two branches of the autonomic nervous system. PNS activity is hypothesized to promote the mobilization of bodily resources to support one's ability to respond to the social environment, including social threats (Porges, 2007; Thayer and Lane, 2009). Resting PNS activity has been shown to stabilize from childhood to adolescence (Dollar et al., 2020; Hinnant et al., 2018) and may be an individual difference with implications for everyday psychosocial and physical functioning (Graziano and Derefinko, 2013; Rahal et al., 2021; Tan et al., 2019). It may also relate to emotion reactivity, although studies have found that resting PNS

Abbreviations: RSA, Respiratory Sinus Arrhythm; TSST, Trier Social Stress Test.

* Corresponding author at: Edna Bennett Pierce Prevention Research Center, Pennsylvania State University, 314 Biobehavioral Health Building, University Park, PA 16802, USA.
E-mail address: rahal@psu.edu (D. Rahal).

https://doi.org/10.1016/j.jad.2022.09.100
Received 15 February 2022; Received in revised form 20 August 2022; Accepted 20 September 2022
Available online 23 September 2022

activity is associated with both reduced and exaggerated emotion reactivity to different forms of stimuli across studies (Balzarotti et al., 2017). To help clarify the link between PNS activity and emotion reactivity, the present study assessed whether resting PNS activity relates to attenuated or greater reactivity of both negative and positive emotions to acute social-evaluative threat, a pervasive and impactful stressor in daily life (e.g., Henze et al., 2017).

1.1. Regulation hypothesis

Higher resting PNS activity—often quantified in the form of high-frequency heart rate variability as respiratory sinus arrhythmia (RSA)—has been related to greater activation of cortical regions, particularly the prefrontal cortex (e.g., Thayer et al., 2012). As such, the neurovisceral integration model (Thayer and Lane, 2009) posits that higher resting PNS activity indicates greater inhibitory control of subcortical regions from the prefrontal cortex, which can promote cognitive and affective processes including emotion regulation and emotion reactivity. Emotion regulation generally refers to the processes that individuals use to influence the intensity and duration of emotion, and common emotion regulatory processes include cognitive reappraisal (i.e., when an individual reframes a given situation to be less negative or more positive) and expressive suppression of emotions (i.e., when an individual inhibits rather than expresses their emotion; e.g., Gross, 1998; Reeck et al., 2016).

In line with the neurovisceral integration model, studies have demonstrated that higher resting PNS activity among young adults is related to self-reported use of emotion regulation strategies including engagement-oriented coping strategies in daily life (Aldao et al., 2016; Fabes and Eisenberg, 1997; Geisler et al., 2010, 2013; Volokhov and Demaree, 2010). Additionally, young adults with higher resting RSA have been shown to more frequently engage in cognitive reappraisal and in expressive suppression, albeit to a lesser extent, both in daily life and in response to an unpleasant film clip compared to their counterparts with lower resting RSA (Geisler et al., 2010; Volokhov and Demaree, 2010). Because emotion regulation processes can effectively down-regulate emotion responses to stress, higher resting RSA has been posited to relate to lower emotion reactivity to stress according to the regulation hypothesis. Consistent with the regulation hypothesis, prior research has found that adults with higher resting RSA show attenuated emotion reactivity to daily stressors and emotionally-evocative film clips (da Estrela et al., 2021; Demaree et al., 2004, 2006; Fabes and Eisenberg, 1997), although associations have not been tested with emotion reactivity to acute social-evaluative stress.

1.2. Flexibility hypothesis

Despite support for the regulation hypothesis, other evidence suggests that resting RSA can be related to greater emotion reactivity in certain circumstances, which has resulted in a competing hypothesis: the flexibility hypothesis. Specifically, studies have found that adults with higher resting RSA show higher emotion reactivity to positive daily events, such as social activities (Isgett et al., 2017; Kok and Fredrickson, 2010), and more negative emotional displays when talking about a distressing film and when completing image-viewing tasks (Butler et al., 2006; Kettunen et al., 2000). According to the flexibility hypothesis, this seemingly contradictory pattern of findings may emerge because higher resting RSA indicates greater chronotropic control of heart rate. Individuals with higher resting RSA can physiologically experience vagal withdrawal or augmentation depending on the stimulus (e.g., in response to stress versus relaxing stimuli), and this physiological flexibility may underlie emotional flexibility (Appelhans and Luecken, 2006). Higher resting RSA may consequently promote attenuated stress responses in certain circumstances and promote emotional flexibility in the form of more intense changes in negative and positive emotion (e.g., larger increases in negative emotion and decreases in positive emotion) in response to other stressful stimuli.

In line with the neurovisceral integration model, individuals with higher resting PNS activity receive relatively greater feedback from cortical regions. They can therefore respond flexibly to situational demands and selectively engage in emotion regulation strategies to either show reduced or enhanced emotion reactivity depending on the stimulus, as opposed to showing a pattern of inflexible reactivity across all stimuli (e.g., Park et al., 2012). For example, RSA may promote flexible responses in the form of exaggerated emotion reactivity when responding to social stimuli because higher RSA enables recruitment of attentional resources to facilitate communication and engagement with other people (Park et al., 2012, 2013; Porges, 2007). Exaggerated emotion reactivity corresponding to higher resting RSA, then, may reflect greater social engagement, allowing individuals to adaptively respond to their environment (Smith et al., 2020). During adolescence, for instance, youth are especially attuned to their social status (Forbes and Dahl, 2012), and they may be more inclined than adults to experience intense responses to certain negative social stimuli (e.g., social evaluation). In contrast, individuals with lower resting RSA may have lower reception of information from the environment and therefore show more inflexible cognitive processes (e.g., rumination, perseverative cognitions) and blunted emotion responses (Ottaviani et al., 2016).

Taken together, prior research suggests that higher resting RSA is associated with attenuated emotion reactivity under certain circumstances, potentially due to emotion regulation, and greater emotion reactivity under other circumstances, potentially reflecting enhanced flexibility, and aspects of emotional valence and the stimulus eliciting changes in emotion may contribute to the different direction of these associations. Many previous studies have tested associations between RSA and emotion reactivity to daily experiences, which are ecologically valid but non-standardized across individuals, and to emotion-inducing clips, which involve passive observation from the participant and often elicit a specific negative emotion such as sadness, anger, or disgust (e.g., Aldao et al., 2016; Demaree et al., 2004, 2006; León et al., 2009). Studies using emotion-inducing clips are well-positioned to examine discrete forms of negative emotional responses, which can have unique functional purposes and implications for health (Keltner & Gross, 1999). However, they do not elucidate whether resting RSA may also underlie and facilitate emotion reactivity to social stress, a ubiquitous experience in everyday life that can negatively impact health (e.g., Brooks and Robles, 2009; Dockray et al., 2009; Fagundes et al., 2013; Rao et al., 2008; Segal et al., 2006). It may be that RSA is particularly relevant to emotion reactivity to social stress, as prior work has suggested that low resting RSA may be a marker of greater sensitivity to social stress; for example, youth with lower RSA have more negative mental health outcomes when experiencing harsh parenting (Hinnant et al., 2015). Additionally, like other daily experiences, social stress can simultaneously increase various negative emotions and decrease various positive emotions as opposed to changing a single discrete emotion. Negative and positive emotion are considered distinct facets of emotion that promote unique action tendencies (e.g., broaden-and-build for positive emotion; Fredrickson, 2001), and studies among adults have been mixed regarding whether associations between resting RSA and reactivity are consistent for both positive and negative emotion (e.g., Butler et al., 2006; Kettunen et al., 2000), and whether RSA is related to positive but not negative emotion reactivity (Fujimura and Okanoya, 2012; Koval et al., 2013) or to negative but not positive emotion reactivity (Demaree et al., 2004, 2006). To help reconcile the mixed evidence regarding the direction of association between resting RSA and emotion reactivity, it is critical to identify how resting RSA may relate to both negative and positive emotion reactivity, in addition to discrete forms of emotion reactivity, to social stress.

1.3. Present study

The present study aimed to test whether resting RSA relates to emotion reactivity to social-evaluative stress. Associations between resting RSA and emotion reactivity (i.e., change in self-reported emotion between before and immediately after the task) and participants' self-reported general use of emotion regulation were tested among a sample of late adolescents. Examining these associations during adolescence may be especially fruitful given that adolescents tend to be particularly sensitive to social status concerns (Forbes and Dahl, 2012), and emotion reactivity peaks during adolescence (Bailen et al., 2019). Given mixed evidence regarding the direction of associations between RSA and emotion reactivity, we did not have a priori hypotheses regarding whether higher resting RSA would relate to attenuated emotion reactivity (in line with the regulation hypothesis) or greater emotion reactivity (in line with the flexibility hypothesis).

In light of prior work on resting RSA and emotion regulation, additional analyses examined associations between RSA and self-reported use of two emotion regulation strategies in everyday life: cognitive reappraisal, an approach-oriented strategy focused on modifying cognitions about the stressor, and expressive suppression, an avoidant strategy focused on hiding or inhibiting emotion. We then tested whether associations between RSA and emotion reactivity were maintained after controlling for these emotion regulation strategies in order to determine whether self-reported use of emotion regulation strategies in daily life may explain how RSA relates to emotion reactivity.

2. Method

2.1. Participants

A subsample of 91 participants (M_{age} = 18.36, *SD* = 0.51; 58.43 % female) completed the TSST as part of a larger three-wave longitudinal study regarding health across the transition to adulthood. The larger study recruited 316 adolescents from the 10th and 11th grades to complete the first wave of the study (M_{age} = 16.40, *SD* = 0.74). Participants were contacted by phone after the second wave of data collection, either when they were completing the 12th grade or one year after graduating high school. Participants from the larger study were eligible to complete this experimental task if they were 18 or older and identified as either Latino or European American. Information about the experimental study was provided to eligible participants, after which they were invited to participate. Participants in the present study did not differ from participants who completed the second wave of the larger study with respect to age, gender, or parents' education ($ps > .10$). Due to technical error, two participants were missing data on RSA, leaving 89 participants in the analytic sample.

Participants were late adolescents from Latino (62.92 %) and European American backgrounds (37.08 %). Parents reported annual family income and parents' education, and participants were socioeconomically diverse (*M* = $91,253, *SD* = $92,417, range = $12,000–$770,000; 45.45 % of parents averaged vocational school or lower levels of education across both parents). They also reported the number of family members living in the household, and this information was used to identify the poverty line for that family size so that family income-to-needs ratio could be calculated (*M* = 3.50, *SD* = 2.67, range = 0.55–15.38). Annual income was divided by the poverty line for that family size, with family income-to-needs ratios below 1 indicating being below the poverty line ($n = 9$). Measures of positive emotion were included partway through data collection and administered to 76 participants. These participants did not differ from the other participants with respect to gender or ethnicity based on chi-squared analyses, ps = .717 and .258 respectively, or resting RSA, negative emotion reactivity, parents' education, family income-to-needs ratio, or age based on *t*-tests, ps = .277–832. Prior manuscripts have examined the roles of adiposity, depressive symptoms, psychological resources, and subjective social status in stress reactivity using data from this sample (Chiang et al., 2017, 2019a, 2019b; Rahal et al., 2020).

2.2. Procedures

Study procedures were approved by the University of California, Los Angeles Institutional Review Board. Participants provided demographic information as part of a psychosocial survey from the larger longitudinal study, and parents reported family income, number of family members in the household, and each parent's highest level of education. As part of a separate laboratory visit, participants completed the Trier Social Stress Test (TSST), a well-validated social evaluative stress paradigm (Kirschbaum et al., 1993) that allows for examining a range of emotions including overall negative emotion reactivity, discrete negative emotion reactivity (e.g., sadness, anger), and overall positive emotion reactivity, as opposed to eliciting a single discrete emotion in line with emotion-induction tasks (Campbell and Ehlert, 2012). Notably, the TSST can elicit emotion reactivity comparable to that for real-life stressors and can be systematically tested in the laboratory with a standardized, validated protocol (Henze et al., 2017; Kirschbaum et al., 1993).

Visits were conducted between 12 pm and 6 pm. Participants completed written consent and then had electrodes attached to each wrist and below the collarbone in line with an alternative lead II configuration for assessment of RSA. Participants then watched a neutral-content nature video for 20 min so that participants could acclimate to the environment and provide a valid baseline. Heart rate was measured continuously during the last 10 min of this baseline period using electrocardiogram. After the 20 min period, participants reported their current levels of emotion. As part of the TSST (Kirschbaum et al., 1993), participants were then told that they would need to prepare and present a speech to an evaluative panel regarding why they are qualified candidates for a job. They had 5 min to prepare the speech and presented for 5 min to two confederates in white lab coats who were trained to provide nonverbal negative feedback. Immediately afterward, they completed a mental arithmetic task for 5 min in which they subtracted 2935 by 13 repeatedly as quickly as possible. Confederates asked them to restart from the beginning each time they made an error and instructed them to go more quickly after any pauses and after three consecutive correct answers. After completing the mental arithmetic task, participants again completed reports of their current emotion. Participants stayed in the lab for an additional 60 min, during which they completed psychosocial surveys, including reports of general emotion regulation, and resumed watching the nature video. The experimenter then removed the electrodes and debriefed the participant. Participants received $150 as compensation.

2.3. Measures

2.3.1. RSA

High-frequency heart rate variability was used to measure RSA (Porges, 2007). The sampling rate of the ECG data collection was 500 Hz, and the frequency band parameters that were used to compute RSA is 0.12–0.40 Hz. ECG data were converted to inter-beat-intervals, and artifacts were edited by two research assistants certified CardioEdit Reliable (CardioEdit software, 2007). Editing was minimal and consistent across research assistants; six randomly selected files were edited by both research assistants and all differences in RSA values between research assistants were under 0.02. RSA was estimated from the software CardioBatch using the Porges–Bohrer Method over 30-second epochs, natural log-transformed to produce normal distributions, and then averaged across epochs (Porges, 1985; Porges and Bohrer, 1990; Riniolo and Porges, 2000). Values were recorded for the last 10 min of baseline. RSA values from the first 5 min were strongly correlated with those from the last 5 min, $r(87) = 0.94$, $p < .001$. Therefore, RSA across the entire 10 min baseline period was used to estimate resting RSA.

2.3.2. Emotion reactivity

Participants reported emotion experienced “at that moment” at baseline and immediately after the TSST using selected items from the

Profile of Mood States (POMS; McNair et al., 1981), the Positive and Negative Affect Schedule-X (Watson and Clark, 1999), and prior studies of daily emotion (e.g., Telzer and Fuligni, 2009). Participants completed eight items of the PANAS-X negative emotion subscale (e.g., afraid, nervous, upset). Items were supplemented with the fear and guilt subscales of the PANAS-X, which each included five items (e.g., scared, shaky for fear; guilty, ashamed, dissatisfied with self for guilt), as well as three subscales of the POMS: the depression subscale, which included seven items (e.g., miserable, unhappy, worthless), the tension/anxiety subscale, which included five items (e.g., anxious, uneasy), and the anger subscale, which included five items (e.g., bitter, furious, angry). Items from the negative emotion PANAS scale overlapped with items from the other PANAS emotion subscales, but not items from the POMS subscales. Due to the time restrictions imposed as part of the task protocol, items were omitted from the administered emotion scales based on face validity, with priority for retaining items that were administered as part of the daily protocol of the larger parent study.

Finally, they completed five items regarding positive emotion (e.g., enthusiastic, happy) taken from daily checklist measures (e.g., Telzer and Fuligni, 2009). Participants rated how they felt at that moment using these items on a 5-point scale (1 = Not at all, 2 = A little, 3 = Moderately, 4 = Quite a lot, 5 = Extremely). These items were designed to be administered quickly for multiple assessments, and items overlapped with those from other scales of positive emotion. All scales were administered both at baseline and immediately following completion of the TSST. In primary analyses, reactivity was quantified as a change score (i.e., Emotion Post-TSST – Emotion at Baseline). In sensitivity analyses, reactivity was assessed by predicting emotion post-TSST as an outcome while simultaneously covarying for emotion at baseline. Alpha inter-item reliabilities were consistently high across items for each subscale (αs = [0.71–0.88] for PANAS-X subscales; [0.79–0.88] for POMS subscales; [0.85–0.88] for positive emotion subscale).

2.3.3. Self-reported emotion regulation

After completing the TSST, participants completed the Emotion Regulation Questionnaire (Gross and John, 2003). Participants rated 10 items regarding their emotional experience and how they generally control their emotions on a 7-point scale (1 = Not at all, 7 = A lot). There were two subscales: four items regarding expressive suppression (e.g., "I keep my emotions to myself"; α = 0.66) and six items regarding cognitive reappraisal (e.g., "I control my emotions by changing the way I think about the situation I'm in"; α = 0.88). An average was calculated for each subscale, with higher values indicating more frequent use of that strategy.

3. Results

Descriptive statistics and pairwise correlations between study variables are presented in Table 1. Prior to the task, participants reported low levels of negative emotion ($M = 1.21$, $SD = 0.29$, range 1–2.38) and moderate levels of positive emotion ($M = 2.79$, $SD = 0.87$, range 1–4.6). The task elicited emotion reactivity from participants, as there was a significant increase in all forms of negative emotion and a significant

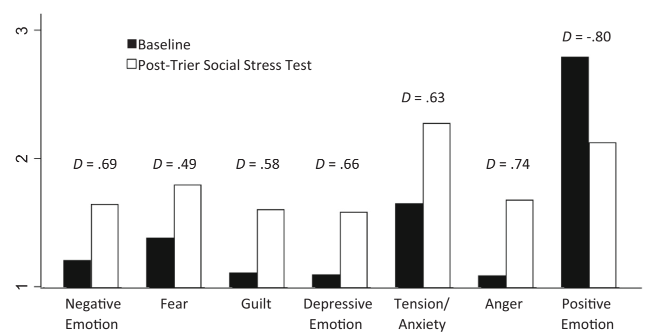

Fig. 1. Changes in each emotion rating between before and after the Trier Social Stress Test. *Note*: All changes were significant, $ps < .0001$. Effect sizes for Cohen's D for paired samples t-tests are reported above the pair of bars for each emotion. All items were rated on 5-point Likert scales (1 = not at all, 2 = a little, 3 = moderately, 4 = quite a lot, 5 = extremely), represented on the y-axis.

Table 1
Descriptive statistics and correlations between study variables.

	M	*SD*	*Min*	*Max*	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Resting RSA	7.15	0.98	3.95	10.15	–										
2. Negative emotion reactivity	0.40	0.55	−0.88	2.25	0.28**	–									
3. Fear reactivity	0.38	0.81	−1.80	3.20	0.15	0.75***	–								
4. Guilt reactivity	0.46	0.78	−0.80	3.40	0.26*	0.73***	0.38***	–							
5. Depressive reactivity	0.47	0.73	−0.29	3.86	0.29**	0.70***	0.43***	0.77***	–						
6. Tension/anxiety reactivity	0.60	0.98	−1.80	2.80	0.06	0.66***	0.76***	0.35***	0.37***	–					
7. Anger reactivity	0.57	0.77	−0.60	4.00	0.37***	0.53***	0.25*	0.37***	0.55***	0.19	–				
8. Positive emotion reactivity	−0.68	0.84	−2.60	1.60	−0.26*	−0.37***	−0.21	−0.27*	−0.34**	−0.21	−0.30**	–			
9. Age	18.36	0.51	18.00	20.00	−0.16	−0.07	−0.08	−0.24*	−0.26*	0.02	0.04	−0.01	–		
10. Income-to-needs ratio	3.50	2.67	0.55	15.38	0.12	0.13	0.02	0.14	0.17	0.10	0.15	−0.06	0.07	–	
11. Parents' education	7.47	1.92	2.00	10.50	0.01	0.04	−0.13	0.17	0.12	−0.18	0.01	0.09	−0.26*	0.47***	–

Note: Parents' education was evaluated on the following scale: 1 = some elementary school; 2 = completed elementary school; 3 = some junior high school; 4 = completed junior high school; 5 = some high school; 6 = graduated from high school; 7 = trade or vocational school; 8 = some college; 9 = graduated from college; 10 = some medical, law, or graduate school; 11 = graduated from medical, law, or graduate school.

* $p < .05$.
** $p < .01$.
*** $p < .001$.

decrease in positive emotion between before and after TSST, all *ts* = 4.69–7.13 and *ps* < .0001 (Fig. 1).

Pairwise correlations indicated that higher baseline RSA was associated with greater increases in negative emotion, guilt, depressive emotion, anger, and a greater decline in positive emotion; participants with higher resting RSA showed greater changes in all emotions except for fear and tension/anxiety (Table 1). With respect to baseline emotion, higher resting RSA was related to higher positive emotion at baseline, *r* (74) = 0.33, *p* = .003 (Fig. S1), and not to any negative emotion at baseline, *ps* > .36. Age, family income-to-needs ratio, and parents' education were not related to any form of reactivity, all *ps* > .05. When examining associations across forms of emotion reactivity, general negative emotion reactivity was modestly to strongly correlated with each discrete form of negative emotion reactivity and modestly related to positive emotion reactivity.

3.1. RSA and emotion reactivity

Next, linear regression models tested resting RSA as a predictor of each form of emotion reactivity, controlling for gender, ethnicity, age, family income-to-needs ratio, and parents' education. Gender was dummy-coded (0 = male, 1 = female), ethnicity was dummy-coded (0 = European American, 1 = Latino), and resting RSA, age, family income-to-needs ratio, and parents' education were mean-centered. As displayed in Fig. 2, when controlling for these factors, higher resting RSA continued to be associated with greater emotion reactivity.

More specifically, we first found that higher resting RSA was associated with significantly larger increases in overall negative emotion from baseline to immediately following the task, *p* = .008, 95 % CI [0.04, 0.26]. β = 0.29 (Table 2). When examining discrete forms of negative emotion, we found that higher resting RSA was related to larger

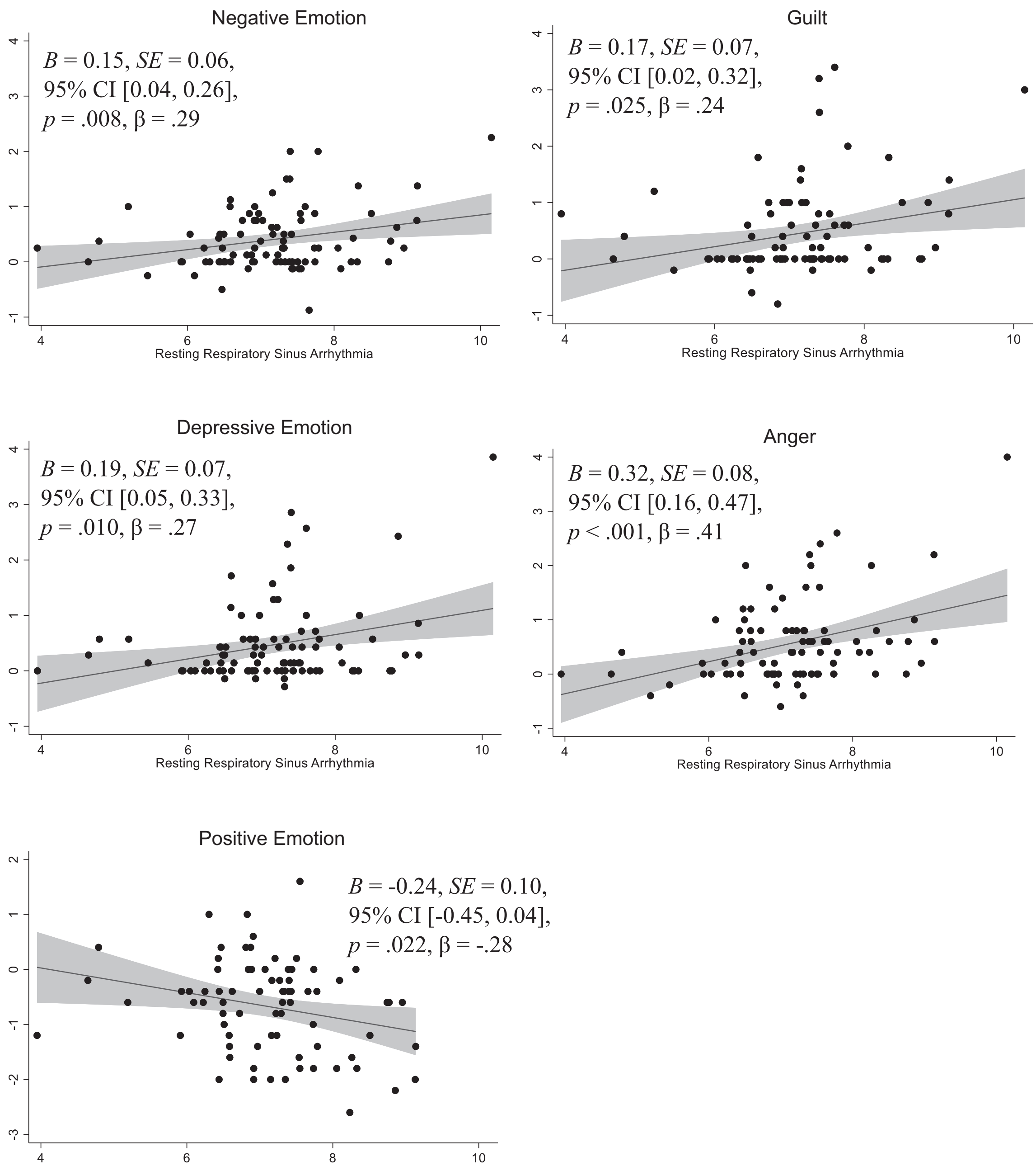

Fig. 2. Emotion reactivity as a function of resting respiratory sinus arrhythmia. *Note*: CI = confidence interval. Negative emotion values indicate that levels of emotion declined between baseline and immediately following the Trier Social Stress Test. Shaded regions represent the 95 % confidence interval.

Table 2
Emotion reactivity as a function of resting respiratory sinus arrhythmia.

	Negative emotion		Fear		Guilt		Depressive emotion		Tension/anxiety		Anger		Positive emotion	
	B	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*
Intercept	0.38***	0.06	0.32***	0.09	0.40***	0.08	0.42***	0.07	0.56***	0.11	0.56***	0.08	−0.69***	0.11
Resting RSA	0.15**	0.06	0.11	0.09	0.17*	0.07	0.19**	0.07	0.05	0.10	0.32***	0.08	−0.24*	0.10
Age	−0.02	0.11	−0.19	0.18	−0.26	0.15	−0.31*	0.14	−0.12	0.21	0.19	0.16	−0.03	0.20
Female	0.08	0.11	0.26	0.18	−0.03	0.15	0.13	0.14	0.26	0.21	0.20	0.16	−0.14	0.21
Latino	−0.13	0.13	0.17	0.20	0.02	0.17	−0.03	0.16	−0.07	0.24	−0.20	0.18	0.08	0.24
Parents' education	−0.02	0.03	−0.07	0.05	0.01	0.04	−0.01	0.04	−0.17**	0.06	0.01	0.05	0.05	0.06
Income-to-needs	0.02	0.02	0.04	0.04	0.03	0.03	0.04	0.03	0.10*	0.04	−0.01	0.03	−0.02	0.04

Note: RSA = respiratory sinus arrhythmia. Resting respiratory sinus arrhythmia, age, parents' education, and income-to-needs ratio were mean-centered. Female and Latino were dummy-coded (0 = male, 1 = female; 0 = European American, 1 = Latino).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

increases in guilt ($p = .025$, 95 % CI [0.02, 0.32]. β = 0.24) depressive emotion ($p = .010$, 95 % CI [0.05, 0.33]. β = 0.27), and anger ($p < .001$, 95 % CI [0.16, 0.47]. β = 0.41) compared to participants with lower resting RSA, *ps* < .025. No associations emerged between resting RSA and changes in fear or tension/anxiety, *ps* > .20, βs < 0.14.

Lastly, we examined associations between RSA and positive emotion. Results indicated that greater resting RSA was associated with larger declines in positive emotion from baseline to immediately following the task, $p = .009$, 95 % CI [−0.45, −0.04]. β = −0.28.

3.2. RSA, emotion reactivity, and emotion regulation processes

To determine the role of emotion regulation strategies in the associations between resting RSA and emotion reactivity, we also examined whether resting RSA was related to self-reported emotion regulation and whether associations between resting RSA and emotion reactivity were maintained over and above self-reported emotion regulation. First, resting RSA was not correlated with cognitive reappraisal, $r(87) = -0.16$, $p = .14$, or expressive suppression, $r(87) = -0.01$, $p = .92$. Correlations suggested that higher cognitive reappraisal was related only to lower fear reactivity, $r(87) = -0.35$, $p < .001$, and depressive emotion reactivity, $r(87) = -0.26$, $p = .014$, and that expressive suppression was not correlated with any form of emotion reactivity, all *ps* > .06.

In regression models predicting reactivity from resting RSA, cognitive reappraisal, expressive suppression, and all covariates simultaneously, all significant associations between resting RSA and emotion reactivity were maintained (Table 3). Full results for associations between cognitive reappraisal and expressive suppression and each form of emotion reactivity are presented in Table 3.

3.3. Sensitivity analyses

As a robustness check, analyses were repeated using residualized change models, predicting emotion post-TSST from resting RSA while simultaneously controlling for baseline levels of that emotion. All previously described associations between resting RSA, cognitive reappraisal, and expressive suppression and emotion reactivity as calculated using change scores were maintained with one exception: the association between resting RSA and positive emotion reactivity was no longer significant in the residualized change model, $B = -0.16$, $SE = 0.11$, 95 % CI [−0.38, 0.05], $p = .134$, β = −0.16. Full results are presented in Table S1.

4. Discussion

Although lower resting RSA and difficulties with emotion regulation are consistently related to poorer mental health (e.g., Beauchaine, 2015), there has been mixed evidence in support of the regulation hypothesis and flexibility hypothesis with regard to how RSA is related to emotion reactivity. Specifically, higher resting RSA has been related to both lower emotion reactivity according to the regulation hypothesis, potentially through the use of emotion regulation, and greater emotion reactivity according to the flexibility hypothesis, potentially through greater attention to the emotional stimuli and flexibility of responses (Balzarotti et al., 2017). To better understand the link between RSA and emotion processes, the present study investigated how resting RSA relates to varied forms of emotion reactivity to a social-evaluative paradigm that elicits active responses to a stressor with high ecological validity (Henze et al., 2017; Kirschbaum et al., 1993). Overall, findings supported the flexibility hypothesis in the context of social-evaluative

Table 3
Emotion reactivity as a function of resting respiratory sinus arrhythmia, cognitive reappraisal, and expressive suppression.

	Negative emotion		Fear		Guilt		Depressive emotion		Tension/anxiety		Anger		Positive emotion	
	B	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*
Intercept	0.40***	0.06	0.35***	0.09	0.41***	0.08	0.43***	0.07	0.58***	0.11	0.57***	0.08	−0.70***	0.11
Resting RSA	0.14*	0.06	0.07	0.09	0.17*	0.07	0.17*	0.07	0.03	0.11	0.31***	0.08	−0.23*	0.10
Age	−0.03	0.11	−0.15	0.18	−0.29	0.15	−0.30*	0.14	−0.11	0.22	0.17	0.16	−0.04	0.21
Female	0.04	0.12	0.10	0.18	−0.01	0.16	0.06	0.15	0.16	0.22	0.16	0.17	−0.08	0.22
Latino	−0.18	0.13	0.08	0.20	−0.01	0.17	−0.07	0.16	−0.13	0.24	−0.24	0.18	0.11	0.24
Parents' education	−0.04	0.03	−0.10	0.05	−0.01	0.05	−0.03	0.04	−0.19**	0.07	−0.01	0.05	0.06	0.06
Income-to-needs	0.02	0.02	0.04	0.04	0.03	0.03	0.04	0.03	0.10*	0.04	−0.01	0.03	−0.02	0.04
Cognitive reappraisal	−0.01	0.01	−0.03**	0.01	0.00	0.01	−0.01	0.01	−0.02	0.01	−0.01	0.01	0.02	0.01
Expressive suppression	−0.03	0.02	−0.01	0.03	−0.05	0.03	−0.01	0.03	−0.01	0.04	−0.03	0.03	0.00	0.04

Note: RSA = respiratory sinus arrhythmia. Resting respiratory sinus arrhythmia, age, parents' education, income-to-needs ratio, cognitive reappraisal, and expressive suppression were mean-centered. Female and Latino were dummy-coded (0 = male, 1 = female; 0 = European American, 1 = Latino).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

stress; higher resting RSA was generally related to higher levels of emotion reactivity with respect to both greater increases in negative emotion (specifically guilt, depressive emotion, and anger) and reductions in positive emotion following the stressor suggesting that associations between resting RSA and emotion reactivity may be more closely related to aspects of the task rather than the valence of emotion. Furthermore, associations were maintained after controlling for self-reported use of cognitive reappraisal or expressive suppression. No associations emerged between resting RSA and self-reported use of emotion regulation strategies, suggesting that perceived general use of these emotion regulation strategies did not explain associations between resting RSA and emotion reactivity.

Results indicated that resting RSA was associated with greater acute increases in negative emotion and decreases in positive emotion in response to social-evaluative threat. Associations were observed for both negative and positive emotion reactivity, suggesting that resting RSA supports flexibility and responsiveness to social-evaluative threat. Consistent with this notion, previous research has shown that individuals with higher RSA may be more responsive to their social context; for instance, high-risk home environments have been found to particularly impact youth with higher RSA (Gordis et al., 2010; Miller et al., 2020; Tabachnick et al., 2020) and high-quality environments and parent relationships have been related to positive psychological outcomes in youth with higher RSA (Eisenberg et al., 2012; Van der Graaff et al., 2016). Specifically, higher resting RSA may support a greater capacity to mount psychophysiological resources to flexibly respond to and adaptively manage the task at hand when the stimulus or environment elicits active responses (Porges, 2007). If so, one would expect higher resting RSA to be associated with greater emotion reactivity to the TSST, a taxing, interpersonal stress task that threatens one's self-value, self-esteem, and status.

Since active engagement and attention would activate resources to manage the threat effectively, responding flexibly in the context of the TSST may manifest as greater acute changes in emotion following stress. By contrast, there is minimal direct threat to the safety and value of the individual in tasks involving more passive responding, such as viewing negative film clips. As such, conserving psychophysiological resources may be optimal, in which case flexibly responding would manifest as blunted reactivity. Findings in the present study may have differed from prior research suggesting that higher resting RSA is related to attenuated daily emotion reactivity (e.g., da Estrela et al., 2021) because the use of a standardized stressor allowed for measurement of emotion immediately before and after the task. In contrast, daily studies assess naturalistic stressors and often include a temporal lag in measurement of emotion from stressor onset. Assessing emotion immediately versus shortly following the stressor may yield different results because a shorter temporal lag may minimize engagement in emotion regulatory strategies. It is possible that individuals with higher resting RSA mount a larger emotion response immediately following the stressor, as observed in the present study, but with time are also better able to use specific strategies to downregulate their immediate responses such that they show an overall pattern of attenuated emotion reactivity. Research should continue to examine how RSA relates to emotion reactivity across task paradigms, incorporating non-social stimuli (e.g., film clips) and interpersonal stress, and time by employing burst sampling in order to identify the circumstances in which RSA relates to attenuated versus greater emotion reactivity.

Associations between resting RSA and greater negative emotion reactivity were driven by guilt, depressive emotion, and anger rather than fear and tension/anxiety. Specifically, results showed that higher RSA was related to greater depressive emotion reactivity but not anxious emotion reactivity, which converges with evidence that higher RSA is often related to lower depression but not anxiety (Yaroslavsky et al., 2013). We also found the largest effect size for the association between resting RSA and anger reactivity. Meta-analyses have indicated that anger is often associated with greater blood pressure (Suls et al., 1995). Given that PNS activity can influence blood pressure through activation of baroreceptors in the heart, it is possible that PNS activity relates to capacity for acute anger reactivity through its effects on blood pressure during state anger, whereas blood pressure generally relates to trait anger. Further, a prior study similarly found that greater anger but not fear reactivity was related to greater cortisol secretion (Moons et al., 2010). With these past findings, our results suggest that anger reactivity to social-evaluative threat may be uniquely tied to physiology.

Although negative and positive emotion are conceptually distinct and promote different action tendencies (Fredrickson, 2001), RSA was related to both greater increases in negative emotion and greater decreases in positive emotion following acute social-evaluative threat in the present study. Studies have suggested that people with higher PNS activity show greater increases in positive emotion, but not necessarily decreases in negative emotion, in response to daily positive activities (Fujimura and Okanoya, 2012; Isgett et al., 2017; Kok and Fredrickson, 2010; Koval et al., 2013); however, relatively few studies have assessed positive emotion reactivity to experimental stressors. The present study extends prior findings by showing that higher resting RSA may similarly relate to changes in positive emotion in response to both positive daily activities and more taxing negative events. Additionally, there have been discrepant findings regarding whether RSA is related to attenuated versus greater emotion reactivity in previous studies (e.g., da Estrela et al., 2021; Demaree et al., 2004, 2006; Fabes and Eisenberg, 1997), many of which have measured only negative emotion reactivity or used stimuli designed to elicit discrete negative emotions. Because resting RSA was similarly related to both greater negative and positive emotion reactivity in the present study, aspects of the task paradigm rather than the valence of the emotion measured may account for differences in associations between resting RSA and emotion reactivity across previous studies.

All associations between resting RSA and emotion reactivity were maintained when controlling for self-reported use of emotion regulation strategies, suggesting that self-reported cognitive reappraisal and expressive suppression did not explain associations between RSA and emotion reactivity in the present study. These findings are at odds with previous research showing that higher resting RSA is related to greater use of emotion regulation strategies including cognitive reappraisal and expressive suppression (Geisler et al., 2010; Volokhov and Demaree, 2010). It is possible that participants may not accurately appraise their use of emotion regulation strategies or may have used different strategies in the context of the TSST as opposed to daily stressors. For instance, higher resting RSA has been found to relate to use of engagement-oriented as opposed to avoidant coping (e.g., Aldao et al., 2016; Geisler et al., 2010, 2013) and psychological benefits from written disclosure (O'Connor et al., 2005; Sloan and Epstein, 2005). Future studies should include alternative measures of emotion regulation (e.g., using eye-tracking to determine attentional control, instructing participants to use specific strategies as part of an experimental paradigm) and administer survey measures of participants' use of varied emotion regulation strategies during the task as opposed to in daily life. Additionally, rather than assessing baseline RSA, studies can examine how other aspects of RSA, such as RSA post-task or changes in RSA from during the task to post-task, may relate to use of emotion regulation strategies as individuals who successfully use emotion regulation strategies during the task may better downregulate their physiology after the task, or higher levels of PNS activity post-task may enable individuals to better recruit cognitive resources to engage in emotion regulation. Although the stressor in the present study involved speaking, which can lead to misspecification of respiratory rates and thereby preclude valid assessment of RSA during the task (Shader et al., 2018), future studies can utilize other stress protocols that enable estimation of RSA (e.g., physical stressors, nonverbal social stressors) to determine whether greater vagal withdrawal during the task relates to greater emotion regulation.

Although these findings highlight the association between resting

RSA and emotion reactivity, further research is needed to understand the relevance of this association for affective disorders and other downstream outcomes. Clinical populations often show elevated emotion reactivity (Bylsma et al., 2008), and thus elevated emotion reactivity is commonly viewed as maladaptive. However, a blunted or lack of a response to acute stress can also be indicative of task disengagement, which is also related to negative health outcomes including substance use among adolescents (Carroll et al., 2017; Rahal et al., 2022). For instance, given greater concern with social relationships and changes in emotional processes during adolescence, more intense emotional responses may be coherent to contexts of social stress because such displays may help youth communicate when they are uncomfortable or distressed to peers, and may show peers that they care about their relationship. In the context of the TSST, higher emotional distress may convey that they are actively trying to perform well despite the challenge imposed, whereas individuals who are less distressed by the task may signal that they are less concerned with the confederates' evaluation of them. There is also evidence that higher RSA is related to better mental and physical health outcomes during adolescence (Graziano and Derefinko, 2013; Rahal et al., 2021; Tan et al., 2019). Further investigation of how higher resting RSA coupled with heightened emotion reactivity relates to health outcomes may be useful in disentangling when emotion reactivity is a risk factor for affective disorders and other adverse outcomes.

4.1. Limitations

Findings should be interpreted in the context of study limitations. First, resting RSA was measured as participants watched a nature video and after participants had time to acclimate to the laboratory environment. Because RSA is highly sensitive to aspects of the environment, baseline RSA could be better assessed by including multiple assessments and incorporating measures in the home rather than the lab environment. Second, although the present study used a well-validated social-evaluative stress task (Kirschbaum et al., 1993), future studies should consider using multiple task paradigms including other ecologically valid social stressors (e.g., arguments) and non-social stressors (e.g., cold pressor task). Further, exhaustive scales were not administered due to concerns regarding the timing of the protocol, although the majority of items were included. Third, associations may have been stronger in the present study given our sample of adolescents. Adolescents may be particularly responsive to social-evaluative stress, as both concern with social status and emotion reactivity are heightened during adolescence relative to other periods of life (Bailen et al., 2019; Forbes and Dahl, 2012). This, in turn, may promote greater emotion reactivity to social stress. Thus, future studies should replicate findings among different age groups, as results may not generalize to older individuals, who show full maturation of neural regions involved in emotion regulation (Pozzi et al., 2021), and younger samples who are experiencing further development of the autonomic nervous system (Hinnant et al., 2018). Nonetheless, findings may have implications for adults in light of prior research suggesting that RSA may become a stable individual difference by adolescence (Dollar et al., 2020; Hinnant et al., 2018), and that lower RSA is associated with poorer mental health (e.g., depression) to a similar extent in adolescents, emerging adults, and older samples (Koenig et al., 2017; Rottenberg et al., 2007; Yaptangco et al., 2015). Fourth, the current sample size was relatively small, and future studies with larger sample sizes should replicate the findings in the current study as well as associations between resting RSA and emotion regulation strategy use that have been observed in other empirical studies (Geisler et al., 2010; Volokhov and Demaree, 2010).

5. Conclusion and implications

Taken together, late adolescents with higher resting RSA showed greater emotion reactivity to social-evaluative threat with respect to both increases in negative emotion, largely driven by guilt, depressive emotion, and anger reactivity, and decreases in positive emotion. These associations appeared to be unrelated to cognitive reappraisal and expressive suppression. The pattern of results suggested that resting RSA may promote more flexible responses to social-evaluative stress in line with the flexibility hypothesis, as participants with higher resting RSA may be more responsive when actively engaging with negative environmental stimuli and consequently show greater changes in emotion. As such, the present findings may have implications for understanding the physiological basis underlying emotional dynamics, particularly under stressful circumstances. Taken together with results from prior research utilizing other paradigms, findings also point to the notion that associations between resting RSA and emotion reactivity may differ by aspects of the task paradigm (e.g., social evaluative stress versus daily stressors). By using an intensive social-evaluative task, we examined emotion reactivity to an ecologically-valid social stressor and extended the extant literature. Future studies should continue to test the circumstances in which resting RSA relates to attenuated and exaggerated emotion reactivity.

Funding

This work was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development under Grant [R01-HD062547], UCLA California Center for Population Research funded by the National Institute of Child Health and Human Development under Grant [R24-HD041022], UCLA Older Americans Independence Center funded by the National Institute of Aging under Grant [P30-AG028748], UCLA Norman Cousins Center for Psychoneuroimmunology, University of California Institute for Mexico and the US, American Psychological Association, and Division 38 of the American Psychological Association. Danny Rahal was supported by the National Institute On Drug Abuse of the National Institutes of Health [F31-DA051181] and by the Prevention and Methodology Training Program [PAMT; T32 DA017629]. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. None of these funders were involved in the study design, in the collection, analysis and interpretation of data, in the writing of the report, and in the decision to submit the article for publication.

CRediT authorship contribution statement

Danny Rahal completed data analyses and wrote the manuscript. Julienne Bower and Michael Irwin secured grant funding for the study and contributed to the editing and writing of the manuscript. Andrew Fuligni secured grant funding for the study, designed the overall study, oversaw data collection, and contributed to the editing and writing of the manuscript. Jessica Chiang secured grant funding for the study, designed the study, led data collection, and wrote and edited the manuscript. All authors contributed to and have approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank the participants for their involvement in this study and the families who were involved in the parent study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jad.2022.09.100.

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