Patterns and individual differences in the coordination of sympathetic and parasympathetic nervous system activity during rest and acute stress tasks

David G. Weissman

Department of Psychology, Harvard University, Cambridge, MA

Wendy Berry Mendes

Department of Psychiatry, University of California, San Francisco, CA

Corresponding Author: David G. Weissman, Harvard University, William James Hall, 33 Kirkland Street, Cambridge, MA, 02138, phone: (617) 496-1581

Abstract

Autonomic nervous system (ANS) activity is a core and central component of emotion. The myriad social and cognitive challenges faced by humans require flexible modulation of ANS activity for different contexts. In this study, simultaneous activity of the parasympathetic and sympathetic nervous system was measured using respiratory sinus arrhythmia (RSA) and pre-ejection period (PEP), respectively. Samples combined four previous studies (N=325) in which RSA and PEP were collected continuously during a resting baseline and an acute stressor, the Trier Social Stress Task. The concurrent relation between RSA and PEP responses was modeled in order to determine the extent to which SNS and PNS activity is coordinated at rest, in response to a stressor, and during recovery, and whether this coordination was moderated by age, race, sex, or baseline RSA and PEP. Overall, RSA and PEP were reciprocally coupled within task periods, perhaps reflecting shared regulatory mechanisms in the brain, independent of reciprocal responses to environmental demands. However, recovery from a stressor was characterized by uncorrelated activity and coactivation on average. Individuals also vary in the extent to which their SNS and PNS are reciprocally coupled; women, younger adults, and individuals with higher baseline RSA showed more reciprocal coupling than men, older adults, and those with lower baseline RSA, respectively, perhaps reflecting a greater range of physiological responding in the former group.

Introduction

Autonomic nervous system activity is a core and central component of the emotional response, although the centrality and specificity of autonomic responding as it relates to emotion and stress reactions are still topics of considerable debate and disagreement (Barrett, 2006; Friedman, 2010). Autonomic activity can be measured by a variety of different measures, which, with varying degrees of mechanistic specificity, index the level of bodily arousal in response to a physical or mental task. Common notions of the function of the sympathetic nervous system (SNS) refer to it as the "fight or flight" system, suggesting that its activity contributes to high arousal, active states, whereas the parasympathetic nervous system (PNS) is referred to as the "rest and digest" system, suggesting an association between its activity and relaxation and restorative processes. However, the extent to which these two systems function on a single continuum or a more complex dynamic interplay is the subject of influential theorizing, and warrants systematic investigation.

Autonomic Space

The SNS and PNS seemingly opposite roles may lead one to assume that their activity functions along a single-axis continuum. However, the autonomic space model (Berntson, Cacioppo, & Quigley, 1991) suggests that the autonomic nervous system is not an unidimensional, dichotomous system in which the activity of the SNS and PNS are universally reciprocal – when one activity in one system increases activity in the other system decreases. Instead, depending on the situation and individual differences, the two branches can shape peripheral responses, in particular heart rate (HR) through multiple forms of coordinated and uncoordinated activity, which can be represented as points in a two-dimensional state space

(Figure 1). The possible activity patterns in this conceptualization include reciprocal patterns of activity, in which SNS and PNS activity are negatively correlated; SNS activation combined with PNS withdrawal leads to the reciprocal SNS state (top left) in which HR is elevated, while PNS activation combined with SNS withdrawal leads to the reciprocal PNS state (bottom right), in which HR is decreased. However, activity patterns can also be positively correlated, either through co-activation (top right) and co-inhibition (bottom left), leading to influences that counteract each other and therefore smaller changes in HR. Uncorrelated activity, through uncoupled increases or decreases in either system can also occur. This independent relationship between these two systems would allow for flexible modulation of somatic activity to meet diverse environmental demands. However, there are still gaps in our knowledge regarding how context and individual differences might influence these different relations between the two branches of ANS.

Because the heart is under tonic inhibition by the vagus nerve, the PNS has a greater range of possible effects on HR through increased or decreased activity. Thus, as would be expected by the law of initial values, higher baseline RSA is likely associated with greater magnitude of and variability in ANS responses to stress (Berntson et al., 1991; Rigoni, Morganti, & Braibanti, 2017). Polyvagal theory argues that this higher baseline vagal activity impacts socioemotional functioning by allowing for more flexible emotional reactivity and regulation (Porges, Doussard-Roosevelt, & Maiti, 1994).

Autonomic Responses to Stress

Autonomic responses are elicited when encountering and managing stressors (Allen & Crowell, 1989), an essential and unavoidable demand of daily life (Almeida, 2005) with consequences for emotion functioning and well-being (Serido, Almeida, & Wethington, 2004).

The Trier Social Stress Task (TSST; Kirschbaum, Pirke, & Hellhammer, 2008) is a laboratory stressor with robust, well documented effectiveness at inducing psychological distress and physiological stress responses (Allen, Kennedy, Cryan, Dinan, & Clarke, 2014), including a strong activation of the hypothalamic pituitary adrenal cortical axis (HPA: Dickerson & Kemeny, 2004). Traditionally, the TSST involves the participant planning and delivering a short speech to stoic evaluators, followed by a mental arithmetic task, then, in some cases, a recovery period.

PEP is a measure of the time between the electrical impulses that initiate ventricle contraction and the opening of the aortic valve, which is primarily initiated by the SNS. Decreases in PEP indicate an increase in SNS activity. Participants delivering evaluated speeches typically show and increase in heart rate and a decrease in pre-ejection period (PEP) relative to baseline (Cacioppo, Uchino, & Berntson, 1994).

RSA is a measure of high frequency heart rate variability in the respiratory frequency band that reliably indexes PNS control of the heart via the vagus nerve (Berntson, Cacioppo, & Quigley, 1993). The effect of the TSST on PNS activity is less consistent across studies (Allen et al., 2014). However, a meta-analysis found a small but significant (g=-.27*)* effect size of decreases in respiratory sinus arrhythmia (RSA), an indicator of PNS activity, during the speech part of the TSST (Shahrestani, Stewart, Quintana, Hickie, & Guastella, 2015), although it is possible that simply speaking itself in the absence of social stress or evaluation may alter RSA (Cacioppo et al., 1994).

In one study, in which RSA and PEP were measured simultaneously during the TSST in a sample of adult women, the between-subjects correlations of RSA and PEP with HR were negative and positive, respectively, while the correlation of RSA with PEP was low to moderate and not significant in a relatively small sample size (Cacioppo et al., 1994). The lack of a strong between-subjects relation between RSA and PEP reactivity during social stress suggests that the relative magnitude of SNS and PNS influence on the heart might be variable between people. Further, while evidence from pharmacological blockade of the SNS and PNS in the same sample suggests that the influence of the SNS and PNS on heart period responses to orthostatic stress (i.e. standing vs. sitting) are reciprocal, their influence on heart period responses to the TSST is uncorrelated (Cacioppo et al., 1994a, 1994b), suggesting that SNS and PNS regulation of individuals' responses to social stress are orthogonal. Cross-situational, within person analyses of noninvasive measures of SNS and PNS functioning (PEP and RSA), such as through mixed effects modeling, can be revelatory in evaluating the nature of coordinated activity between the two systems as individuals navigate different situations.

Individual differences in autonomic responses to stress

Higher baseline PNS activity leads to more flexibility in PNS responding to environmental demands, allowing for a greater range of possible physiological states. In response to acute stressors, individuals with higher baseline RSA suppress RSA to a greater extent. However, recovery following the stressor, as indicated by the difference between RSA during the stressor and RSA during a subsequent relaxation or recovery period, might not be associated with baseline levels of RSA (Rigoni et al., 2017). Individual differences along trait dimensions show that people who endorse more of a "belief in a just world" tend to show more SNS activation to a stressor (Tomaka & Blascovich, 1994), as do participants higher (and stable) in self-esteem assessments (Seery, Blascovich, Weisbuch, & Brooke Vick, 2004). Older adults have been found to have larger decreases in both RSA and PEP during laboratory stressors than younger adults (Uchino, Uno, Holt-Lunstad, & Flinders, 1999; Uchino, Holt-Lunstad, Bloor, &

Campo, 2005), potentially indicating an increasingly reciprocal autonomic response to stress with increasing age and consistent with the general idea of less complexity in biological responses with older age (Lipsitz, & Goldberger, 1992). Females have been found to have higher resting heart rate variability (e.g. RSA) than males, despite having higher heart rates (Koenig & Thayer, 2016). Racial differences in ANS activity have also been observed, with black adult participants having higher baseline RSA than white participants (Dorr, Brosschot, Sollers, & Thayer, 2007; Kemp et al., 2016). However, aggregate levels of activity may not capture variability in dynamic responses across multiple systems. To our knowledge, the nature of coordinated responses in the PNS and SNS simultaneously has not been compared systematically as a function of participant age, sex, race, or baseline autonomic activity.

The Current Study

The current study combines data from four studies utilizing the TSST among adolescent and adult participants, diverse in age, race, and sex. In all studies, RSA and PEP were measured and data were binned in 1-minute increments during the five periods of the TSST 1) baseline, 2) speech prep, 3) speech, 4) mental math or question and answer, and 5) recovery. A total of 20 minutes of physiological data was examined for each subject. The resulting large sample size allows us to use multilevel modelling approaches to examine both within and between-subject effects on coordinated autonomic activity. This study aims to test the following hypotheses. 1) Despite some evidence to the contrary (Cacioppo et al., 1994b), we expect that, overall, RSA and PEP will be reciprocally coupled (i.e. positively correlated) during the TSST within individuals; 2) This pattern will vary based on the demands of the task, however. When the task is novel and activation is strongest – during the preparation and speech delivery time—reciprocal SNS activity is expected, whereas during the recovery period uncorrelated activity is expected, during what has been referred to as the “vagal rebound” (Mezzacappa et al., 2001; Page-Gould, Mendes, & Major, 2010); 3) There will be significant individual differences in the pattern of coupling. Given that higher baseline RSA is thought to indicate a greater capacity to flexibly modulate autonomic activity, participants with higher baseline RSA are expected to exhibit more reciprocal activity across the task. Whether individual differences in patterns of coupling are related to participant sex, race, and age, and whether those differences are independent of or mediated by baseline RSA was explored.

Method

Participants and Procedure

This study is a reanalysis of data from four previous studies where RSA and PEP were collected during the TSST. Exact procedures and details for each individual study are described elsewhere (Akinola & Mendes, 2008; Ayduk, Gyurak, Akinola, & Mendes, 2012; Mendes & Koslov, 2013; Page-Gould, Mendoza-Denton, & Mendes, 2014). A total of 325 adult participants completed the studies. For all four studies, the TSST consisted of a 5-minute baseline, either a 3- or 5-minute speech preparation, followed by a 7- or 5-minute speech, and ending with a 5 minute recovery period. In all studies, participants remained seated for all task periods and were instructed to refrain from postural changes. Speech preparation was entirely mental. No writing was permitted. In two of the studies the speech was followed by mental arithmetic, and in the other two, it was followed by a question and answer task. In two of the studies, half of the participants received positive affective responses from the evaluators (they smiled and nodded during the TSST compared to the standard TSST evaluator feedback which includes the evaluators scowling and shaking their heads). These participants were included, but positive feedback was included as a covariate in all between-subject analyses. Sex was not recorded as a variable in one of the studies (N = 67). Age and race were only recorded as variables in one of the studies that focused on race differences. This study included 68 black and 73 white participants, 79 female and 62 male participants. Mean age was 29.0 (*SD* = 10.7, Range 15 to 55).

Measures

Autonomic Nervous System

In all studies, electrocardiography (ECG100C) and impedance cardiography (HIC) were collected and integrated with an MP150 system (BIOPAC Systems Inc, Goleta, CA). Sensors to measure ECG were applied in a lead II configuration and impedance cardiography was obtained using four mylar bands that completely encircled the neck and chest area. A 1 mA AC current at 100 kHz was passed through the outer bands, and z0 and dZ/dt were recorded from the inner bands. All signals were filtered on-line and sampled at 1000 Hz.

RSA was edited and analyzed using the HRV (2.5) module from Mindware Technologies (Gahanna, OH). Visual inspection of the waveforms focused on detecting ectopic beats and accurate detection of R spikes in the ECG. HRV was scored in 1-minute bins. The HRV module detrended the data using a first order polynomial to remove the mean and any linear trends, cosine tapered the data, submitted it to Fast Fourier Transformation, and took the natural log integral of the high frequency power (.15–.40 Hz) as an index of RSA.

PEP was edited and analyzed using the IMP (3.0) module from Mindware Technologies (Gahanna, OH) to edit impedance data. Visual inspection focused on accurate Q, R, S placement in the ECG trace and accurate detection of the B-, X-, and Z-points (aortic valve opening, aortic valve closing, and dz/dt max, respectively) on the dZ/dT waveform. PEP was calculated as the time interval in ms between the Q-point of the ECG and the B-point of the dZ/dt signal. PEP was averaged over 1-minute bins. Baseline RSA and PEP were be calculated by taking the mean of the 5 baseline bins.

Analysis

RSA and PEP reactivity were standardized within subject. Four three-level mixed effects structural equation model were tested in MPlus. This approach to identifying variability in the degree of temporal covariation between two physiological signals is best suited for data in which the number of physiological observations per subject (25) is less than the number of subjects (325) (Helm, Miller, Kahle, Troxel, & Hastings, 2018).

Models 1 and 2 were tested in all 325 participants. Model 1 tested the relation between task period and RSA-PEP coupling. Model 1 is an intercept only model, so participant j's coupling during task period k (S_{jk}) is defined at level 1 as $S_{jk} = S_{j0.}$ The relation between task period and coupling is then estimated at level 2 as:

$$S_{j0} = S_0 + \gamma_1{*}\text{prep} + \gamma_2{*}\text{speech} + \gamma_3{*}\text{math} + \gamma_4{*}\text{QA} + \gamma_5{*}\text{recovery}$$

Each of the variables "prep," "speech," "math," "QA," and "recovery" is a dichotomous variable representing the task period. The intercept S_0 therefore is equal to coupling during the baseline period, and γ_1 to γ_5 represent the difference in coupling relative to baseline. S_0 is the random of the relation between within-subject standardized RSA and within-subject standardized PEP and is therefore derived via the equation:

$$\text{RSA} = S_0{*}\text{PEP}$$

In Model 2, levels 2 and 3 were the same as in Model 1, but Model 2 estimated the relation between individual and study-level characteristics and RSA-PEP coupling, so in Model 2, participant j's coupling during task period k (S_{jk}) is defined at level 1 as

$$S_{jk} = S_{j0} + \beta_1{*}\text{Study2} + \beta_2{*}\text{Study3} + \beta_3{*}\text{Study4} + \beta_4{*}\text{Positive} + \beta_5{*}\text{RSAb} + \beta_6{*}\text{PEPb}$$

Each of the variables "Study2" to "Study4" is a dichotomous variable indicating whether the participant was part of that study. "Positive" is a dichotomous variable indicating if the feedback subjects received from evaluators was positive, instead of neutral. "RSAb" is the participant's (grand mean centered) baseline RSA, and "PEPb" is the participant's (grand mean centered) baseline PEP. The intercept S_{j0} therefore is an estimate of coupling of participants in the reference study, who received neutral feedback, with average baseline RSA and PEP.

Model 3 was estimated in the 258 participants whose sex was recorded. In addition to the parameters in Model 2, the relation between participant sex and RSA-PEP coupling and between sex and baseline RSA, and the indirect effect of sex on RSA-PEP coupling via baseline RSA were also estimated.

Model 4 was tested only among the 131 participants for whom we had variability in race and age. In addition to the parameters of Model 2, the relations between this RSA-PEP coupling and baseline RSA, baseline PEP, sex, race, and age were calculated. Paths were also included from sex, race, and age to baseline RSA and PEP. MPlus code for all analyses can be found at github.com/dgweissman/autonomic-balance.

Results

Mean autonomic activity

Mean baseline RSA was 6.74 (units = $\ln[\text{ms}^2]$; *SD* = 1.22) . Mean baseline PEP was 118.4 (*SD* = 21.0). On average, participants' RSA was significantly lower than baseline during the prep (M_{Dif} = -0.50, *S.E.* = 0.049, t = -10.31, p<.001), speech (M_{Dif} = -0.44, *S.E.* = 0.044, t = -10.04, p<.001), math (M_{Dif} = -0.35, *S.E.* = 0.052, t = -6.80, p<.001), and Q&A (M_{Dif} = -0.39, *S.E.* = 0.068, t = -5.79, p<.001), and significantly higher than baseline during recovery (M_{Dif} = 0.12, *S.E.* = 0.046, t = 2.62, p=*.009*). PEP was significantly lower than baseline during prep

(M_{Dif} = -14.1, *S.E.* = 0.32, t = -44.59, p<.001), speech (M_{Dif} = -11.8, *S.E.* = 0.28, t = -11.80, p<.001), math (M_{Dif} = -11.2, *S.E.* = 0.34, t = -32.94, p<.001), Q&A (M_{Dif} = -6.6, *S.E.* = 0.44, t = -14.84, p<.001), and recovery (M_{Dif} = -3.9, *S.E.* = 0.30, t = -12.96, p<.001). Results are summarized within each of the 4 studies in Table 1. Figure 2 depicts these results plotted in a 2-dimensional state space.

At baseline, female participants (d = .32, t = -2.35, p = .020), black participants (d = .33, t = 1.96, p = .05), and younger participants (r = -.50, p<.001) had higher RSA than males, whites, or older participants, respectively.

RSA-PEP coupling

RSA-PEP coupling at baseline across all participants, regardless of the study or type of feedback received was significant and positive (B = .22, *S.E.* = .031, t = 7.049, p < .001). RSA-PEP coupling did not differ significantly from baseline during preparation, (B = -.009, *S.E.* = .042, t = -.22, p = .324), speech (B = -.044, *S.E.* = .044, t = -1.00, p < .316), or math (B = -.040, *S.E.* = .054, t = -.75, p = .824). Rerunning the model with each as the reference group revealed that RSA-PEP coupling was also significantly greater than 0 during each of the preparation, speech, and math periods. RSA-PEP coupling was significantly lower during the recovery (B = -.182, *S.E.* = .045, t = -4.03, p < .001) and Q&A periods (B = -.245, *S.E.* = .079, t = -3.09, p = .002). Rerunning the analyses with each as the reference group revealed that RSA-PEP coupling did not differ significantly from 0 during either the recovery or Q&A period.

Individual differences in RSA-PEP coupling

RSA-PEP coupling was significantly more reciprocal for participants with higher baseline RSA in the full sample (Figure 3) and for females among the 258 participants for whose sex had been recorded (Figure 4), but baseline PEP was not significantly associated with RSA-

PEP coupling. Females also had significantly higher baseline RSA. The indirect effect of female sex on RSA-PEP coupling via baseline RSA (Figure 4) was significant (*B* = .03; *SE* = .014; *p* = .029), indicating that more reciprocal RSA-PEP coupling among females is partially due to them having higher baseline RSA. However, female sex still significantly predicted more reciprocal RSA-PEP coupling, accounting for the effects of baseline RSA.

Among the 131 participants with variable age, race, and sex, coupling was significantly more reciprocal for females, younger participants, and participants with higher baseline RSA (Figure 5). The association between age and RSA-PEP coupling was fully mediated by younger participants having higher baseline RSA (Indirect effect = -.004; *SE* = .002; *p* = .012). The associations between race and RSA-PEP coupling and between race and baseline RSA were not significant when accounting for the effects of age, sex, and baseline ANS activity. Results of sensitivity analyses controlling for the within subject, within task period effects of respiration rate on RSA and PEP did not differ meaningfully.

Discussion

This study investigated the nature of variability and flexibility in SNS-PNS coupling between and within individuals at rest, and in response to an acute stressor. The results indicate that the SNS and PNS are reciprocally coupled with one another at rest and in response to stressors. Increases in SNS activity tend to be associated with decreases in PNS activity. This reciprocal activity is due to both opposite response patterns to acute stress, but also exist within-situations (e.g. task periods) in which stress exposure is comparable, perhaps reflecting shared control mechanisms in the central nervous system. Conversely, certain states, in particular recovery following an acute stressor, seem to be characterized by uncorrelated activity. In fact, on average, RSA was higher than baseline, and PEP was shorter than baseline during the recovery period, indicating coactivation of the SNS and PNS. Moreover, individuals differ in the strength of their SNS-PNS coupling. Specifically, females and those with higher baseline RSA have more reciprocal SNS-PNS coupling across the TSST.

Across four studies, the SNS and PNS were reciprocally coupled, such that increases in SNS activity, whether they are stimulus-independent endogenous fluctuations at rest, or responses to an acute stressor, tend to be associated with decreases in PNS activity. This is evidenced by the significant positive within-person relation between PEP and RSA across the TSST, even accounting for differences in PEP and RSA between the parts of the task, and by the significant positive relation between PEP and RSA during the baseline, prep, speech, and math periods of the TSST. These reciprocal associations may reflect shared mechanisms of autonomic regulation in the brain. Regions in the brain’s central autonomic network have been found to regulate both the PNS and the SNS. In particular, amygdala activation leads to increases in SNS activity and decreases in PNS activity through activation or disinhibition of sympathoexcitatory neurons in the rostral ventrolateral medulla, and inhibition of vagus nerve activity through the nucleus ambiguus (Thayer & Lane, 2009), and activity in the ventromedial prefrontal cortex has been found to have an inhibitory influence on the amygdala and to lead to increases in PNS activity and decreases in SNS activity (Thayer & Lane, 2009; Zhang et al., 2014). Therefore, while we do find that RSA-PEP coupling is flexible, varying depending on the environmental demands, as predicted by the autonomic space model (Berntson et al., 1991), we also find evidence of a tendency toward reciprocal activation within task periods, including baseline, perhaps reflecting these shared mechanisms of regulation independent of the response to a stressor.

During recovery from an acute stressor, the SNS and PNS were uncorrelated and coactive on average. RSA and PEP were not significantly coupled during the recovery and Q&A portions of the acute stressor. During recovery, RSA was significantly higher than baseline on average, whereas PEP was significantly lower, suggesting coactivation. Taken together, these results suggest that while SNS activity may be slow to return to baseline following a stressor, PNS activity may be augmented to promote recovery, consistent with previous observations of “vagal rebound” (Mezzacappa et al., 2001; Page-Gould et al., 2010). This suggests that certain environmental demands may be associated with non-reciprocal responses from the two autonomic branches, possibly to support flexibility in responding in an uncorrelated manner in response to those demands.

We also observed that individuals differed in the extent to which SNS and PNS activity were reciprocally coupled across the TSST. Females, younger adults, and individuals with higher baseline RSA have more reciprocally coupled SNS and PNS activity. Females and younger adults also had higher baseline RSA on average. Sex but not age differences in RSA-PEP coupling remained significant when accounting for the relation with baseline RSA. Individuals with higher baseline RSA are hypothesized by polyvagal theory to have more flexibility in emotional responses due to a greater range of potential physiological states (Porges et al., 1994). Indeed, higher baseline RSA has been shown to be related to greater decreases in RSA in response to social stressors (Rigoni et al., 2017), as would be expected by the law of initial values (Berntson et al., 1991). This may lead to more reciprocal coupling, as increases in SNS activity indicated by shorter PEP may be accompanied by greater reciprocal PNS withdrawal in individuals with higher baseline RSA. Similarly, the combination of higher baseline RSA, longer baseline PEP, and more reciprocal coupling for females presents a physiological profile with a broader range of physiological reactivity, but also a more consistent, reciprocal relationship between the SNS and PNS.

Limitations and Future Directions

While this study has many strengths, including a large sample size combined across several studies using the same acute stressor, it does have some limitations that raise outstanding questions for future research. First, because of inconsistency in demographic, mental health, and other individual difference variables collected across the studies, we were limited to sex and baseline autonomic activity as indicators of potential individual differences in multiple studies. Our power was therefore limited to detect possible age and race-related differences in RSA-PEP coupling. Future work examining RSA-PEP coupling with larger samples and in relation to characteristics of emotion functioning like mental health and emotion regulation could further illuminate how the extent to which SNS and PNS activity are coordinated and may vary between individuals and contribute to emotion functioning. Further, while the studies included all used the TSST, protocols were similar, and differences were controlled for statistically, inconsistencies nonetheless existed. For example, a Q&A period replaced the math task in studies that used positive feedback because mental arithmetic typically results in a diverting of attention away from the evaluators (looking away, closed eyes). Nevertheless it was interesting to observe that less coupling was observed in the Q&A task, especially given this task was associated with less overall SNS activation than the speech or math task. Replication in large sample size studies with consistent protocols could reinforce the findings of these analyses. In addition, while not necessarily a limitation of the study, as 1 minute epochs are common and reliable units of analyses in ANS research, and using shorter epochs has costs for the reliability of the measurement of RSA especially (Beauchaine et al., 2019; Berntson et al., 1997), the length of the epochs used here to reflect coupling likely impacts the results to some extent, which may make it more difficult to generalize these results to future work that uses different epoch lengths. Future work should examine the temporal dynamics of ANS control at different levels of temporal precision. Finally, response to and recovery from an acute social stressor is only a small slice of the complex social and emotional milieu that individuals navigate daily. Future work should evaluate SNS-PNS coupling across a broader range of social and emotional situations and inductions.

Conclusion

Through a reanalysis of data from four different studies, we present a coherent picture of the coordinated activity of the PNS and SNS at baseline and in response to an acute stressor. Overall, the SNS and PNS respond inversely to stress and are reciprocally coupled within task periods, perhaps reflecting shared regulatory mechanisms in the brain, independent of reciprocal responses to environmental demands. However, recovery from a stressor is characterized by uncorrelated activity and coactivation on average as the SNS recovers slowly, while PNS activity rebounds and augments to accelerate recovery. Individuals also vary in the extent to which their SNS and PNS are reciprocally coupled, with females, younger adults, and individuals with higher baseline RSA demonstrating more reciprocal coupling, perhaps reflecting a greater range of physiological responding.

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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

Allen, A. P., Kennedy, P. J., Cryan, J. F., Dinan, T. G., & Clarke, G. (2014, January 1). Biological and psychological markers of stress in humans: Focus on the Trier Social Stress Test. *Neuroscience and Biobehavioral Reviews*, Vol. 38, pp. 94–124. https://doi.org/10.1016/j.neubiorev.2013.11.005

Allen, M. T., & Crowell, M. D. (1989). Patterns of Autonomic Response During Laboratory Stressors. *Psychophysiology*, *26*(5), 603–614. https://doi.org/10.1111/j.1469-8986.1989.tb00718.x

Almeida, D. M. (2005). Resilience and Vulnerability to Daily Stressors Assessed via Diary Methods. *Current Directions in Psychological Science*, *14*(2), 64–68. https://doi.org/10.1111/j.0963-7214.2005.00336.x

Ayduk, O., Gyurak, A., Akinola, M., & Mendes, W. B. (2012). Consistency over flattery: Self-verification processes revealed in implicit and behavioral responses to feedback. *Social Psychological and Personality Science*, *4*(5), 538–545. https://doi.org/10.1177/1948550612471827

Barrett, L. F. (2006). Are Emotions Natural Kinds? *Perspectives on Psychological Science*, *1*(1), 28–58. https://doi.org/10.1111/j.1745-6916.2006.00003.x

Beauchaine, T. P., Bell, Z., Knapton, E., McDonough-Caplan, H., Shader, T., & Zisner, A. (2019). Respiratory sinus arrhythmia reactivity across empirically based structural dimensions of psychopathology: A meta-analysis. *Psychophysiology*, e13329. https://doi.org/10.1111/psyp.13329

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1991). Autonomic determinism: The modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. *Psychological Review*, *98*(4), 459–487. https://doi.org/10.1037/0033-295X.98.4.459

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., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., … Van Der Molen, M. W. (1997). Heart rate variability: Origins methods, and interpretive caveats. *Psychophysiology*, *34*(6), 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

Cacioppo, J. T., Uchino, B. N., & Berntson, G. G. (1994). Individual differences in the autonomic origins of heart rate reactivity: The psychometrics of respiratory sinus arrhythmia and preejection period. *Psychophysiology*, *31*(4), 412–419. https://doi.org/10.1111/j.1469-8986.1994.tb02449.x

Cacioppo, John T., Berntson, G. G., Binkley, P. F., Quigley, K. S., Uchino, B. N., & Fieldstone, A. (1994a). Autonomic cardiac control. II. Noninvasive indices and basal response as revealed by autonomic blockades. *Psychophysiology*, *31*(6), 586–598. https://doi.org/10.1111/j.1469-8986.1994.tb02351.x

Cacioppo, John T., Berntson, G. G., Binkley, P. F., Quigley, K. S., Uchino, B. N., & Fieldstone, A. (1994b). Autonomic cardiac control. III. Psychological stress and cardiac response in autonomic space as revealed by pharmacological blockades. *Psychophysiology*, *31*(6), 599–608. https://doi.org/10.1111/j.1469-8986.1994.tb02352.x

Dorr, N., Brosschot, J. F., Sollers, J. J., & Thayer, J. F. (2007). Damned if you do, damned if you don't: The differential effect of expression and inhibition of anger on cardiovascular recovery in Black and White males. *International Journal of Psychophysiology*. https://doi.org/10.1016/j.ijpsycho.2007.03.022

Friedman, B. H. (2010). Feelings and the body: The Jamesian perspective on autonomic specificity of emotion. *Biological Psychology*, *84*(3), 383–393. https://doi.org/10.1016/J.BIOPSYCHO.2009.10.006

Helm, J. L., Miller, J. G., Kahle, S., Troxel, N. R., & Hastings, P. D. (2018). On Measuring and Modeling Physiological Synchrony in Dyads. *Multivariate Behavioral Research*, 1–23. https://doi.org/10.1080/00273171.2018.1459292

Kemp, A. H., Koenig, J., Thayer, J. F., Bittencourt, M. S., Pereira, A. C., Santos, I. S., … Lotufo, P. A. (2016). Race and Resting-State Heart Rate Variability in Brazilian Civil Servants and the Mediating Effects of Discrimination: An ELSA-Brasil Cohort Study. *Psychosomatic Medicine*. https://doi.org/10.1097/PSY.0000000000000359

Kirschbaum, C., Pirke, K.-M., & Hellhammer, D. H. (2008). The 'Trier Social Stress Test' – A Tool for Investigating Psychobiological Stress Responses in a Laboratory Setting. *Neuropsychobiology*, *28*(1–2), 76–81. https://doi.org/10.1159/000119004

Koenig, J., & Thayer, J. F. (2016). Sex differences in healthy human heart rate variability: A meta-analysis. *Neuroscience & Biobehavioral Reviews*, *64*, 288–310. https://doi.org/10.1016/J.NEUBIOREV.2016.03.007

Mendes, W. B., & Koslov, K. (2013). Brittle smiles: Positive biases toward stigmatized and outgroup targets. *Journal of Experimental Psychology: General*, *142*(3), 923–933. https://doi.org/10.1037/a0029663

Mezzacappa, E. S., Kelsey, R. M., Katkin, E. S., Sloan, R. P., Sibolboro Mezzacappa, E., Kelsey, R. M., … Sloan, R. P. (2001). Vagal Rebound and Recovery From Psychological Stress. *Psychosomatic Medicine*, *63*(4), 650–657.

Page-Gould, E., Mendes, W. B., & Major, B. (2010). Intergroup contact facilitates physiological recovery following stressful intergroup interactions. *Journal of Experimental Social Psychology*, *46*(5), 854–858. https://doi.org/10.1016/j.jesp.2010.04.006

Page-Gould, E., Mendoza-Denton, R., & Mendes, W. B. (2014). Stress and coping in interracial contexts: The influence of race-based rejection sensitivity and cross-group friendship in daily experiences of health. *Journal of Social Issues*, *70*(2), 256–278. https://doi.org/10.1111/josi.12059

Porges, S. W., Doussard-Roosevelt, J. A., & Maiti, A. K. (1994). Vagal Tone and the Physiological Regulation of Emotion. *Monographs of the Society for Research in Child Development*, *59*(2/3), 167.

Rigoni, D., Morganti, F., & Braibanti, P. (2017). The Role of Baseline Vagal Tone in Dealing with a Stressor during Face to Face and Computer-Based Social Interactions. *Frontiers in Psychology*, *8*, 1986. https://doi.org/10.3389/fpsyg.2017.01986

Seery, M. D., Blascovich, J., Weisbuch, M., & Brooke Vick, S. (2004). The relationship between self-esteem level, self-esteem stability, and cardiovascular reactions to performance feedback. *Journal of Personality and Social Psychology*. https://doi.org/10.1037/0022-3514.87.1.133

Serido, J., Almeida, D. M., & Wethington, E. (2004). Chronic Stressors and Daily Hassles: Unique and Interactive Relationships with Psychological Distress. *Journal of Health and Social Behavior*, *45*(1), 17–33. https://doi.org/10.1177/002214650404500102

Shahrestani, S., Stewart, E. M., Quintana, D. S., Hickie, I. B., & Guastella, A. J. (2015). Heart rate variability during adolescent and adult social interactions: A meta-analysis. *Biological Psychology*, *105*, 43–50. https://doi.org/10.1016/j.biopsycho.2014.12.012

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart-brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, Vol. 33, pp. 81–88. https://doi.org/10.1016/j.neubiorev.2008.08.004

Tomaka, J., & Blascovich, J. (1994). Effects of Justice Beliefs on Cognitive Appraisal of and Subjective, Physiological, and Behavioral Responses to Potential Stress. *Journal of Personality and Social Psychology*. https://doi.org/10.1037/0022-3514.67.4.732

Uchino, B. N., Uno, D., Holt-Lunstad, J., & Flinders, J. B. (1999). Age-related differences in cardiovascular reactivity during acute psychological stress in men and women. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *54B*(6), 339–346. https://doi.org/10.1093/geronb/54B.6.P339

Uchino, Bert N., Holt-Lunstad, J., Bloor, L. E., & Campo, R. A. (2005). Aging and Cardiovascular Reactivity to Stress: Longitudinal Evidence for Changes in Stress Reactivity. *Psychology and Aging*, *20*(1), 134–143. https://doi.org/10.1037/0882-7974.20.1.134

Zhang, S., Hu, S., Chao, H. H., Ide, J. S., Luo, X., Farr, O. M., & Li, C. R. (2014). Ventromedial prefrontal cortex and the regulation of physiological arousal. *Social Cognitive and Affective Neuroscience*, *9*(7), 900–908. https://doi.org/10.1093/scan/nst064

Table 1: Summary of Autonomic Indices During the Trier Social Stress Test Across 4 Studies

Study	**Task Period**	**HP**		**RSA**		**PEP**	
		M	SD	M	SD	M	SD
1	Baseline	921.6	130.1	6.98	1.37	117.6	20.3
	Prep	724.8	123.1	6.91	1.61	103.3	21.7
	Speech	744.4	124.5	6.96	1.81	107.4	21.9
	Math	758.6	123.9	6.97	1.77	106.6	21.4
	Recovery	860.3	125.9	7.79	2.03	114.1	22.3
2	Baseline	897.2	124.0	6.69	1.26	118.8	15.0
	Prep	784.3	127.9	6.30	1.27	112.5	18.4
	Speech	759.0	107.9	6.19	1.17	110.0	17.8
	Q&A	784.0	111.4	6.17	1.12	115.7	16.7
	Recovery	819.9	131.6	6.46	1.19	116.5	16.1
3	Baseline	871.3	134.8	6.55	1.04	115.4	14.7
	Prep	725.8	133.8	6.14	1.17	102.2	17.2
	Speech	692.3	115.2	5.91	1.09	100.9	17.5
	Q&A	742.9	120.6	6.02	1.20	107.2	18.5
	Recovery	835.6	130.3	6.33	1.15	109.1	17.1
4	Baseline	923.5	157.6	6.63	1.16	125.1	13.4
	Prep	697.5	143.6	5.83	1.18	110.1	13.4
	Speech	710.5	142.0	6.09	1.06	113.9	12.5
	Math	743.8	152.4	6.21	1.04	114.2	12.8
	Recovery	833.4	156.5	6.26	1.10	121.3	12.7

Note: HP = heart period (milliseconds), RSA = respiratory sinus arrhythmia (ln[ms^2]), PEP = pre-ejection period (milliseconds)

Figure 1: Theoretical representation of autonomic activity as a 2-dimensional state space

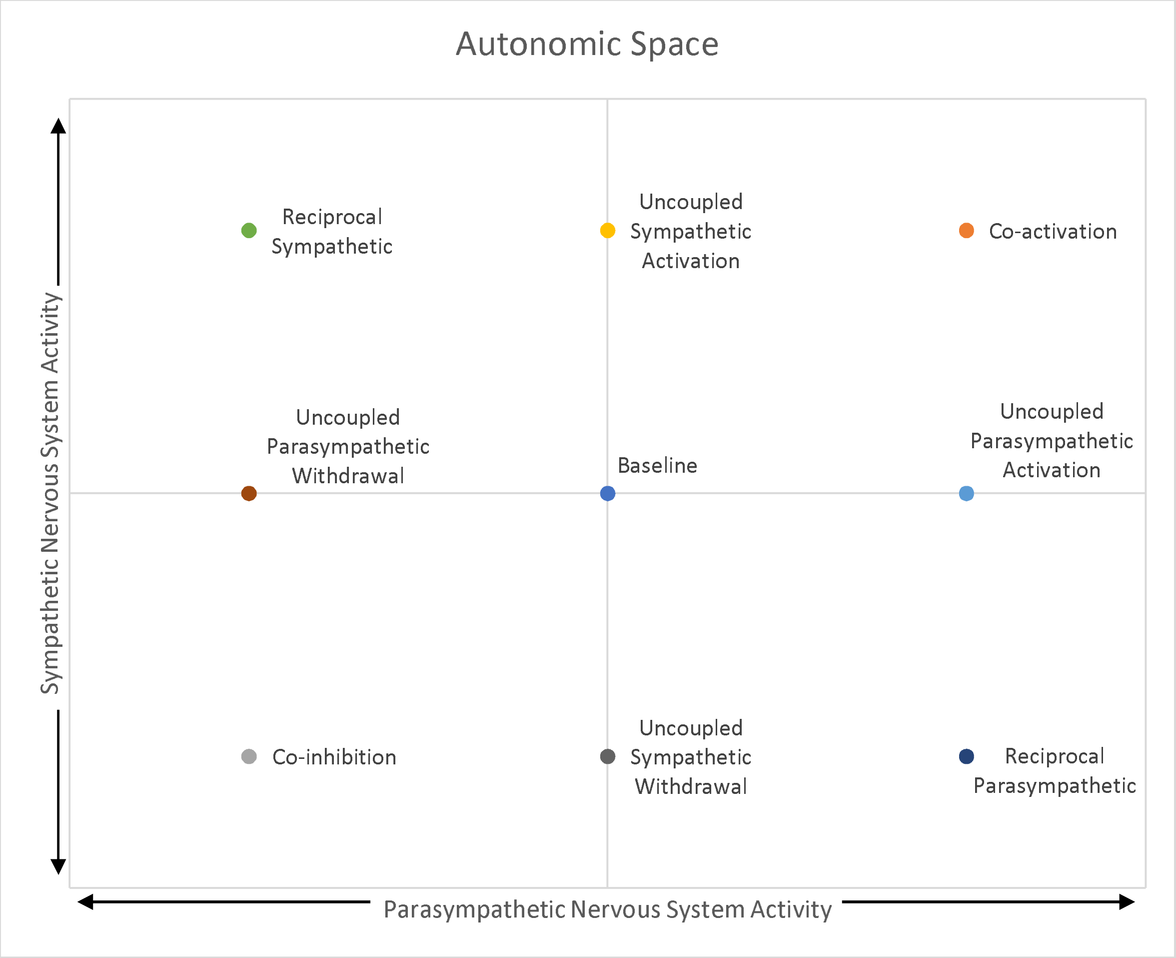

Figure 1: A representation of autonomic activity as a two-dimensional state space (Berntson et al., 1991)

Figure 2: Autonomic activity during the Trier Social Stress Task

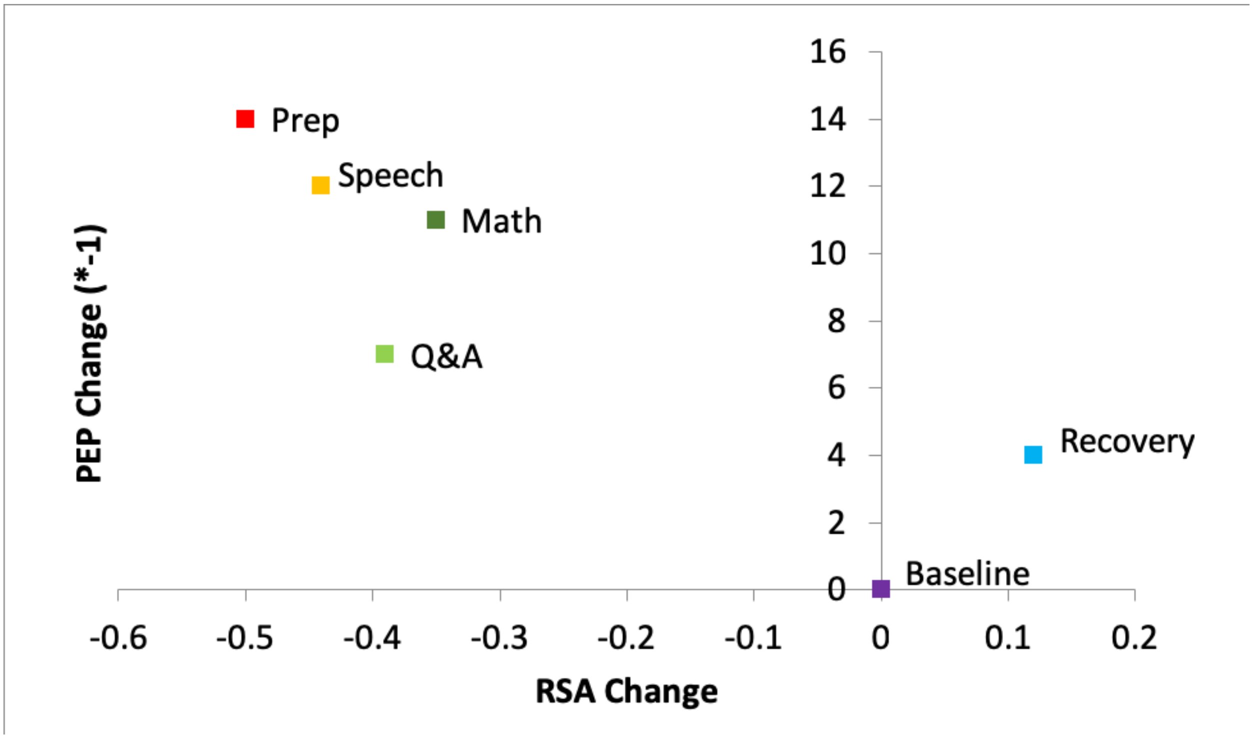

Figure 2: Mean autonomic activity during each part of the Trier Social Stress Task is plotted in a 2-dimensional state space.

Figure 3: Multilevel Structural Equation Model 2: Within and Between Person Influences on RSA-PEP coupling across 4 studies

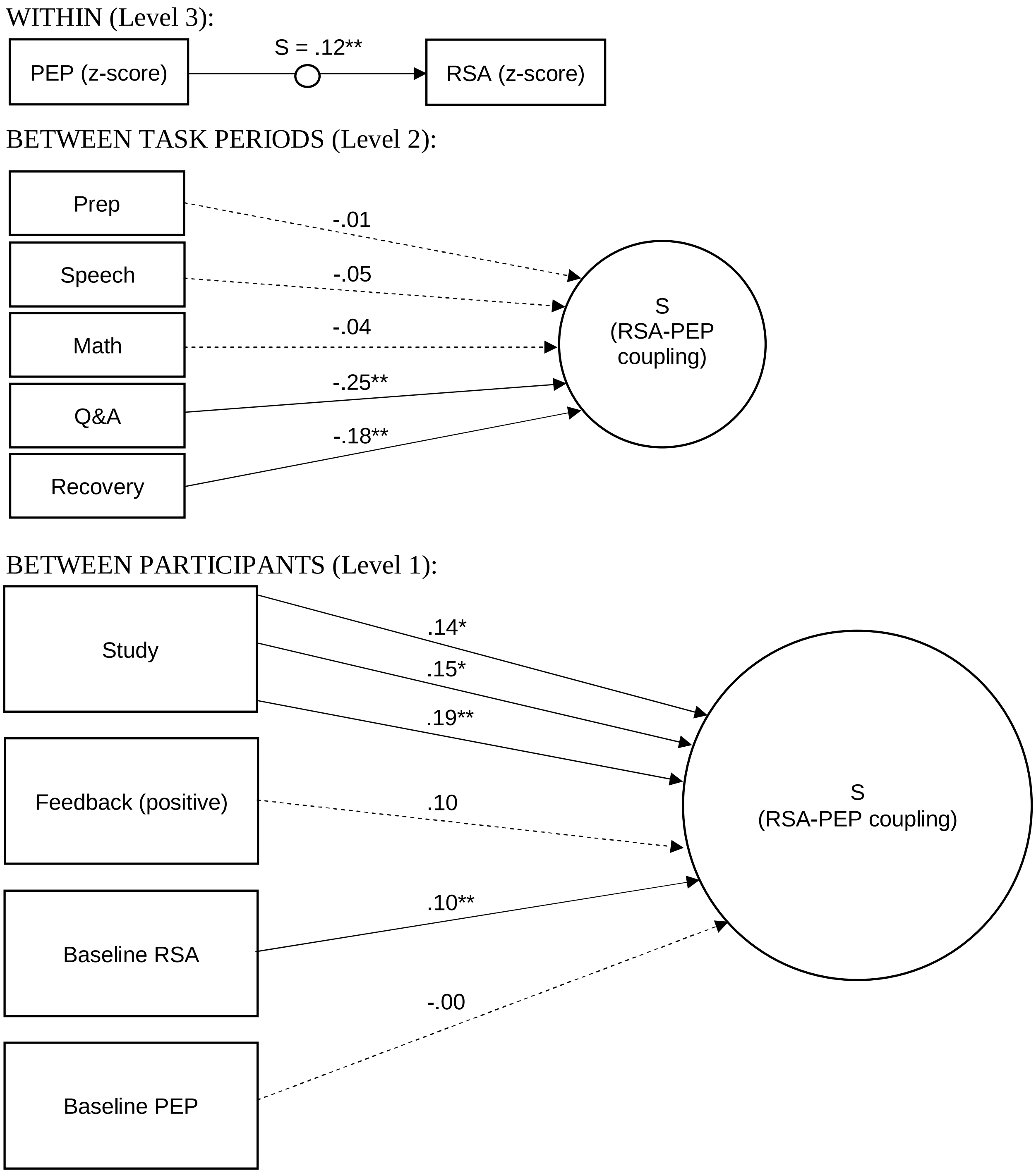

Figure 3: Results of three-level multilevel structural equation modelling of factors contributing to within-person and individual differences in RSA-PEP coupling (N=325). The random slope (S) of the relation between RSA and PEP, standardized within-subjects was used as a dependent variable on levels 1 and 2. Coupling during each task period relative to coupling at baseline was

evaluated on level 2. On level 1, “Study” refers to categorical variables for the 3 studies from which data was combined for this analysis. These separate variables were dummy coded, so each path represents the difference between patterns in one study relative to the reference study. “Feedback” represents whether, for that participant, confederate judges responded with positive (i.e. smiling) compared to with the traditional neutral expression. Coefficients are unstandardized. †p<.1, *p < .05, **p < .01.

Figure 4: Multilevel Structural Equation Model 3: Individual differences in RSA-PEP coupling across 3 studies based on sex and baseline autonomic activity

BETWEEN PARTICIPANTS (Level 1):

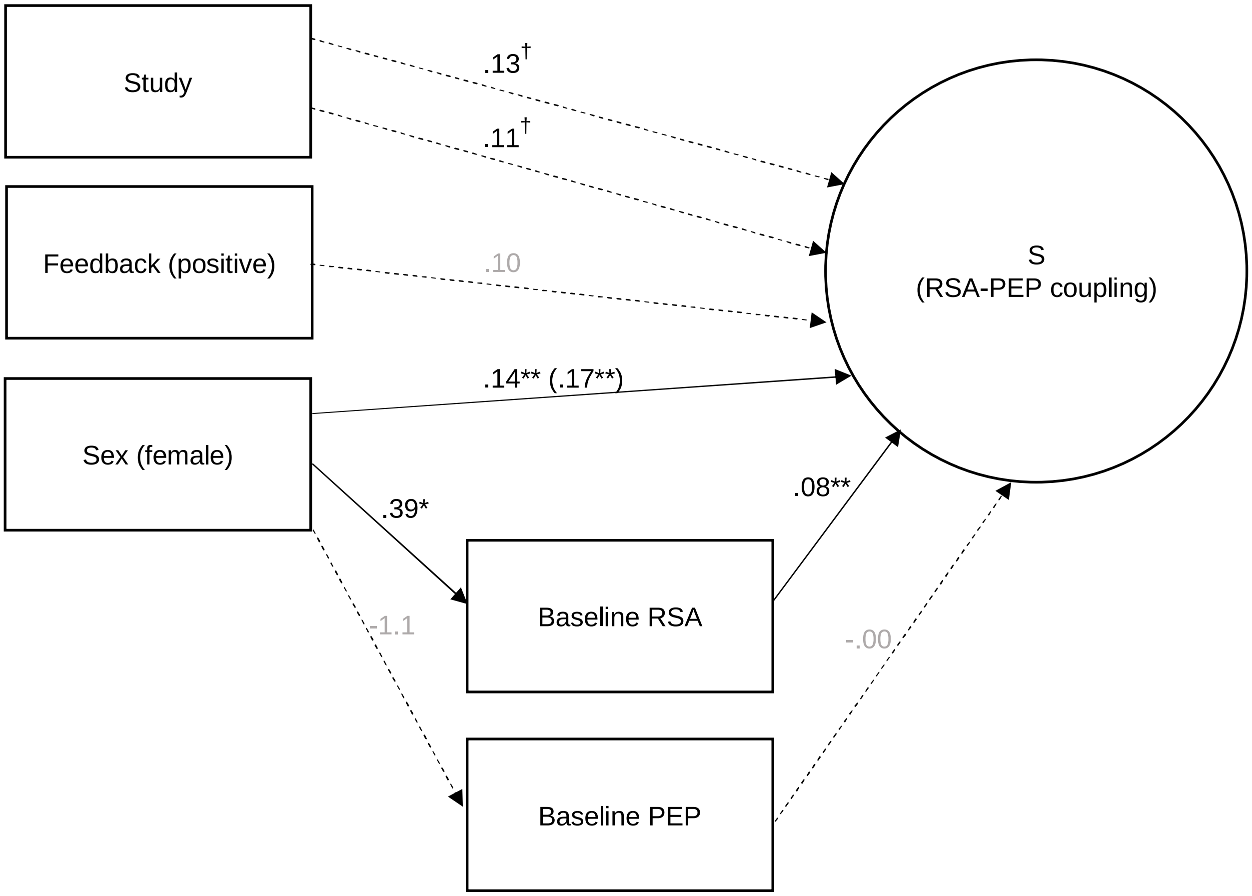

Figure 4: Results of three-level multilevel structural equation modelling of factors contributing to within-person and individual differences in RSA-PEP coupling (N=258). Levels 2 (between task periods) and 3 (within participant and task period) and of the model are not shown in this figure. The random slope (S) of the relation between RSA and PEP, standardized within-subjects (level 3) was used as a dependent variable in between participant (level 1) and between task period analyses. “Study” refers to categorical variables for the 3 studies from which data was combined for this analysis. These separate variables were dummy coded, so each path represents the difference between patterns in one study relative to the reference study. Participants from the 4th study had to be excluded due to missing data on sex. “Feedback” represents whether, for that participant, confederate judges responded with positive (i.e. smiling) compared to with the traditional neutral expression. Coefficients are unstandardized. . Solid lines indicate significant paths. Dotted lines indicate nonsignificant paths. †p<.1, *p < .05, **p < .01.

Figure 5: Multilevel Structural Equation Model 4: Individual differences in RSA-PEP coupling based on sex, race, age, and baseline autonomic activity

BETWEEN PARTICIPANTS (Level 1):

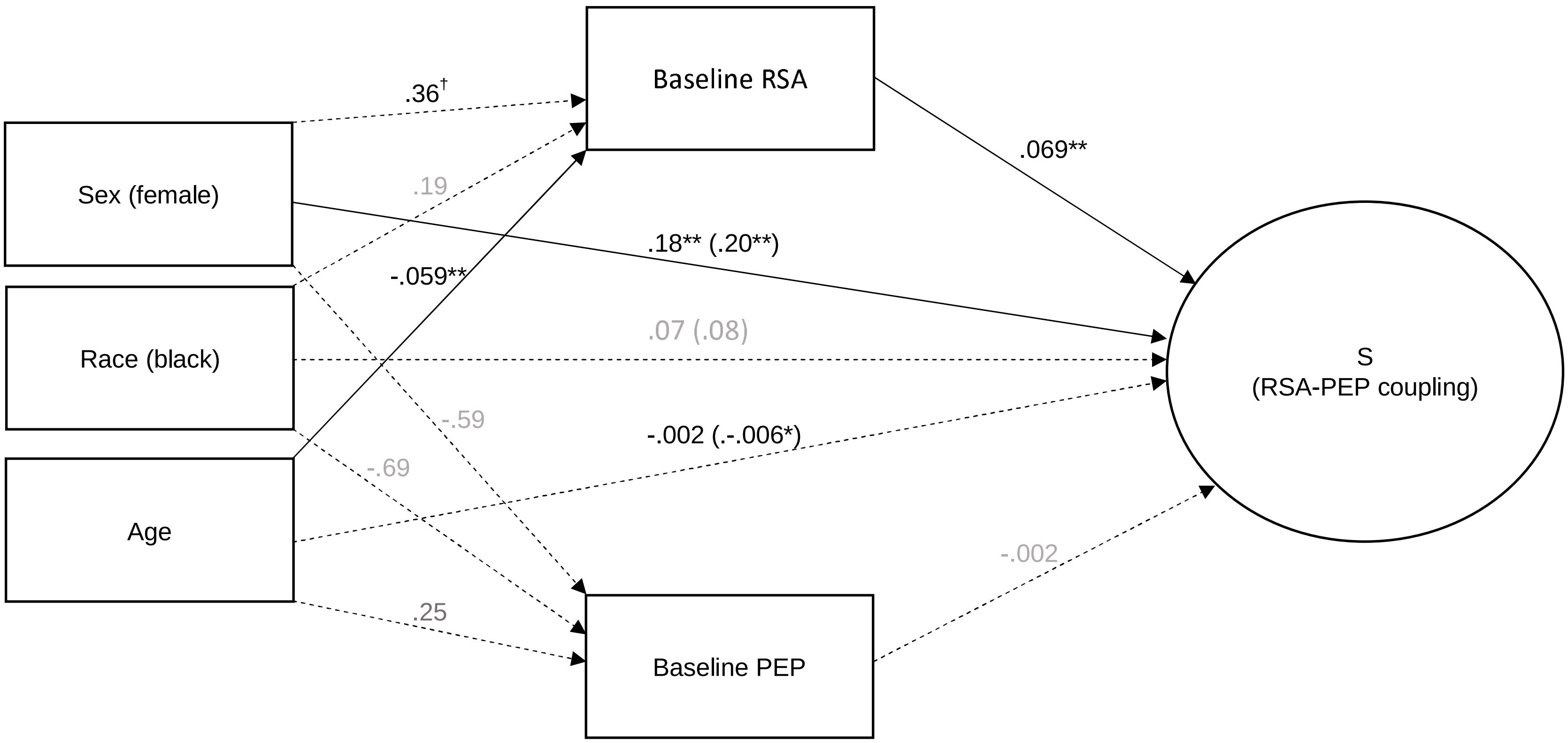

Figure 5: Results of multilevel structural equation modelling of factors contributing to individual differences in RSA-PEP coupling. Levels 2 (between task periods) and 3 (within participant and task period) and of the model are not shown in this figure. The random slope (S) of the relation between RSA and PEP, standardized within participants and task period (level 3) was used as a dependent variable in between participant (level 1) and between task period (level 2) analyses. Coefficients are unstandardized. Solid lines indicate significant paths. Dotted lines indicate nonsignificant paths. †p<.1, *p < .05, **p < .01.