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An Examination of Cardiac Vagal Control Indices and Cognitive Stress Appraisal in Cigarette Smokers

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Abstract

Identifying factors that influence how individuals who smoke cigarettes respond to stress is important as stress is a risk factor for smoking and its maintenance. This study examined the modulatory role of cardiac vagal control (CVC), a physiological correlate of self-regulation, on cognitive stress appraisal processes of adults who smoke. Sixty daily cigarette smokers were randomized to receive positive or negative feedback during a modified Trier Social Stress Test. Pre- and post-task stress appraisals were assessed and resting and reactivity CVC measures were computed. Moderated regression models assessed if the relation between feedback condition and post-task stress appraisal varied as a function of CVC. We hypothesized that participants receiving negative feedback would report greater post-task stress appraisal compared to participants receiving positive feedback, and the strength of the effect of both feedback groups would be greater at higher levels of CVC. All models showed significant main effects of feedback condition ($b = -0.42$, $p = 0.01$; $b = -0.45$, $p = 0.01$) on post-task stress appraisal: participants receiving negative feedback reported greater post-task stress appraisal. No significant main or interactive effects of CVC and feedback condition on post-task stress appraisal were observed. This study demonstrates that stress appraisals of daily cigarette smokers are sensitive to social feedback, but are not moderated by individual differences in CVC. Future investigations are needed to clarify whether this finding is explained by smoking-specific impairments in CVC as well as the distinct and interactive effects of physiological and psychological processes implicated in stress and smoking risk.

Keywords Cigarettes · Autonomic regulation · Cognitive appraisal · Smoking · Stress

Introduction

The relationship between stress and cigarette use is well established. Stressful life events are associated with the onset and maintenance of smoking behavior in established smokers and are frequently cited as risk factors for smoking relapse and poor cessation outcomes (Cohen & Lichtenstein, 1990; McKee et al., 2003). Greater emotional reactivity to stress induction has also been associated with shorter duration of past quit attempts (Calhoun et al., 2007), and both general and acute levels of psychological distress have been prospectively linked to stress-induced smoking (Siegel et al., 2017). Moreover, acute stress reactivity, as indexed by self-report measures of emotional distress, predicts the number of cigarettes smoked early in a quit attempt and mediates the relationship between past month general distress levels and stress-induced smoking (Siegel et al., 2017). Despite great interest in the relation between stress and smoking, there remains a paucity of experimental work characterizing processes that may serve to alter the stress response in individuals who smoke. This is particularly important given stress does not unilaterally contribute to maladaptive outcomes, such as smoking.

How one appraises a stressor, i.e., an individual's perception of external demands of a stressor relative to their available coping resources, (Lazarus & Folkman, 1984) is central to emotion regulation and coping (Wang & Saudino,

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2011). Indeed, stress appraisal is thought to have a greater influence on one's mental health than the stressor itself (Lazarus, 1966; Lazarus & Folkman, 1984). For example, a threat response may occur when one appraises the demands of the situation as greater than their resources to cope; in contrast, a challenge response may result when resources exceed demands (Blascovich & Mendes, 2000; Tomaka et al., 1997). In the context of smoking, a threat appraisal may be associated with greater negative emotional reactivity and avoidant coping (Garey et al., 2016). For example, perceived ability to handle emotional distress (without smoking) assessed prior to a quit attempt was found to predict abstinence 12 months post quit (Nohlert et al., 2018). Experimental work has also found that the use of reappraisal, as compared to other emotion regulation strategies, is associated with greater ability to refrain from smoking, both acutely and over a 1-week period, as well as reduced craving, and greater avoidance of smoking (Beadman et al., 2015). Given the importance of processes such as appraisal on the stress response, recent attention has shifted to identifying physiological mechanisms that may promote or inhibit the stress response and subsequent regulatory control. However, this area remains relatively unexplored in smokers.

One candidate physiological process associated with adaptive stress responding consistent with environmental demands is cardiac vagal control (CVC). CVC can be measured via heart rate variability in the high frequency range (Berntson et al., 1997a, b; Malik et al., 1996; Pumprla et al., 2002; Shaffer & Ginsberg, 2017), and is thought to reflect the parasympathetic nervous system's (PNS) predominantly inhibitory influence on the electrical activity of the heart via the vagus nerve (Beauchaine, 2001; Porges, 1995a). Porges' Polyvagal theory (1995a, b, 2007) posits that in humans CVC serves as a context sensitive system that assists in emotional processing and regulatory control, and is a critical index of heart–brain communication. Empirical work supporting this perspective has shown greater CVC reactivity (i.e., vagal withdrawal), and to a lesser extent, greater CVC at rest (i.e., vagal tone), affect emotional processing. For example, irrespective of valence, greater CVC reactivity has been observed in response to emotionally salient versus neutral stimuli (Frazier et al., 2004). Related, Muhtadie et al. (2015) found that greater CVC reactivity was associated with heightened social sensitivity to both positive and negative feedback during a mock job interview (Muhtadie et al., 2015). Further, Human and Mendes (2018) found a significant association between greater CVC reactivity and more accurate perceptions of others' personality traits (Human & Mendes, 2018). Significant associations between greater CVC at rest and affectively significant experiences regardless of valence have also been observed (Kettunen et al., 2000). Together, these findings suggest CVC may serve to regulate the *general* exertion of metabolic efforts that enable an individual to meaningfully attend to and engage with stimuli in their environment.

Examining the role of CVC in stress appraisal among individuals who smoke is particularly important given well established relations between cigarette use and heightened sympathetic nervous system activity, reduced PNS modulation, and overall reduced CVC (Dinas et al., 2013; Middlekauff et al., 2014). Smoking-induced reductions in CVC are concerning as they may impede regulatory efforts necessary to refrain from smoking during stress. For example, reduced CVC in response to laboratory stress has been associated with increased likelihood of smoking and greater smoking reward (Ashare et al., 2012). While this work is helpful in characterizing how smoking-related impairments in CVC may potentiate stress-precipitated smoking behavior, the extent to which variability in CVC affects stress appraisal in smokers has not been examined. Given observed impairments in CVC in smokers, its links to self-regulatory processes and stress precipitated smoking, we sought to investigate whether CVC plays a role in cognitive appraisal in daily smokers. This investigation may inform current thinking regarding how to alter cognitive and affective mechanisms that confer smoking. For example, given the importance of appropriately allocating attention to salient environmental cues when appraising a stressor as a threat or challenge, it is conceivable that smoking-induced deficits in autonomic function may blunt this sensitivity and in turn alter appraisal processes. However, no studies to date have examined how physiological processes, like CVC, modulate appraisal processes in adults who smoke.

To bridge this gap, the current study leveraged the modified Trier Social Stress Test (TSST; Birkett, 2011; Taylor et al., 2010), which randomizes participants to receive either positive or negative non-verbal feedback while giving a speech, to study the moderating role of CVC on stress appraisal in adults who smoke daily. We predicted there would be a significant main effect of social feedback condition on post-task stress appraisal; participants would report greater post-task stress appraisal scores in response to negative feedback, indicating they perceived the task demands as outweighing their individual coping resources. Conversely, we hypothesized that those receiving positive feedback would report lower post-task stress appraisal scores. Regarding the moderating role of CVC, we predicted that the effect of feedback condition on post-task stress appraisal would be stronger among those evidencing greater CVC (i.e., greater CVC would be associated with greater sensitivity to the manipulation of the feedback condition). Our expectation that CVC would positively modulate the effect of feedback condition on stress appraisal is consistent with the perspective that CVC reflects the general exertion of self-regulatory processes that occurs in response to salient environmental cues, irrespective of valence (Muhtadie et al., 2015; Porges,

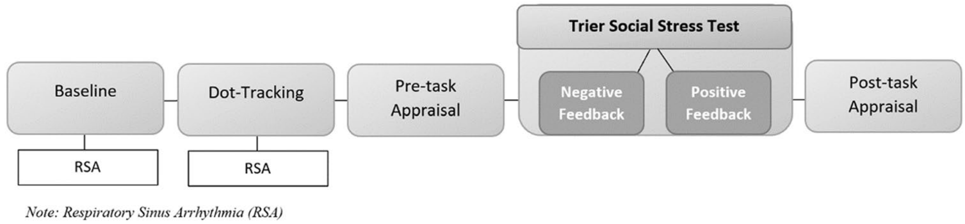

Fig. 1 Timeline of study procedures and measures

1995a, b). Findings will contribute to a limited literature examining these relations in adults who smoke and may inform how smoking-related impairments in autonomic function influence other regulatory processes implicated in stress and smoking behavior.

Methods

Participants

Participants were recruited from the local New Brunswick, New Jersey area via online and posted community advertisements (e.g. Craigslist, community bulletin boards, newspaper advertisements, etc.). Eligible participants were (1) 21–50 years old, (2) smoking at least ten cigarettes per day, (3) computer proficient, and (4) fluent in English. Exclusion criteria included (1) history or presence of bipolar spectrum or psychotic spectrum disorders, (2) current suicidal or homicidal ideation, (3) evidence of current (non-nicotine) substance use disorder, or (4) reported use of a pharmacological aid for smoking cessation and/or active attempts to reduce cigarette use in the past month. Individuals with visual, hearing, or cognitive impairments that would interfere with study participation or provision of informed consent were excluded, as were those with medical conditions or medications that might increase risk of stress exposure or confound autonomic nervous system reactivity.

Procedure

The data reported in this paper were collected as part of a larger study funded by the National Institute on Drug Abuse [R03 DA041556-01A1] examining psychological and physiological stress response profiles in adult cigarette smokers. Eligibility criteria was first assessed via a telephone screen before eligible participants were invited to complete a single in-person laboratory visit that lasted approximately 3–4 h. Upon arrival, participants were consented using procedures approved by the Rutgers University Institutional Review Board. Breath levels of carbon monoxide (CO) were obtained at the start of the visit to verify smoking status (CO > 8 ppm; Javors et al., 2005) before participants were asked to smoke a cigarette to standardize baseline craving and nicotine withdrawal. Physiological sensors were then attached before participants completed a series of computerized tasks and underwent a laboratory stress provocation paradigm. Although not discussed in this report, additional smoking and stress reactivity measures were collected as part of the parent study. At the end of the visit participants were debriefed and compensated $80. See Fig. 1 for a timeline of study procedures and measure administration.

Laboratory Stress Provocation: Trier Social Stress Test

The modified TSST is a standardized laboratory protocol for inducing moderate psychological distress in a controlled setting. The TSST involves participants giving an impromptu speech in front of confederate evaluators (Birkett, 2011; Taylor et al., 2010). The modification of this test for the current study included participants being unknowingly randomized to receive positive or negative non-verbal feedback during their speech.

Participants were told that during the next portion of the study they will have to give a 5-min speech explaining why they believe they are the best applicant for a job of their choosing in front of a panel of judges with expertise in speech evaluation and in reading non-verbal behavior. Following written informed consent, the experimenter introduced the two evaluators, one male and one female, with at least one matched for race/ethnicity, who provided the participants with their final instructions. Upon receipt of final instructions, the evaluators and experimenter left the room while the participants were provided with a brief 2-min preparation period. During this 2-min period, the experimenter notified the evaluators of their assigned feedback condition using a randomized sequence generator. Evaluators then re-entered the room, sat across from the participant, and instructed them to begin the 5-min speech task. Approximately 30 s into the speech, the evaluators began to gradually display the assigned positive or negative non-verbal feedback. Non-verbal positive feedback consisted of evaluators smiling, nodding, and showing interest and enthusiasm during the participant speech, whereas non-verbal negative feedback consisted of the evaluators frowning, shaking their heads, and looking uninterested in the participants speech (e.g., Akinola & Mendes, 2008; Muhtadie et al., 2015). At the end of 5 min the evaluators then engaged the participant in a 5-min question-and-answer (Q&A) session; during this time, evaluators continued to provide positive or negative feedback. The Q&A session was used rather than the standard math task because participants often close their eyes or look away from the evaluators during the math task (i.e., sensory rejection task), which can reduce the impact of the different evaluative feedback. Following the speech and Q&A portions, the evaluators left the room and participants were allotted a 5-min recovery period before being provided instructions for the next portion of the study.

Measures

Demographics and Smoking-Relevant Indices

A participant information form was used to collect demographic information including age, sex, and body mass index (BMI). A timeline followback (TLFB) procedure assessed the number of cigarettes smoked per day (CPD) over the past 28 days (Robinson et al., 2014), and the Fagerström Test for Cigarette Dependence (FTCD) assessed nicotine dependence. The FTCD is a 6-item measure that includes yes/no items (scored as 1 or 0) and multiple-choice items (scored from 0 to 3). Item scores are summed to give a total score from 1 to 10 with higher scores indicative of greater dependence (Fagerström, 2012; Heatherton et al., 1991). In the current investigation, internal consistency for the FTCD scale was $\alpha = 0.31$. The low value observed here is consistent with previous reports for this measure (Etter et al., 1999). Lastly, a Smoking History Questionnaire (SHQ) was administered to assess participant smoking history and patterns of use (i.e., age of onset of smoking initiation, years being a daily smoker, etc.) (Brown et al., 2002).

Cognitive Stress Appraisal

Cognitive stress appraisal was assessed both prior to and after the TSST by assessing how demanding participants perceived the task to be relative to their available coping resources. Using a 7-point scale (1 = "Strongly Disagree" to 7 = "Strongly Agree"), participants completed an 11-item measure consisting of five resource (e.g., pre-task: "I expect to perform well on this task"; post-task: "I performed well on this task") and six demand items (e.g., pre-task: "The upcoming task is very stressful"; post-task: "The task was stressful") (Mendes et al., 2007). Task appraisal scores were then used to compute a stress appraisal index defined as the ratio of demands over resources where smaller numbers were associated with "challenge" states (i.e., when resources outweigh demands) and higher numbers were associated with "threat" states (i.e., when demands outweigh resources) (Mendes et al., 2007). In the current sample, both the demand ($\alpha = 0.80$) and resource ($\alpha = 0.81$) items used to compute our post-task appraisal index yielded good internal consistency. A pre-task stress appraisal index was also computed to assess how demanding participants perceived the task to be in relation to their available coping resources directly after being introduced and preparing for the task, but prior to completing the TSST procedures and receiving social feedback. Pre-task demand ($\alpha = 0.83$) and resource ($\alpha = 0.84$) items also yielded good internal consistency.

Physiological Data Acquisition and Processing

Electrocardiograph (ECG) and impedance cardiography (ICG) recordings were sampled at a rate of 1000 Hz using Acknowledge Software and wireless MP150 Data Acquisition Systems (BIOPAC Systems, Inc.). ECG sensors were placed using a modified lead II configuration while two pairs of mylar tapes were placed around the participant's neck and torso for ICG. Physiological data were recorded in 5- and 2-min segments, for a total of 27 min.

Participants were first asked to complete a 5-min resting baseline. During this period, physiological activity was recorded while participants engaged in a low demand cognitive task used to standardize mental activity (Jennings et al., 1992). Specifically, participants were instructed to look at the computer as a series of different colored rectangles sequentially presented on the screen (lasting 10 s each). Participants were asked to silently track how many blue rectangles they saw over the course of the task. Following baseline, participants completed a 5-min (minutes 6–10) computerized dot-tracking task adapted from (Alvarez & Franconeri, 2007). Developed as a visual attention task, dot-tracking requires participants to focus on a cross in the middle of the computer screen as they keep track of moving dots in their peripheral vision. Participants are asked to keep track of certain dots that start off yellow, but as they move around the screen, they transition to black. At the end of each trial all dots stop moving and participants use the mouse to identify the initial yellow dots. Participants completed 16 trials of the task, with the number of moving dots on the screen increasing every 4 trials. Participants then completed the TSST; minutes 11–22 captured vagal activity during each phase of the TSST procedures (2-min prep, 5-min speech, 5-min Q&A period). The final recording (minutes 23–27) consisted of a 5-min recovery period.

Physiological data were scored offline in 1-min epochs using Mindware software version 3.1.12 (Mindware Technologies, Ltd.) and in accordance with standard guidelines (Task Force of the European Society of Cardiology; Malik et al., 1996). Z0 readings derived from ICG were used to estimate respiration. Interbeat interval (IBI) data was derived from ECG recordings using an R-peak identification algorithm with a low pass filter setting of 0.003 Hz and a high pass filter of 0.42 Hz. Data were linearly detrended and a baseline and muscle noise filter detected signals between 0.25 and 0.40 Hz. CVC data in the high frequency range was defined as the natural log of the variance occurring between 0.12 and 0.40 Hz, corresponding with respiratory sinus arrhythmia (RSA), a reliable index of parasympathetic control of cardiac function (Berntson et al., 1993). Trained research assistants visually inspected the data for additional cleaning, including removal of misplaced R-peaks and insertion of missing R-peaks, with no more than one R-peak estimated within a 1-min segment. We allowed for the removal of up to 10 s of poor-quality data at the beginning or end of a minute-long segment. Insertion of R-peaks was based on estimation from remaining data, RR interval distance from measured and cleaned ECG recording, or by dividing long R-peaks into equal intervals.

Indices of Cardiac Vagal Control

We examined resting and reactivity measures of vagal activity for the present report. CVC at rest was indexed as the average RSA value during the 5-min baseline period. CVC reactivity was indexed as the difference between the lowest RSA value during the dot-tracking task and the average RSA value during baseline. Computed difference values were multiplied by − 1 to facilitate interpretation of negative change scores (i.e., positive CVC reactivity scores reflected greater vagal withdrawal). This approach is consistent with established guidelines for computing CVC reactivity as task minus baseline (Berntson et al., 1997a, b). As a mentally demanding task, dot-tracking is an ideal manipulation for examining changes in CVC as a function of cognitive effort and attentional demand, as it reliably induces vagal withdrawal, but does not include any social or emotional cues (Hagan et al., 2017; Human & Mendes, 2018).

Analytic Strategy

Sample descriptive characteristics were first examined including data distributions and identification of potential outliers. Potential outliers were revisited to ensure validity and z-tests were used to assess skew and kurtosis for non-normally distributed data to be considered for transformation. Specifically, a z-score was obtained for each predictor and criterion variable of interest by dividing the skew and excess kurtosis values for each variable's distribution by their respective standard errors. For medium-sized samples ($50 < n < 300$) the null hypothesis, assuming a normal distribution, is rejected at absolute z-values over 3.29, corresponding with an alpha level of 0.05 (Kim, 2013). Calculated skew and kurtosis z-values revealed each pre- and post-task stress appraisal variables' data to be non-normally distributed ($zs > 3.29$). Two outliers at the high end of each variable's distribution were identified and transformed using a modified Winsorization approach (Reifman & Keyton, 2010). However, analyses using both Winsorized and non-Winsorized appraisal scores yielded similar results, therefore non-Winsorized variables were retained. All reported findings reflect raw values for pre- and post-task appraisal scores. Calculated skew and kurtosis z-values for all other variables showed no significant outliers and each variable's distribution was approximately normal (all $zs < 3.29$). Pearson's zero-order correlations were then conducted between theoretically relevant covariates (age, sex, respiration rate, and BMI which have been found to be empirically related to CVC), and predictor and criterion variables of interest. Significant correlations between candidate covariates and task appraisals observed at $r \geq .20$ were included as model covariates (Cohen, 1988, 1992). Based on this determination the final model covariates included age, pre-task stress appraisal, and CVC at rest. All models were run with and without covariates.[1]

To assess if the effect of social feedback condition (i.e., positive or negative feedback) on post-task stress appraisal varied as a function of CVC, three moderated regression analyses were computed using SPSS PROCESS v3 macro (Hayes, 2017). PROCESS produces 95-percentile bias-corrected intervals, estimated using a random resampling process with 1000 samples (i.e., bootstrapping), to determine statistical significance of main and interaction effects. This approach assists in minimizing sampling error and produces unstandardized parameter estimates (Hayes, 2017). Thus, the coefficients in the current report reflect unstandardized values (i.e., *b* weights).

For the first and second models, social feedback condition served as the predictor (*X*-variable), post-task stress appraisal as the outcome (*Y*-variable), and either CVC at rest or CVC reactivity served as the moderator (M-variable), respectively. This allowed us to assess the independent and conditional effects of the social feedback condition and each CVC index on post-task stress appraisal. In our third model, feedback condition served as the predictor, CVC reactivity as the moderator, post-task stress appraisal as the outcome, and CVC at rest as a model covariate. This allowed us to examine whether CVC reactivity would hold greater predictive utility above and beyond any pre-existing influence of

[1] Although the samples' average respiration rate for the baseline and dot-tracking recording periods were not significantly correlated with either CVC at rest or CVC reactivity, respectively, we ran additional analyses that included each respiration rate variable as an additional covariate. This decision was based on past work showing the effects of respiration rate and lnHF values (Shaffer & Ginsberg, 2017) Across all re-computed models, the average respiration rate variables had no significant effect on post-task stress appraisal (all $ps > 0.05$). As such, we did not covary for respiration rate in our final models given the current analyses were already slightly underpowered.

Table 1 Sample characteristics and group differences between randomized social feedback conditions

	Social feedback condition				
	Total sample N = 60 Mean (SD)	Negative N = 27 Mean (SD)	Positive N = 33 Mean (SD)	Tests of group differences	Hedges' g effect size estimates
Sex	62% Male	60% Male	64% Male	$\chi^2(1) = .12, p = .79$	0.05[b]
Age	34.57 (7.05)	35.30 (7.16)	33.97 (7.00)	$t(58) = .72, p = .47$	0.19
BMI	25.30 (3.51)	24.97 (3.32)	25.58 (3.69)	$t(58) = .66, p = .51$	0.17
FTCD	3.80 (1.49)	3.93 (1.52)	3.69 (1.49)	$t(57) = .61, p = .55$	0.16
CPD	14.05 (4.89)	14.19 (5.48)	13.94 (4.43)	$t(58) = .19, p = .85$	0.05
Pre-task appraisal	0.83 (0.73)	0.95 (.93)	0.73 (.51)	$t(58) = 1.16, p = .25$	0.30
Post-task appraisal	1.04 (0.98)	1.40 (1.31)	.74 (.41)	$t(58) = 2.71, p = .01$	0.71
CVC Resting	6.01 (1.29)	5.94 (1.17)	6.14 (1.39)	$t(58) = -.56, p = .55$	0.15
CVC Reactivity[a]	0.66 (0.69)	0.64 (0.67)	0.71 (0.72)	$t(57) = -.39, p = .70$	0.10

Sex (1 = Female, 2 = Male), *BMI* body mass index, *FTCD* Fagerström test of cigarette dependence, *CPD* cigarettes per day, *CVCrest* average baseline RSA, *CVCreac* Difference between Minimum RSA during dot-tracking and Average Baseline RSA multiplied by – 1

[a]Due to a malfunction with the dot-tracking software, we were not able to record ECG data for 1 participant during their dot-tracking epoch. RSA values used for computing the CVC reactivity index are based on a sample of n = 59

[b]Phi used to compute effect size estimate for χ^2 test of group differences in sex between feedback conditions

CVC at rest when examining its direct and indirect effects on post-task stress appraisal. Power analyses were based on our third model, which estimated that an N = 62, with an α set at .05, is needed to detect a medium sized effect ($f^2 = .167$ [R^2 change/1 – cumulative R^2] = .167). This included up to three covariates (age, CVC at rest, pre-task stress appraisal) accounting for 30% of the anticipated variance and three predictors (i.e., feedback condition, CVC reactivity and the interaction term) contributing an additional 10% variance. Given our final sample size of 60, the analyses for this report are slightly underpowered.

Results

Participant Characteristics and Randomization

Table 1 provides sample characteristics and mean group differences between feedback conditions. χ^2 and Independent t-tests showed no significant differences in participant characteristics between groups (all $ps > .05$ and Hedges' $gs < .20$).

Cognitive Stress Appraisal

On average, participants reported resource scores of 4.93 ($SD = 1.32$) and demand scores of 4.40 ($SD = 1.35$) during the pre-task appraisal assessment, and average resource scores of 3.48 ($SD = 1.46$) and demand scores of 3.67 ($SD = 1.50$) during the post-task appraisal assessment. A stress index was computed as the ratio of demands over resources, which served as an index of pre-task stress appraisal ($M = 0.83$, $SD = .73$) and post-task stress appraisal ($M = 1.04$, $SD = .98$) scores in relation to the TSST. Independent *t*-tests showed no significant differences between groups for pre-task appraisal [$t(58) = 1.16$, $p = .25$, Hedges' $g = .30$], however significant differences were observed for post-task stress appraisal [$t(58) = -2.71$, $p = .01$, Hedges' $g = .70$].

Physiological Responses

Data from ECG recordings during baseline and the dot-tracking task were used to compute resting and reactivity indices of CVC. Due to a malfunction with the dot-tracking software, we were not able to record ECG data for one participant during their dot-tracking epoch. Considering this, the RSA values used for computing our CVC reactivity index are based on a sample of n = 59. Mean baseline RSA, which served as our resting index of CVC, was 6.05 ($SD = 1.29$), while mean RSA during dot-tracking was 6.00 ($SD = 1.13$). The average difference between lowest RSA during dot-tracking and average RSA during baseline was computed and multiplied by – 1 to derive our CVC reactivity index ($M = 0.68$, $SD = 0.70$). Independent *t*-tests showed no significant differences between groups on either CVC index ($ps > .05$, Hedges' $gs < .20$).

Table 2 Effects of social feedback condition and CVC reactivity on post-task stress appraisal controlling for CVC at rest, age, and pre-task stress appraisal

R	R^2		F		p
0.85	0.72		22.22		< 0.001
	b	t	p	95% CI Lower Limit	95% CI Upper Limit
Constant	0.66	0.96	0.34	−0.73	2.05
Age	−0.00	−0.32	0.75	−0.03	0.02
Pre-task Appraisal	1.03	10.37	< 0.001	0.83	1.23
CVC Resting	−0.02	−0.25	0.81	−0.15	0.12
CVC Reactivity	−0.23	−1.35	0.18	−0.57	0.11
Condition	−0.45	−3.01	0.01	−0.74	−0.15
Condition × CVC Reactivity	0.15	0.70	0.49	−0.28	0.59

Primary Analyses: CVC Indices, Social Feedback, and Stress Appraisal

The first model examining the interactive effects of condition and CVC at rest on post-task stress appraisal was not significant [$F(3,56) = 2.59$, $p = 0.06$, $R^2 = 0.12$, $f^2 = 0.14$]. However, within the model the effect of condition was significant ($b = -0.64$, $p = 0.01$), with individuals randomized to the positive feedback condition reporting lower post-task stress appraisal scores (i.e., greater resources to demands). When covariates for age and pre-task stress appraisal were added, the re-computed model was significant [$F(5,54) = 26.17$, $p < 0.001$, $R^2 = 0.71$, $f^2 = 2.45$], the effect of feedback condition remained significant ($b = -0.42$, $p = 0.01$), and a significant effect was also observed for pre-task stress appraisal ($b = 1.03$, $p < 0.001$), with higher pre-task stress appraisal associated with higher post-task stress appraisal. Squared semi-partial correlations showed condition and pre-task stress appraisal independently accounted for 4.6% and 58.1% of the variance in post-task stress appraisal, respectively. Resting CVC did not have significant main or interactive effects on post-task stress appraisal in either model.

The second moderation model examining the interactive effects of condition and CVC reactivity on post-task stress appraisal yielded a marginal model effect [$F(3,55) = 2.83$, $p = 0.05$, $R^2 = 0.13$, $f^2 = 0.15$]. The effect of condition was significant ($b = -0.67$, $p = 0.01$), with no significant main or interactive effects observed for either CVC reactivity or CVC reactivity × feedback condition (ps > 0.05). When age and pre-task stress appraisal covariates were included, the overall model became significant [$F(5,53) = 27.13$, $p < 0.001$, $R^2 = 0.72$, $f^2 = 2.57$], with significant effects for feedback condition ($b = -0.45$, $p = 0.01$) and pre-task stress appraisal ($b = 1.03$, $p < 0.001$): lower pre-task stress appraisal and positive feedback condition were associated with lower post-task stress appraisal scores. Squared semi-partial correlations showed condition and pre-task stress appraisal independently accounted for 5.0% and 59.0% of the variance in post-task stress appraisal, respectively. CVC reactivity was not significantly predictive of post-task stress appraisal.

The third moderation model examining the interactive effects of condition and CVC reactivity on post-task stress appraisal when accounting for CVC at rest was not significant [$F(4,54) = 2.11$, $p = 0.09$, $R^2 = 0.14$, $f^2 = 0.16$]. As with the first two models, the effect of social feedback condition was significant ($b = -0.66$, $p = 0.01$). Similarly, when controlling for age and pre-task stress appraisal, the overall model became significant [$F(6,52) = 22.22$, $p < 0.001$, $R^2 = 0.72$, $f^2 = 2.57$], with significant effects observed for feedback condition ($b = -0.45$, $p = 0.01$) and pre-task stress appraisal ($b = 1.03$, $p < 0.001$), but no significant main or interactive effects for either CVC index (all ps > 0.05). Squared semi-partial correlations showed condition and pre-task stress appraisal independently accounted for 4.9% and 58.2% of the variance in post-task stress appraisal, respectively. Table 2 provides full model results. Figure 2 shows the non-significant interaction of the simple slopes.

Discussion

Compelling evidence suggests cigarette smoking alters regulatory function and increases stress reactivity in individuals who smoke (Middlekauff et al., 2014). Yet few studies have examined how physiological measures of regulatory ability relate to other critical determinants of stress responding in smokers. To bridge this gap, the current study examined how individual differences in resting and reactivity measures of CVC influences how individuals who smoke appraised a socio-evaluative stress task. Identifying how individual differences in CVC, a physiological correlate of self-regulatory

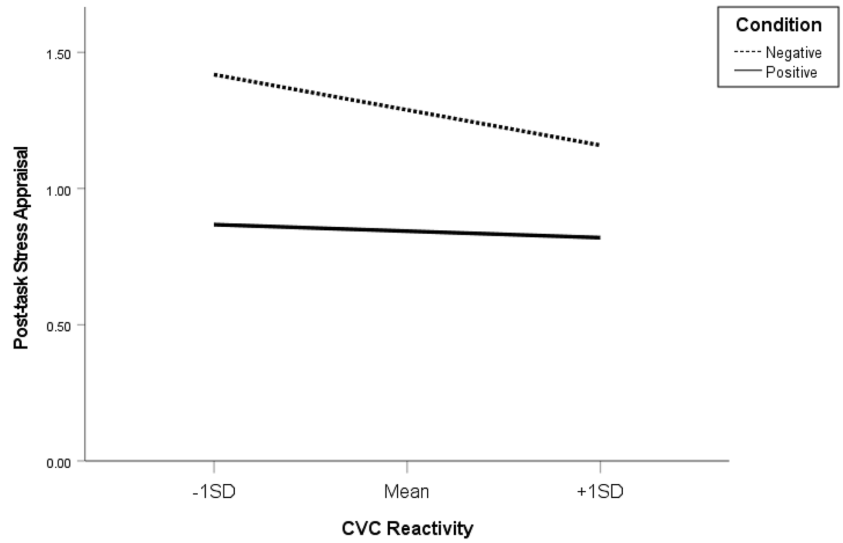

Fig. 2 Plot of the simple slopes for the non-significant interaction between social feedback condition and CVC reactivity on post-task stress appraisal

ability, moderate stress appraisal may be of particular importance in people who smoke given the robust relations between smoking and stress.

This study experimentally confirmed that stressor context (i.e., positive or negative social feedback condition) influences stress appraisals in adults who smoke. Relative to individuals receiving positive social feedback, individuals randomized to the negative feedback condition reported significantly greater post-task stress appraisal scores characterized by greater perceived demands and fewer coping resources. These findings are consistent with studies examining demand and resource appraisals in healthy, non-smoking samples (Muhtadie et al., 2015), and demonstrate the critical role of contextual cues in shaping task appraisal processes. Given extant work suggesting greater CVC may facilitate sensitivity to salient context cues (Human & Mendes, 2018; Muhtadie et al., 2015), we were particularly interested in characterizing how the effects of social feedback condition on post-task stress appraisal may vary as a function of resting and reactivity measures of CVC. In contrast to study hypotheses, we found no significant main or interactive effects of either CVC index and feedback condition on post-task stress appraisal. Findings from this study have several implications when considering the relationship between these factors in adults who smoke and can inform future investigative efforts.

First, smoking-related deficits in autonomic function have been well characterized (Bodin et al., 2017; Dinas et al., 2013; Hayano et al., 1990; Middlekauff et al., 2014) and may have obscured the ability to detect the distinct effects of CVC indices on stress appraisal, as only adults who smoke daily were included in this study. In Kim et al.'s (2018) meta-analysis of CVC and stress, the authors posited that a patient's medical and psychological history are essential when evaluating the relationship between CVC and stress-related outcomes. Studies that have considered the role of a broader set of modifiable health factors on CVC also lend support for this perspective. For example, research examining the association between increased cardiovascular risk and Post-Traumatic Stress Disorder (PTSD), another condition marked by dysregulated stress response, found smoking, alcohol dependence, and sleep disturbance account for 94% of the observed variance between PTSD symptoms and attenuated CVC in young adults with and without PTSD (Dennis et al., 2014). Findings such as this not only represent an intermediary set of behavioral mechanisms that might link aspects of clinical pathology and CVC, but further underscore the challenges smoking can introduce when interpreting the relatedness of these constructs. This may explain the lack of association between either CVC index and pre- and post-task stress appraisal processes observed in our report. Yet, most of the work examining CVC and stress relations focuses on non-smoking individuals, highlighting the research gap filled by the current investigation. Although our participants were otherwise healthy, based upon self-reported inclusion and exclusion criteria, future work examining indices of CVC and stress responding in adults who smoke would benefit from incorporating a control, non-smoker comparison group to further discern the distinct effects of smoking-related autonomic dysfunction on stress appraisal between groups.

Study designs that consider the relative contributions of and interactions between both PNS and SNS branches may also assist in providing a more comprehensive picture of smoker autonomic response patterns in the context of stress. Ashare et al.'s (2012) investigation of whether changes in autonomic reactivity mediate the ability to resist smoking following acute stress provides support for this multi-measure approach. Specifically, the authors used high frequency heartrate variability (HF-HRV) to examine vagal function and a low-to-high frequency HRV ratio (LF/HF) to examine shifts in sympathovagal balance in a sample of abstinent smokers exposed to a stress-imagery induction. Relative to relaxing imagery, greater HF-HRV reductions in response to stress was associated with longer time to smoking lapse. A relation that was not observed for the sympathovagal measure despite greater LF/HF increases also occurring in response to stress vs. relaxing imagery (Ashare et al., 2012). While the use of the LF/HF ratio as a metric of sympathovagal balance has received criticism in the psychophysiology literature (Berntson et al., 1997a, b), findings suggest that reductions in vagal function may be more relevant for stress-precipitated smoking behavior compared to overall shifts in sympathovagal balance. Ongoing work incorporating multiple measures of autonomic activity are needed to replicate and extend these findings to measures of cognitive regulation implicated in stress and smoking risk.

Together, the current study demonstrated that stress appraisals of adults who smoke daily are sensitive to social feedback and highly related to anticipatory appraisal processes. Yet, contrary to expectations based on extant literature in healthy, non-smoking adult samples, the hypothesis that individual differences in resting and reactivity measures of CVC would moderate the effect of social feedback condition on post-task stress appraisals among daily smoking adults was not supported. Future studies comparing CVC relations to cognitive appraisal processes among adults who smoke and those who do not may help resolve inconsistencies across investigations. While parasympathetic measures of autonomic function have been linked to stress-precipitated smoking behavior in the context of acute stress, additional studies are needed to clarify how smoking-induced deficits in autonomic function may relate to other regulatory stress processes among adults who smoke.

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Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical Approval All study procedures were reviewed and approved by the Rutgers University Institutional Review Board and adhere to the tenets of the Declaration of Helsinki.

Informed Consent Informed consent was obtained from all individual participants included in this study.

References

Akinola, M., & Mendes, W. B. (2008). The dark side of creativity: Biological vulnerability and negative emotions lead to greater artistic creativity. *Personality and Social Psychology Bulletin, 34*(12), 1677–1686. https://doi.org/10.1177/0146167208323933

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. *Journal of Visualization, 7*(13), 14.1–4.10. https://doi.org/10.1167/7.13.14

Ashare, R. L., Sinha, R., Lampert, R., Weinberger, A. H., Anderson, G. M., Lavery, M. E., Yanagisawa, K., & McKee, S. A. (2012). Blunted vagal reactivity predicts stress-precipitated tobacco smoking. *Psychopharmacology (Berlin), 220*(2), 259–268. https://doi.org/10.1007/s00213-011-2473-3

Beadman, M., Das, R. K., Freeman, T. P., Scragg, P., West, R., & Kamboj, S. K. (2015). A comparison of emotion regulation strategies in response to craving cognitions: Effects on smoking behaviour, craving and affect in dependent smokers. *Behaviour Research and Therapy, 69*, 29–39. https://doi.org/10.1016/j.brat.2015.03.013

Beauchaine, T. (2001). Vagal tone, development, and Gray's motivational theory: Toward an integrated model of autonomic nervous system functioning in psychopathology. *Development and Psychopathology, 13*(2), 183–214. https://doi.org/10.1017/s0954579401002012

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1993). Respiratory sinus arrhythmia: Autonomic origins, physiological mechanisms, and psychophysiological implications. *Psychophysiology, 30*(2), 183–196. https://doi.org/10.1111/j.1469-8986.1993.tb01731.x

Berntson, G. G., Thomas Bigger, J., Jr., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., & Stone, P. H. (1997a). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology, 34*(6), 623–648.

Berntson, G. G., Thomas Bigger, J., Jr., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & Van Der Molen, M. W. (1997b). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology, 34*(6), 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

Birkett, M. A. (2011). The Trier Social Stress Test protocol for inducing psychological stress. *Journal of Visualized Experiments*. https://doi.org/10.3791/3238

Blascovich, J., & Mendes, W. B. (2000). Challenge and threat appraisals: The role of affective cues. In *Feeling and thinking: The role of affect in social cognition* (pp. 59–82). Cambridge University Press.

Bodin, F., McIntyre, K. M., Schwartz, J. E., McKinley, P. S., Cardetti, C., Shapiro, P. A., Gorenstein, E., & Sloan, R. P. (2017). The association of cigarette smoking with high-frequency heart rate variability: An ecological momentary assessment study. *Psychosomatic Medicine, 79*(9), 1045–1050. https://doi.org/10.1097/PSY.0000000000000507

Brown, R. A., Lejuez, C. W., Kahler, C. W., & Strong, D. R. (2002). Distress tolerance and duration of past smoking cessation attempts. *Journal of Abnormal Psychology, 111*(1), 180–185. https://www.ncbi.nlm.nih.gov/pubmed/11866171

Calhoun, P. S., Dennis, M. F., & Beckham, J. C. (2007). Emotional reactivity to trauma stimuli and duration of past smoking cessation attempts in smokers with posttraumatic stress disorder. *Experimental and Clinical Psychopharmacology, 15*(3), 256–263. https://doi.org/10.1037/1064-1297.15.3.256

Cohen, J. (1988). *Statistical power analysis for the social sciences*. Routledge.

Cohen, J. (1992). Statistical power analysis. *Current Directions in Psychological Science, 1*(3), 98–101.

Cohen, S., & Lichtenstein, E. (1990). Perceived stress, quitting smoking, and smoking relapse. *Health Psychology, 9*(4), 466–478. https://doi.org/10.1037//0278-6133.9.4.466

Dennis, P., Watkins, L., Calhoun, P., Oddone, A., Sherwood, A., Dennis, M., Rissling, M., & Beckham, J. (2014). Posttraumatic stress, heart-rate variability, and the mediating role of behavioral health risks. *Psychosomatic Medicine 76*(8), 629–637. https://doi.org/10.1097/PSY.0000000000000110

Dinas, P. C., Koutedakis, Y., & Flouris, A. D. (2013). Effects of active and passive tobacco cigarette smoking on heart rate variability. *International Journal of Cardiology, 163*(2), 109–115. https://doi.org/10.1016/j.ijcard.2011.10.140

Etter, J. F., Duc, T. V., & Perneger, T. V. (1999). Validity of the Fagerstrom test for nicotine dependence and of the Heaviness of Smoking Index among relatively light smokers. *Addiction, 94*(2), 269–281. https://doi.org/10.1046/j.1360-0443.1999.94226910.x

Fagerström, K. (2012). Determinants of tobacco use and renaming the FTND to the Fagerstrom Test for Cigarette Dependence. *Nicotine and Tobacco Research, 14*(1), 75–78. https://doi.org/10.1093/ntr/ntr137

Frazier, T. W., Strauss, M. E., & Steinhauer, S. R. (2004). Respiratory sinus arrhythmia as an index of emotional response in young adults. *Psychophysiology, 41*(1), 75–83. https://doi.org/10.1046/j.1469-8986.2003.00131.x

Garey, L., Farris, S. G., Schmidt, N. B., & Zvolensky, M. J. (2016). The role of smoking-specific experiential avoidance in the relation between perceived stress and tobacco dependence, perceived barriers to cessation, and problems during quit attempts among treatment-seeking smokers. *Journal of Contextual Behavioral Science, 5*(1), 58–63. https://doi.org/10.1016/j.jcbs.2015.11.001

Hagan, M. J., Bush, N., Mendes, W. B., Arenander, J., Epel, E., & Puterman, E. (2017). Associations between childhood adversity and daily suppression and avoidance in response to stress in adulthood: Can neurobiological sensitivity help explain this relationship? *Anxiety, Stress and Coping, 30*(2), 163–175. https://doi.org/10.1080/10615806.2016.1259473

Hayano, J., Yamada, M., Sakakibara, Y., Fujinami, T., Yokoyama, K., Watanabe, Y., & Takata, K. (1990). Short- and long-term effects of cigarette smoking on heart rate variability. *American Journal of Cardiology, 65*(1), 84–88. https://doi.org/10.1016/0002-9149(90)90030-5

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. Guilford Publications.

Heatherton, T. F., Kozlowski, L. T., Frecker, R. C., & Fagerstrom, K. O. (1991). The Fagerstrom Test for Nicotine Dependence: A revision of the Fagerstrom Tolerance Questionnaire. *British Journal of Addiction, 86*(9), 1119–1127. https://doi.org/10.1111/j.1360-0443.1991.tb01879.x

Human, L. J., & Mendes, W. B. (2018). Cardiac vagal flexibility and accurate personality impressions: Examining a physiological correlate of the good judge. *Journal of Personality, 86*(6), 1065–1077. https://doi.org/10.1111/jopy.12375

Javors, M. A., Hatch, J. P., & Lamb, R. J. (2005). Cut-off levels for breath carbon monoxide as a marker for cigarette smoking. *Addiction, 100*(2), 159–167. https://doi.org/10.1111/j.1360-0443.2004.00957.x

Jennings, J. R., Kamarck, T., Stewart, C., Eddy, M., & Johnson, P. (1992). Alternate cardiovascular baseline assessment techniques: Vanilla or resting baseline. *Psychophysiology, 29*(6), 742–750. https://doi.org/10.1111/j.1469-8986.1992.tb02052.x

Kettunen, J., Ravaja, N., Naatanen, P., & Keltikangas-Jarvinen, L. (2000). The relationship of respiratory sinus arrhythmia to the co-activation of autonomic and facial responses during the Rorschach test. *Psychophysiology, 37*(2), 242–250. https://www.ncbi.nlm.nih.gov/pubmed/10731774

Kim, H.-Y. (2013). Statistical notes for clinical researchers: Assessing normal distribution (2) using skewness and kurtosis. *Restorative Dentistry and Endodontics, 38*(1), 52–54. https://doi.org/10.5395/rde.2013.38.1.52

Lazarus, R. S. (1966). *Psychological stress and the coping process*. McGraw-Hill.

Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal, and coping*. Springer.

Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal, 17*(3), 354–381. https://doi.org/10.1093/oxfordjournals.eurheartj.a014868

McKee, S. A., Maciejewski, P. K., Falba, T., & Mazure, C. M. (2003). Sex differences in the effects of stressful life events on changes in smoking status. *Addiction, 98*(6), 847–855. https://doi.org/10.1046/j.1360-0443.2003.00408.x

Mendes, W. B., Gray, H. M., Mendoza-Denton, R., Major, B., & Epel, E. S. (2007). Why egalitarianism might be good for your health: Physiological thriving during stressful intergroup encounters. *Psychological Science, 18*(11), 991–998. https://doi.org/10.1111/j.1467-9280.2007.02014.x

Middlekauff, H. R., Park, J., & Moheimani, R. S. (2014). Adverse effects of cigarette and noncigarette smoke exposure on the autonomic nervous system: Mechanisms and implications for cardiovascular risk. *Journal of American College of Cardiology, 64*(16), 1740–1750. https://doi.org/10.1016/j.jacc.2014.06.1201

Muhtadie, L., Koslov, K., Akinola, M., & Mendes, W. B. (2015). Vagal flexibility: A physiological predictor of social sensitivity. *Journal of Personality and Social Psychology, 109*(1), 106–120. https://doi.org/10.1037/pspp0000016

Nohlert, E., Ohrvik, J., & Helgason, A. R. (2018). Self-perceived ability to cope with stress and depressive mood without smoking predicts successful smoking cessation 12 months later in a quitline setting: A secondary analysis of a randomized trial. *BMC Public Health, 18*(1), 1066. https://doi.org/10.1186/s12889-018-5973-9

Porges, S. W. (1995a). Cardiac vagal tone: A physiological index of stress. *Neuroscience and Biobehavioral Reviews, 19*(2), 225–233. https://doi.org/10.1016/0149-7634(94)00066-a

Porges, S. W. (1995b). Orienting in a defensive world: Mammalian modifications of our evolutionary heritage. A Polyvagal Theory. *Psychophysiology, 32*(4), 301–318. https://doi.org/10.1111/j.1469-8986.1995.tb01213.x

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*(2), 116–143. https://doi.org/10.1016/j.biopsycho.2006.06.009

Pumprla, J., Howorka, K., Groves, D., Chester, M., & Nolan, J. (2002). Functional assessment of heart rate variability: Physiological basis and practical applications. *International Journal of Cardiology, 84*(1), 1–14. https://doi.org/10.1016/s0167-5273(02)00057-8

Reifman, A., & Keyton, K. (2010). In N. J. Salkind (Ed.), Winsorize *Encyclopedia of research design* (pp. 1636–1638). SAGE.

Robinson, S. M., Sobell, L. C., Sobell, M. B., & Leo, G. I. (2014). Reliability of the Timeline Followback for cocaine, cannabis, and cigarette use. *Psychology of Addictive Behaviors, 28*(1), 154–162. https://doi.org/10.1037/a0030992

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health, 5*, 258. https://doi.org/10.3389/fpubh.2017.00258

Siegel, A., Korbman, M., & Erblich, J. (2017). Direct and indirect effects of psychological distress on stress-induced smoking. *Journal of Studies on Alcohol and Drugs, 78*(6), 930–937. https://doi.org/10.15288/jsad.2017.78.930

Taylor, S. E., Seeman, T. E., Eisenberger, N. I., Kozanian, T. A., Moore, A. N., & Moons, W. G. (2010). Effects of a supportive or an unsupportive audience on biological and psychological responses to stress. *Journal of Personality and Social Psychology, 98*(1), 47–56. https://doi.org/10.1037/a0016563

Tomaka, J., Blascovich, J., Kibler, J., & Ernst, J. M. (1997). Cognitive and physiological antecedents of threat and challenge appraisal. *Journal of Personality and Social Psychology, 73*(1), 63–72. https://doi.org/10.1037/0022-3514.73.1.63

Wang, M., & Saudino, K. J. (2011). Emotion regulation and stress. *Journal of Adult Development, 18*(2), 95–103. https://doi.org/10.1007/s10804-010-9114-7

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