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Examining the Relation between Physiological and Psychological Components of Stress Reactivity and Recovery in Cigarette Smokers

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Abstract

Cigarette smokers exhibit reduced physiological stress reactivity, yet it is unclear whether blunted reactivity predicts differences in subjective recovery and vice versa. The study examined whether basal heart rate and heart rate reactivity were related to recovery in anxiety following stress, and conversely, whether initial self-reported anxiety and anxiety reactivity were related to heart rate recovery. Fifty-six smokers completed a ten-minute baseline period, a four-minute stressor, and a ten-minute recovery period during which heart rate and anxiety were continuously assessed. Results indicated significant linear ($p < .01$, $d=0.31$) and quadratic ($p=0.02$, $d=0.27$) effects of baseline heart rate and reactivity (linear $p < .01$, $d=0.80$; quadratic $p < .01$, $d=0.66$) on recovery in anxiety and significant linear ($p < .01$, $d=0.88$) and quadratic ($p < .01$, $d=0.74$) effects of anxiety reactivity on heart rate recovery. These findings suggest that reduced reactivity in both heart rate and anxiety predicted slower recovery in the opposite domain. Findings offer initial evidence for psychophysiological integration in cigarette smokers.

Introduction

Cigarette smoking is one of the leading causes of death in US adults and a major cause of cardiovascular disease (U.S. Department of Health and Human Services, 2014).

Experimental research suggests that cigarette smoking, and broader nicotine use, have acute effects on cardiovascular functioning by reliably increasing the activity of the sympathetic branch of the autonomic nervous system (Ahmad, Selvaraj, & Meenakshisundaram, 2015; Grassi et al., 1994; Richards, Stipelman, Bornovalova, Daughters, Sinha, & Lejuez, 2011; Trap-Jensen, 1988; Winniford, 1990). Yet, repeated sympathetic activation in the context of persistent nicotine use may also be associated with long-term negative effects on cardiovascular functioning (Lucini, Di Fede, Parati, & Pagani, 2005). For example, despite exhibiting an increase in heart rate during stress (Childs and de Wit, 2010; McKee et al.,

2011), adult smokers frequently exhibit blunted cardiovascular stress reactivity as compared to non-smokers (Childs and de Wit, 2009). Initial observations of attenuated cardiovascular reactivity to stress observed in female (Girdler, Jamner, Murray, Jarvik, Soles, & Shapiro, 1997) and male smokers (Roy, Steptoe, & Kirschbaum, 1994) have recently been replicated (Childs and de Wit, 2009; Ginty et al., 2014) and extended to adolescent smokers (Evans, Greaves-Lord, Euser, Tulen, Franken, & Huizink, 2012), suggesting a developmentally invariant effect.

Dysregulated physiological responses to stress, which may be characterized by a blunted response, and also, poor recovery (Dhoble, Brian, Lahr, Allison, & Kopecky, 2014), may contribute to or serve as markers of morbidity and mortality (Dhoble et al., 2014; Thayer & Lane, 2007). For example, within a non-selected sample, reduced heart rate recovery was associated with increased likelihood for future cardiovascular risk status (i.e., higher systolic and diastolic blood pressure and greater carotid intima-media thickness; Chida & Steptoe, 2010) and an increased likelihood of death (Lahiri, Kannankeril, & Goldberger, 2008). Moreover, the combination of stress and smoking appear to additively decrease heart rate variability (HRV) (Ashare et al., 2012), suggesting effects on both the parasympathetic and sympathetic branches of the autonomic nervous system. These findings have important clinical implications given established links between stress and smoking (Cohen & Lichtenstein, 1990; Wills, Sandy, & Yaeger, 2002) as well as work indicating that dysregulation in the stress response systems are linked to worse smoking outcomes. For example, reduced cardiovascular stress reactivity is associated with a faster time to re-initiate smoking and greater self-reported satisfaction and craving relief from smoking during an experimental lapse paradigm (Ashare et al., 2012) and shorter time to lapse following a quit attempt (al'Absi et al., 2005). These findings suggest that a dysregulated stress response in smokers increases the risk for morbidity and mortality in the long-term and smoking maintenance in the short-term.

Although dysregulation in physiological reactivity to stress is observed in cigarette smokers and may be associated with worse smoking outcomes, there is little research examining whether physiological dysregulation is associated with an individual's subjective response (e.g., self-reported changes in affect) to stress. Better characterizing the links between the physiological and subjective stress response has direct implications for psychosocial interventions that often rely upon changing cognitions to effect long-term change. However, there is limited knowledge regarding the interplay between subjective and physiological processes across the stress response within smokers, and further clarification of this interplay may help to improve interventions. To the extent that subjective stress reactivity affects recovery in physiological responses, this would support the development of cognitive-behavioral interventions targeting emotion regulatory processes (e.g., appraisal). In contrast, the observation that physiological reactivity drives subjective recovery would support augmenting behavioral interventions. Biobehavioral components designed to directly target the autonomic nervous system, for example, could then be more commonly implemented.

To date, empirical research in unselected, or non-smoking, samples suggests that subjective arousal and physiological arousal may be concordant, discordant, or prospectively related

(Levenson, 1988; Mauss, Levenson, McCarter, Wilhelm & Gross, 2005). A recent review (Campbell and Ehlert, 2012) on the cross-sectional and prospective associations of these components of the stress response revealed mixed findings, with approximately twenty-five percent of the studies reporting significant associations between physiological indices of stress reactivity (e.g., cortisol or cardiovascular response) and subjective indices (e.g., self-reports of perceived emotional distress, negative affect, helplessness, or anxiety). However, there is some evidence that self-reported anxiety (Gonzalez-Bono et al., 2012), as well as appraisal styles (Jameson, et al., 2010), affect cardiovascular responses to stress (Jameson, et al., 2012) as well as recovery (Gonzalez-Bono et al., 2012). These findings are aligned with biosocial theories that suggest that cognitive processes may have an immediate impact on physiology (Blaskovich, 1992; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012). Further, observed differences in the stress response in smokers, such as attenuated heart rate reactivity and attenuated subjective distress recovery (i.e., jitteriness and restless) in response to a laboratory stressor may be associated and hold meaningful implications for differences in smoking behavior (Childs and de Wit, 2009).

Given the limited examination of these relations within a population of smokers, as well as the mixed results of prior research on the associations between physiological and subjective components of stress reactivity in a general sample (Campbell and Ehlert, 2012), the current study sought to examine the effects of the physiological and subjective stress response on recovery from a laboratory stressor in a sample of daily smokers. Specifically, we examined: 1) whether measures of baseline heart rate and heart rate reactivity to a stressor predicted subjective recovery from stress. We hypothesized that higher resting heart rate and attenuated heart rate reactivity to a stressor would predict slower subjective recovery, as indexed by self-reported anxiety. To investigate reciprocal effects, the study also examined: 2) whether baseline anxiety and anxiety reactivity to a stressor predicted physiological recovery from stress. We hypothesized that greater baseline anxiety and blunted anxiety reactivity to a stressor would be related to slower heart rate recovery.

Method

Participants

The current sample consisted of 56 adults (46.4% female; $M_{\text{age}} = 29.33$, $SD = 11.92$) who were recruited from the greater Burlington, Vermont area. Participants were originally recruited to participate in a research study to examine the effects of Panic Disorder and nicotine withdrawal on anxious responding during a biological challenge (Leyro & Zvolensky, 2013). Of the sample, 91.1% identified as White/Caucasian, 3.6% Black/Non-Hispanic, 3.6% 'other,' and 1.8% as Asian; 37.8% of the sample identified as Hispanic. Participants completed an initial phone screen to determine eligibility based on current frequency and intensity of smoking (i.e., 15 cigarettes per day). Inclusion criteria included the following: being a daily smoker for at least the past year, 18 to 65-years-of-age, reporting current Panic Disorder, and a willingness to abstain from smoking for 12-hours. Exclusion criteria included a reduction in the number of cigarettes smoked per day by more than half of their normal amount within the past six months, report of a current medical condition (e.g., cardiovascular, endocrine, pulmonary, respiratory, or gastrointestinal illness)

contraindicated for CO₂ administration or that would confound interpretation of heart rate data, a prior history of PD without current symptoms, current use of nicotine replacement therapy, current substance use dependence other than nicotine, current or past manic or psychotic episode, current suicidality, any current use of psychotropic medication (e.g., benzodiazepines, beta-blockers, mood stabilizers; anti-psychotics) that could impact the effect of the CO₂ challenge, and prior experience with the CO₂ challenge. Eligible participants were invited to the laboratory to complete two study sessions.

Procedure

Session One: Upon arrival to the first session, participants completed a written informed consent. Advanced doctoral students then administered the *Structured Clinical Interview of DSM-IV Disorders* (SCID-I/NP; First, Spitzer, Gibbon, & Williams, 1994) to determine a current diagnosis of panic disorder and to further assess inclusion/exclusion criteria. Participants next completed self-report measures of smoking history and current affect as well as a carbon monoxide (CO > 8 ppm; Javors, Hatch, & Lamb, 2005) analysis of breath. Eligible participants were then randomized to either abstain from smoking for at least 12 hours prior to the second session, or to smoke as usual. Participants were also asked to abstain from any other substance use including marijuana, alcohol and prescription medications, such as benzodiazepines, 24-hours before the visit.

Session Two: Participants first completed a CO analysis of breath to confirm abstinence in the smoking deprivation group (<8–10 ppm (Javors et al., 2005; Morabia et al., 2001) or greater than 50% reduction from the first session. Participants in the smoke-as-usual group were asked to smoke one cigarette prior to the experimental procedures to standardize time since smoking. Next, physiological recording equipment was placed on the participants and they were seated in a separate room where they were asked to stay attentive, but relatively still for the duration of the procedure. A ten-minute baseline period was used to establish pre-experimental baseline for physiological measures (Forsyth & Eifert, 1998). Next, they completed a four-minute “challenge” period during which they breathed in 10% CO₂-enriched air through a continuous positive airway pressure (CPAP) mask that was placed over their nose and mouth, through which both regular room air quality and 10% CO₂-enriched air were administered. Participants were not given any information concerning the CO₂ delivery (onset or offset time points), as is standard protocol for challenge work (Zvolensky & Eifert, 2001). During the challenge, participants were prompted at each minute to complete ratings of their anxiety using subjective units of distress (SUDs). Next, participants removed the CPAP mask and completed a ten-minute recovery period during which they rated their SUDs every minute (Figure 1). A portable capnograph including nasal canula and pulse plethysmograph was used to measure continuous levels of end-tidal CO₂ (i.e., CO₂ contained in the exhaled breath), respiration, spirometry, and heart rate. At the end of the recovery period participants were unhooked from the mask and physiological recording equipment, debriefed, and compensated \$40 for their participation. All procedures were approved by the university’s Institutional Review Board.

Measures

Demographics—General demographic information was collected, including sex/gender, age, and race/ethnicity.

Smoking History Questionnaire—(SHQ; Brown, Lejuez, Kahler, & Strong, 2002): The SHQ was used to assess smoking history, including when a participant became a regular smoker, number of previous quit attempts, periods of abstinence, and the number of cigarettes smoked per day.

Minnesota Nicotine Withdrawal Scale—(MNWS; Hughes & Hatsukami, 1986): The MNWS was used to assess symptoms of nicotine withdrawal rated on a 4-point scale from 0 (*not present*) to 3 (*severe*). The MNWS was administered at multiple time points throughout the experimental manipulation to examine changes in withdrawal symptom severity throughout the manipulation, including prior to equipment hook-up, prior to the CO₂ onset, and following its termination. The MNWS has been shown to be a valid measure of nicotine withdrawal (Piper et al., 2004; Piper et al., 2008) and internal consistency in the current sample over the three-time points was adequate (range of observed Cronbach's α s = 0.84-.87).

Structural Clinical Interview for the DSM-IV, non-patient version—(SCID-I/NP for the DSM-IV; First, Spitzer, Gibbon, & Williams, 1994): The SCID-I/NP was used to assess current and past psychopathology to ensure study inclusion/exclusion criteria were met. The principle investigator or a trained research assistant conducted all interviews. Interviews were audio-recorded and a senior level graduate student cross-checked approximately 20% of the interviews with an inter-rater agreement of .98 (98% agreement), with no cases of disagreement with regard to PD diagnosis.

The Fagerström Test for Cigarette Dependence—(FTCD; Fagerström, 2012): The FTCD was used to assess cigarette dependence. The FTCD has been found to be associated with other indices of dependence, such as cotinine levels, and smoking history (Payne, Smith, McCracken, McSherry, & Antony, 1994; Pomerleau, Carton, Lutzke, Flessland, & Pomerleau, 1994). It also exhibits high test-retest reliability (Pomerleau et al., 1994).

Subjective Units of Distress Scale—(SUDS; Wolpe, 1958): SUDs ratings were used to assess self-reported anxiety throughout the stressor using a visual-analog scale (VAS) ranging from 0 (*no anxiety right now*) to 100 (*extreme anxiety right now*). These ratings were collected at one-minute intervals before the stressor to assess baseline anxiety, during the stressor, and following the stressor. All ratings collected during the 10-minute recovery period were used as the dependent variable.

Cardiovascular Response—A BCI Capnocheck II Handheld Capnograph/Oximeter (Model 8401): manufactured by Smiths Medical was used to capture physiological data, including heart rate. Heart rate was collected continuously throughout the procedure, and raw data was averaged and provided via a Martel infrared printout (Model MCP8850B) at

15-second intervals. These intervals were then used to calculate mean heart rate at every minute of the baseline period, four-minute stressor, and recovery period.

CO₂ Challenge—The CO₂ challenge is a single four-minute administration of 10% CO₂-enriched air (10% CO₂, 21% O₂, 69% NO₂) (Feldner, Zvolensky, & Schmidt, 2004). During the challenge, 10% CO₂-enriched air is fed through a 2-cm in diameter PVC pipe to a 3-cm in diameter tube connected to a continuous positive airway pressure (CPAP) mask worn by participants. Participants only receive CO₂-enriched air during the challenge portion of the task, and receive regular breathing quality air during the baseline and recovery periods. The CO₂ challenge has commonly been used as a stress-inducing task to assess how well individuals can manage distress (Brown et al., 2005; Leyro et al., 2010). Administration of 10% CO₂ results in significant changes in pre-to post end-tidal CO₂ (ETCO₂), increased arousal, and increases in emotional and physical distress (Zvolensky & Eifert, 2001). Performance on the CO₂ challenge appears to be associated with the likelihood of a lapse during a quit attempt for cigarette smokers and greater negative affect and urges to smoke on quit day (Abrantes, Strong, Lejuez, Kahler, Carpenter, & Price, 2008). Therefore, the CO₂ challenge appears to reliably induce distress and a stress response in adult smokers.

Data Analytic Strategy

Data from all of the participants were included in these secondary-data analyses. Since the original study recruited participants with current PD and participants were randomized to twelve hours of smoking deprivation or to smoke-as-usual (Leyro & Zvolensky, 2013), PD status and self-reported withdrawal symptoms via the MNWS were included as covariates to account for any differences in heart rate and self-reported anxiety (i.e., SUDs anxiety ratings) due to group randomization. Cigarette dependence (Fagerström, 2012) and sex were also included as covariates to control for potential differences in heart rate or self-reported anxiety due to sex or nicotine use (Nillni, Berenz, Rohan, & Zvolensky, 2012). Additionally, all time invariant predictors were mean-centered, and repeatedly assessed predictor variables were grand-mean centered before completing longitudinal data analyses.

Individual growth curve models were conducted in SAS University Edition (SAS® Studio) to examine the primary hypotheses. Models were conducted in an incremental fashion to determine the significance of first the covariates, intercepts, linear and quadratic slopes, and then the predictor variables on the outcomes of interest. First, a simplified intercepts-only model was examined to determine whether there was a significant fixed intercept (or common starting point) or a random intercept (variable starting point) for heart rate and anxiety during recovery. This model also included covariates of panic disorder status, randomization status, sex, age, and number of cigarettes smoked per day. Any significant covariates were retained for future models. The next two models examined the linear and quadratic effects of time on heart rate recovery and anxiety recovery to determine whether the recovery profiles were best defined by a linear and/or quadratic function. The effects of time were entered as fixed and random effects to determine whether there was a significant fixed and/or random slope. The final, full growth curve model included significant covariates, a linear (Time) and quadratic (Time²) effect of time, a linear and quadratic effect of baseline heart rate or self-reported anxiety, and a linear and quadratic effect of reactivity

in heart rate or self-reported anxiety. For all the models examined, the model log likelihood values were compared to determine if there was significant improvement in each subsequent model. Post-hoc analyses were conducted to examine the effects of respiration rate on heart rate recovery to determine whether effects persisted despite the influence of respiration on autonomic functioning. A residual difference score was calculated to index change in respiration rate during the laboratory stressor.

Results

Manipulation Checks for Laboratory Protocol and Correlations

Manipulation checks indicated significant changes in both heart rate ($t(45) = 4.08, p < .001$; $M_{HRBaseline} = 79.74, SD = 11.52$; $M_{HRPostCO_2} = 85.34, SD = 11.38$) and self-reported anxiety ($t(53) = 6.59, p < .001$; $M_{ANXBaseline} = 34.69, SD = 27.36$; $M_{ANXPostCO_2} = 62.07, SD = 33.44$) from pre- to post-challenge as well as a significant decrease in heart rate ($t(44) = -4.47, p < .001$; $M_{HRRecovery} = 79.07, SD = 11.92$) and anxiety ($t(53) = -7.56, p < .001$; $M_{ANXRecovery} = 24.09, SD = 29.32$) during recovery.

Next, zero-order (or bivariate, as applicable) correlations were computed among covariates, predictor, and dependent variables (Table 1). Greater baseline self-reported anxiety was significantly associated with greater cigarette dependence (FTCD; $r(54) = 0.45, p < .01$) and withdrawal symptoms at baseline ($r(54) = 0.66, p < .01$). Greater baseline heart rate was significantly associated with less anxiety reactivity ($r(43) = -0.34, p < .01$), and heart rate reactivity was significantly correlated with anxiety reactivity ($r(43) = 0.44, p < .01$).

Determining the indices of heart rate reactivity and subjective reactivity

The indices of heart rate reactivity and subjective reactivity were calculated using the observed residual score (RS), or the difference between the observed peak value and the expected peak value based on a regression between the observed baseline values and peak values, as opposed to the observed difference score (DS), or the difference between the peak value and the baseline value. Use of the RS was determined by guidelines (Burt & Obradovic, 2013) that suggest that the observed RS may be a better index of change when the correlation coefficient (r) between measures at baseline and peak reactivity is less than the ratio between the variability (λ) of the measures at baseline and peak, which was the case for both heart rate ($r = 0.68$ and $\lambda = 1.02$) and self-reported anxiety ($r = 0.58$ and $\lambda = 0.77$).

Aim 1: The effects of physiological reactivity on subjective recovery from stress.

In the first model (Table 2), we found that there was a significant random intercept for anxiety at the start of recovery ($b = 61.78, SE = 5.81, t(36) = 10.64, p < .01$), indicating significant variability in initial self-reported anxiety (i.e., at the onset of the 10-minute recovery) among participants. In regards to the examination of significant covariates on anxiety during recovery, age significantly predicted anxiety ($b = 0.64, SE = 0.30, t(297) = 2.11, p = 0.04, d = 0.24$), and both baseline anxiety ($b = 0.81, SE = 0.13, t(297) = 6.02, p < 0.01, d = 0.70$) and baseline heart rate significantly predicted anxiety ($b = -0.69, SE = 0.31, t(297) = -2.21, p = 0.03, d = 0.26$). PD diagnosis and self-reported withdrawal symptoms did not significantly predict subjective recovery from stress.

Next a reduced model was fit to the data to examine whether there was a significant effect of linear and quadratic time on self-reported anxiety. Results indicated a significant linear and quadratic effect on anxiety throughout the 10-minute recovery period. Both time predictors (Time: $b=-9.47$, $SE=0.84$, $t(41)=-11.37$, $p<.01$, $d=3.55$ and Time² $b=0.62$, $SE=0.07$, $t(41)=9.15$, $p<.01$, $d=2.86$), entered as random effects, significantly contributed to anxiety throughout recovery. This suggests that there was variability in the change in anxiety recovery among participants. Further, significant linear and quadratic effects of time suggest that initially there may be steeper changes in self-reported anxiety over recovery followed by a deceleration over the course of recovery.

The final model was conducted to examine the effects of baseline heart rate and heart rate reactivity during the challenge on recovery in self-reported anxiety following a stressor. Results indicated an improved fit as compared to the previous model. There was a significant linear effect of baseline heart rate (HRBL) on recovery in anxiety (Time $\times$ HRBL; $b=0.19$, $SE=0.07$, $t(297)=2.67$, $p<.01$, $d=0.31$) and a significant quadratic effect of baseline heart rate on recovery in anxiety (Time² $\times$ HRBL; $b=-0.01$, $SE=0.006$, $t(297)=-2.29$, $p=0.02$, $d=0.27$). There also was a significant linear effect for heart rate reactivity (HRR) on recovery in anxiety (Time $\times$ HRR; $b=-0.73$, $SE=0.11$, $t(297)=-6.92$, $p<.01$, $d=0.80$) and a significant quadratic effect (Time² $\times$ HRR; $b=0.05$, $SE=0.009$, $t(297)=5.69$, $p<.01$, $d=0.66$). Finally, there was a significant random effect of time indicating individual variance in the linear change in anxiety over recovery (Table 2). Post-hoc analyses examining the linear and quadratic effects of respiration rate on recovery in anxiety indicated a significant effect on recovery (Time $\times$ Respiration Rate; $b=-0.77$, $SE=0.30$, $t(288)=-2.62$, $p<.01$, and Time² $\times$ Respiration Rate; $b=0.05$, $SE=0.02$, $t(288)=2.18$, $p=0.03$, respectively). However, effects of baseline heart rate and heart rate reactivity on recovery were maintained with the inclusion of respiration rate.

The significant effects of baseline heart rate and reactivity were examined graphically to characterize the relation between resting heart rate, heart rate reactivity and change in anxiety during recovery. Figure 2 represents the predicted trajectory of change in self-reported anxiety for individuals exhibiting baseline heart rate scores that are one standard deviation above and below the sample mean, suggesting higher baseline heart rate predicted a slower subjective anxiety recovery. Figure 3 shows the predicted trajectory of change in anxiety for individuals exhibiting heart rate reactivity one standard deviation above and below the sample mean. Individuals with greater heart rate reactivity to the challenge exhibited an initially faster reduction in subjective anxiety, that eventually slowed and reached levels equivalent to those with smaller heart rate reactivity. Probing of differences in anxiety at both the end of the CO₂ challenge and end of recovery revealed a significant difference in self-reported anxiety at the beginning of recovery ($t(42)=2.84$, $p<.01$) and no significant difference by the end of recovery ($t(42)=-1.08$, $p=.28$).

Aim 2: The effects of subjective reactivity on physiological recovery from stress.

A second model investigated the relation between reactivity in anxiety and physiological recovery (Table 3). We first examined whether there was a significant starting point (i.e. intercept) for heart rate at the beginning of the recovery period and whether there were

significant effects of each proposed covariate on heart rate. There was a significant random intercept for heart rate at the start of recovery ($b=85.17$, $SE=1.74$, $t(36)=49.06$, $p<.01$), indicating variability among the sample. There were no significant effects of the proposed covariates, particularly PD diagnosis and self-reported withdrawal symptoms, on heart rate.

Next, reduced models were fit to the data to examine whether there was a significant linear and quadratic change in heart rate during recovery. Results indicated a significant decrease in heart rate over time. Both time predictors (Time: $b=-1.66$, $SE=0.27$, $t(41)=-6.17$, $p<.01$, $d=1.93$; and Time² $b=0.10$, $SE=0.022$, $t(41)=4.48$, $p<.01$, $d=1.40$), entered as random effects, significantly contributed to heart rate throughout recovery, suggesting that there was variability in heart rate during recovery. As observed with recovery in self-reported anxiety, the significant linear and quadratic effects of time suggest that initially there may be steeper changes in heart rate over recovery followed by a deceleration in the change in heart rate.

The final model was conducted to examine the relation between baseline anxiety, anxiety reactivity, and recovery in heart rate following a stressor. There was a non-significant effect for baseline anxiety, but a significant linear effect for anxiety reactivity (ANXR) on heart rate recovery (Time $\times$ ANXR; $b=-0.08$, $SE=0.010$, $t(302)=-7.62$, $p<.01$, $d=0.88$) as well as a significant quadratic effect (Time² $\times$ ANXR; $b=0.0053$, $SE=0.001$, $t(302)=6.42$, $p<.01$, $d=0.74$) supporting the second hypothesis. This interaction was examined graphically to understand the relation between anxiety reactivity and change in heart rate over time. The predicted trajectory for heart rate based on low versus high anxiety reactivity is shown in Figure 4. Individuals with greater anxiety reactivity exhibited faster initial decreases in heart rate with the rate of recovery slowing over time. Despite this effect, probing of differences in heart rate at both the end of the CO₂ challenge ($t(44)=1.22$, $p=.23$) and end of recovery ($t(43)=-1.6$, $p=.12$) revealed no statistically significant differences. Post-hoc analyses examining the linear and quadratic effects of respiration rate on heart rate recovery were not significant suggesting that individual variations in respiration during the stressor were not associated with recovery in heart rate.

Discussion

The current study examined the relation between physiological and subjective components of the stress response in daily cigarette smokers. To investigate this association, the study first examined whether physiological reactivity to a CO₂ laboratory stressor, as indexed by heart rate, was related to recovery in the subjective response to stress, as indexed by self-reported anxiety. The reverse relation was also examined to investigate whether changes in self-reported anxiety during a stress task were associated with recovery in heart rate. This investigation has important implications for biobehavioral interventions because individual differences in integrated cognitive, affective, and physiological components of the stress response (Blascovich, 1992; Thayer et al., 2012) may differentially impact smoking behaviors.

The results of the growth curve models suggest that both baseline heart rate and heart rate reactivity had a significant effect on subjective recovery from stress in daily smokers. Smokers exhibiting a lower resting heart rate pre-stress or greater heart rate reactivity in

response to stress experienced faster initial decreases in anxiety during recovery that then slowed following a quadratic function. Overall, these results suggest that both lower resting heart rate and greater heart rate reactivity predicts faster, and perhaps more adaptive, subjective recovery to a laboratory stressor. These findings, although preliminary, suggest that a robust cardiovascular stress response in smokers may support emotion regulatory processes, and is aligned with extant work that has suggested vertical integration of the cardiovascular system and affective self-regulation (Schroeder et al., 2003; Thayer, Yamamoto, & Brosschot, 2010). Conversely, it has been suggested that limited flexibility in the physiological response to stress may indicate difficulty adapting to acute stressors, which may undermine successful self-regulation (i.e., heart rate variability; Park, Van Bavel, Vasey, & Thayer, 2013; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012).

For the reverse association, self-reported anxiety at baseline (i.e., pre-stressor) was not significantly associated with heart rate recovery. However, anxiety reactivity significantly predicted heart rate recovery. Again, it appears that a greater increase in anxiety from resting to post-stressor is associated with faster heart rate recovery, which slows over time. Individuals who reported a greater increase in anxiety pre- to post-stressor also evidenced lower heart rate at the end of recovery, although this difference did not reach statistical significance ($p=0.12$). These findings indicate that flexibility observed in physiological systems is reflected in the subjective response to stress.

These results add to the limited literature on individual differences in stress reactivity and recovery in adult smokers as well as the prospective relation between physiological and subjective components of stress. Extant research suggests that, as a group, smokers exhibit an attenuated physiological response to stress as compared to their response to neutral tasks, and compared to the stress response of never or previous smokers (Childs and de Wit, 2009; Ginty et al., 2014). The current findings suggest that there is in fact significant variation in the physiological and subjective response to stress within adult smokers, and that variation in these processes may be related. The results indicate that change in one domain during a stressful task significantly predicts rate of recovery in the other domain, and these findings resemble extant research conducted in non-smoking samples that demonstrated significant concordance between the physiological (e.g., heart rate) and subjective stress response (e.g., perceived stress (Oldehinkel et al., 2011) and negative affect (Wagh et al., 2010)). This significant prospective relation across domains supports models of stress that emphasize the integration of cognitive and physiological components of the stress response (Blascovich and Tomaka, 1996; Thayer et al., 2012). Therefore, how one appraises their experience may impact physiological recovery, and vice versa.

These results provide foundational evidence for future research examining the effects of individual differences in the physiological and subjective components of the stress response on smoking behavior. Prior research has conceptualized both a blunted or reactive response to stress as maladaptive (Childs and de Wit, 2009; Ginty et al., 2014). The current results suggest that a greater subjective and physiological response to stress predicts faster rates of recovery in the opposite domain post stress; however, because there were no significant mean differences in post-challenge heart rate or self-reported anxiety between groups, more research is needed to clarify whether a blunted response to stress does indeed predict the

increased likelihood of smoking maintenance or relapse in current smokers. This relation should also be examined using a multi-modal assessment of smoking behavior (e.g., smoking topography, self-reported urge to smoke, and behavioral smoking-reinforcement tasks) to examine the convergent validity of these measures in assessing changes in stress-precipitated smoking.

When considering the findings, a few limitations should be noted. First, the small sample size may have limited the ability to observe differences in post-recovery anxiety and heart rate. Second, the observed relations between stress reactivity and recovery were not compared to a control task or between smokers and non-smokers, making it difficult to explicate whether the observed patterns are unique to stress, or evidence of a general response pattern, and whether these responses are similar or distinct from previously observed relations in non-smokers (Oldehinkel et al., 2011; Schlotz et al., 2008; Waugh et al., 2010). Finally, additional research is needed for a nuanced examination of the effects of the sympathetic and parasympathetic nervous system on subjective recovery from stress. For example, we were unable to determine whether heart rate reactivity was primarily driven by sympathetic (e.g., ventricular contractility) or parasympathetic (e.g., vagal reactivity) systems because heart rate is dually influenced via both systems. Yet, these findings were observed after controlling for changes in respiration during the period of interest, suggesting the relation is not solely accounted for by respiratory sinus arrhythmia. Future work could further examine the role of heart rate variability, cardiac output, baroreceptor reflex, or respiratory sinus arrhythmia.

A few strengths should also be noted. First, the study selected for smokers without a current medical condition, including cardiovascular, endocrine, pulmonary, respiratory, or gastrointestinal illness, suggesting that the individual differences in physiology were not better explained by a preexisting condition. Further, respiration rate did not account for differences in recovery. Individual differences in pre-stress functioning and reactivity were then predictive of differences in recovery, which may hold significance for identifying moderators between smoking and risk for smoking maintenance and cardiovascular disease.

In conclusion, the current findings suggest that there are key individual differences in stress reactivity and recovery within smokers, and differences in reactivity may be predictive of recovery. It appears that adult smokers who exhibit greater reactivity in one domain exhibit greater responsivity to stress in the other domain followed by a faster rate of recovery. This observed relation may be important for understanding processes that maintain smoking or contribute to lapse, and additional research is needed to examine whether individual differences in stress reactivity and recovery prospectively predict time to lapse or changes in smoking motives. Future research should also examine the role of cognition and affect in stress responsivity and smoking behavior to identify potential mechanisms of change that could be targeted in biobehavioral interventions for smoking cessation.

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Figure 1.

Study Diagram. Heart rate and anxiety were assessed over the 10-minute baseline, 4-minute challenge, and 10-minute recovery period.

Figure 2.

The predicted change in subjective anxiety over the recovery period as a function of low and high baseline heart rate (i.e., 1 SD above and below the mean). The dashed line represents the trajectory for individuals with higher baseline heart rate.

Figure 3.

The predicted change in subjective anxiety over the recovery period as a function of low and high heart rate reactivity (i.e., 1 SD above and below the mean). The dashed line represents the trajectory for individuals with greater heart rate reactivity.

Figure 4.

The predicted change in heart rate over the recovery period as a function of low and high reactivity in anxiety (i.e., 1 SD above and below the mean). The dashed line represents the trajectory for individuals with greater reactivity in anxiety.

Table 1:

Zero-Order (or bivariate) correlations among baseline and challenge study variables.

Variable	1	2	3	4	5	6	M (SD)
1. Sex	1	.08	.04	.04	-.14	.14	46% Female
2. Age		1	.49**	.26	.06	.16	29.33 (11.92)
3. FTCD			1	.56**	.05	.15	4.00 (1.70)
4. Cigarettes per Day				1	-.16	-.19	19.91 (8.00)
5. Panic Disorder Status					1	.55**	34% PD
6. Negative Affectivity						1	23.45 (8.68)

Variable	7	8	9	10	11	12	M (SD)
1. Sex	.16	-.21	-.02	.16	.26	.14	46% Female
2. Age	.19	-.37**	.18	.26	-.27	.04	29.33 (11.92)
3. FTCD	.21	-.27*	.26	.45**	-.22	-.02	4.00 (1.70)
4. Cigarettes per Day	-.03	.12	.02	.12	-.25	-.03	19.91 (8.00)
5. Panic Disorder Status	.08	-.28*	-.003	.17	.13	.08	34% PD
6. Negative Affectivity	.46**	-.67**	-.07	.47**	.14	.31*	23.45 (8.68)

Variable	7	8	9	10	11	12	M (SD)
7. Withdrawal SXS	1	-.40**	-.24	.66**	-.13	-.004	7.34 (5.88)
8. Distress Tolerance		1	-.08	-.50**	-.10	-.11	3.60 (.902)
9. Baseline Heart Rate			1	<.01	-.05	-.34*	77.97 (11.57)
10. Baseline Anxiety				1	-.02	-.01	35.24 (25.64)
11. Heart Rate Reactivity					1	.44**	-.301 (7.95)
12. Anxiety Reactivity						1	1.09 (27.15)

Note:

* $p < .05$,** $p < .01$; Sex (0 = Male, 1 = Female) Panic Disorder Status (0= NO, 1=PD)

Table 2.

Prediction of recovery in anxiety from the CO₂ challenge as a function of time and heart rate reactivity.

Dependent Variable: SUDs for Anxiety	b	SE	df	t	p
Intercept	61.78	5.81	36	10.64	< .01
Baseline Anxiety	0.81	0.13	297	6.02	< .01
Baseline Heart Rate	-0.69	0.31	297	-2.21	0.03
Age	0.64	0.30	297	2.11	0.04
Heart Rate Reactivity	2.24	0.45	297	4.98	< .01
Time	-9.47	0.84	41	-11.37	< .01
Time × Baseline Heart Rate	0.19	0.07	297	2.67	<0.01
Time × Heart Rate Reactivity	-0.73	0.11	297	-6.92	< .01
Time ²	0.62	0.07	41	9.15	< .01
Time ² × Baseline Heart Rate	-0.01	0.006	297	-2.29	0.02
Time ² × Heart Rate Reactivity	0.05	0.009	297	5.69	< .01

Note: Heart rate reactivity was indexed by the residual scores from a linear regression of peak heart rate on baseline heart rate.

Table 3.

Prediction of recovery in heart rate from the CO₂ challenge as a function of time and anxious arousal.

Dependent Variable: Heart Rate	b	SE	df	t	p
Intercept	85.17	1.74	36	49.06	< .01
Baseline Heart Rate	1.03	0.09	302	11.55	< .01
Anxiety Reactivity	0.27	0.04	302	6.20	< .01
Time	-1.66	0.27	41	-6.17	< .01
Time × Baseline Anxiety	-0.0002	0.01	302	-0.02	0.99
Time × Anxiety Reactivity	-0.08	0.01	302	-7.62	< .01
Time ²	0.10	0.02	41	4.48	< .01
Time ² × Baseline Anxiety	-0.00007	0.0009	302	-0.08	0.94
Time × Anxiety Reactivity	0.005	0.001	302	6.42	< .01

Note: Anxiety reactivity was indexed by the residual scores from a linear regression of peak anxiety ratings on baseline anxiety ratings.