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RESEARCH ARTICLE

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The implications of sympathetic and parasympathetic regulatory coordination for understanding child adjustment

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Abstract

The autonomic nervous system (ANS) is comprised of sympathetic and parasympathetic branches that control core adaptive systems, including cardiac regulation, across periods of rest, reactivity, and recovery. Despite their heavily intertwined functions, research examining the coordination of parasympathetic and sympathetic ANS regulation is limited. This study examined the effects of 6-year-olds' (N = 198; 49.5% female; 46% Latinx) capacity for ANS reactivity and recovery in both sympathetic (i.e., pre-ejection period [PEP]) and parasympathetic (i.e., respiratory sinus arrhythmia [RSA]) systems on their caregiver- and examiner-reported adaptability and attention problems at age 8. Results indicated that children's later adaptation was better accounted for by the coordination of their PEP and RSA activity than by either system in isolation. Children who evidenced optimal reactivity and recovery patterns, which entail reciprocal sympathetic and parasympathetic activity, evidenced more adaptability and fewer attention problems at age 8. In contrast, children who displayed discoordinated ANS reactivity patterns (e.g., high activation of both systems) or a total failure to recover (e.g., short PEP connoting high sympathetic activity and low RSA connoting low parasympathetic activity) evidenced poorer adjustment. These findings illustrate the incremental knowledge afforded by the joint consideration of both sympathetic and parasympathetic branches of ANS regulation in concert, as well as the importance of considering both ANS reactivity *and* recovery capacities for understanding adaptation.

KEYWORDS
adaptability, attention problems, autonomic nervous system, coordination, PEP, reactivity, recovery, regulation, RSA

1 | INTRODUCTION

Self-regulation is a "cornerstone" of the development (Shonkoff & Phillips, 2000) and a key contributor to psychological adjustment (Gross & Jazaieri, 2014; Kring, 2008). At the broadest level, self-regulation encompasses abilities to modulate behavior, cognition, emotion, and biology in accordance with contextual demands (Montroy, Bowles, Skibbe, McClelland, & Morrison, 2016; Posner & Rothbart, 2000; Vohs & Baumeister, 2016). Across these systems, emotion regulation, which refers to individuals' capacities to effectively organize, control, and express emotions, has received the bulk of theoretical and empirical consideration in prior studies of child adjustment (Cole, Martin, & Dennis, 2004; Gross, 2013; Posner & Rothbart, 2000). However, a sizable body of literature has also evaluated behavior regulation or the capacity to carry out appropriate observable behaviors while inhibiting situationally undesired responses (Blair, 2003; Ponitz, McClelland, Matthews, & Morrison, 2009). Only in the last 30 years, has the lens of empirical inquiry on self-regulation shifted to consider biological processes (see Gunnar & Vazquez, 2015; Vohs & Baumeister, 2016 for review).

Building on early studies examining global indices of physiological regulation, such as heart rate (Gannon, Banks, Shelton, & Luchetta, 1989), recent investigations have evaluated the contribution of excitatory (i.e., sympathetic) and inhibitory (i.e., parasympathetic) influences on cardiac function to elucidate the adaptive implications of physiological regulation on child development (Berry, Blair, Ursache, Willoughby, & Granger, 2014; Bornstein & Suess, 2000; Katz & Gottman, 1995). However, extant research in this area has typically evaluated sympathetic *or* parasympathetic regulation separately (Bagley & El-Sheikh, 2014; Brenner & Beauchaine, 2011; Calkins, Graziano, & Keane, 2007; Hastings & De, 2008), despite robust evidence that these systems act in concert to modulate physiological functioning (Berntson, Cacioppo, & Quigley, 1991; Berntson, Cacioppo, Quigley, & Fabro, 1994). To address this gap, the current study evaluated the individual and interactive contributions of both sympathetic and parasympathetic regulation to young children's adjustment.

1.1 | Autonomic nervous system (ans) regulation

Although there are multiple measures of physiological regulation (e.g., cortisol and electroencephalography), the ANS is particularly valuable as an accessible and time-sensitive index of the physiological stress response. As a core component of the peripheral nervous system, the ANS regulates multiple physiological systems, including internal organs, smooth muscles, pupil dilation, respiration, and heart rate (McEwen, 2007). Autonomic processes are coregulated by two complementary inputs—the sympathetic excitatory system and the parasympathetic inhibitory system. Ideally, these systems work in concert to mobilize flexible stress reaction *and* recovery. However, studies have primarily focused on each system in isolation rather than on their coordinated (or discoordinated) regulation. In part, this singular emphasis derives from unitary measures of either sympathetic excitation (e.g., alpha-amylase) or parasympathetic inhibition (e.g., pupil dilation).

The cardiac system affords the unique opportunity to examine both branches of ANS regulation as they operate in tandem to modulate heart rate. Indeed, in the earliest conceptualizations of cardiac regulation in the development, Bernston and colleagues argued for a dimensional model of sympathetic *and* parasympathetic influences to characterize ANS control (Berntson & Cacioppo, 2004; Berntson et al., 1991, 1994). In this view, they reasoned, the autonomic space is best conceptualized as a multidimensional rather than bipolar, continuum that flexibly responds to stimuli in either a reciprocal or a nonreciprocal fashion. More recently, contemporary models of adaptive calibration (Del Giudice, Ellis, & Shirtcliff, 2011) and biological sensitivity to context (Boyce & Ellis, 2005) further elaborated these ideas to consider physiological responses as multifaceted processes that determine our adaptive flexibility and environmental sensitivity, respectively.

Electrocardiograms and impedance cardiography enable researchers to assess individuals' pre-ejection period (PEP) as an indicator of sympathetic activity and respiratory sinus arrhythmia (RSA) as an indicator of parasympathetic activity across periods of rest, reaction, and recovery. PEP is a systolic time interval representing the elapsed duration from the beginning of electrical stimulation until the ejection of blood from the left ventricle (Berntson, Lozano, Chen, & Cacioppo, 2004). In situations that warrant cardiac mobilization, such as in response to a startling challenge, PEP intervals will shorten to facilitate an increase in the number of heart cycles per epoch (i.e., heartbeats). However, in situations that demand attentional engagement, such as reading this article, PEP will lengthen to enable a slow and regulated heart rate. RSA represents the naturally occurring variation in heart rate as a function of respiration and is thought to act as a brake or regulator of sympathetic excitation (Porges, 2007). In response to a startling challenge, RSA should decrease to reduce the inhibitory influence of the parasympathetic nervous system and allow for sympathetic mobilization. However, during a challenge that requires sustained attention, RSA should increase (i.e., more parasympathetic activation) to inhibit sympathetic activity (i.e., PEP will lengthen in duration), slow heart rate, and support attentional engagement. Thus, optimal physiological regulation entails the coordinated and reciprocal activation of sympathetic and parasympathetic influences to modulate cardiac function in accord with contextual demands. Given the potential salience of the degree of regulatory coordination for understanding adaptation, this study evaluated sympathetic and parasympathetic indicators of ANS regulation in concert.

In addition to adopting a multisystem perspective on physiological regulation, we also sought to consider the complexity of the regulatory response itself. In the context of a typical daily stressor, the regulatory trajectory begins with an organism at rest, followed by a deflection from resting baseline (i.e., reactivity), and a return toward resting baseline (i.e., recovery). As noted earlier, the specific expression of reactivity and recovery (i.e., the direction of deflection from baseline toward activation or inhibition) will vary by task demands. Likewise, the nature of recovery toward baseline will vary depending on the task demands as reactivity patterns should reverse in the wake of a challenge to restore homeostasis. Although rarely examined in the extant literature, recent findings suggest that the capacity to restore homeostasis, or recover from challenge, is an equally informative dimension of self-regulation (Beckmann & Kellmann, 2004), particularly with regard to the ANS (Obradović & Finch, 2016; Rudd, Alkon, & Yates, 2017). Thus, this investigation examined the implications of sympathetic *and* parasympathetic coordination with regard to cardiac reactivity *and* recovery for understanding children's adjustment.

1.2 | Ans regulation and child adjustment

Much of the early literature examining cardiac stress physiology focused on global indicators, such as heart rate and blood pressure, which reflect the integrated expression of both sympathetic and parasympathetic ANS influences (Gannon et al., 1989; Pfeifer et al., 1983). The advent of cardiography rendered individual studies of PEP and RSA possible, though the relatively greater difficulty of assessing PEP has led to a preponderance of data on RSA. Of the handful of PEP studies, most findings point to positive relations of elongated PEP at rest and appropriate PEP adjustments in response to challenge with children's psychosocial and behavioral outcomes (Brenner & Beauchaine, 2011; El-Sheikh, Erath, Buckhalt, Granger, & Mize, 2008; Kahle, Miller, Lopez, & Hastings, 2016; Keller & El-Sheikh, 2009). However, in a community sample of 235 11-year-olds, Bagley and El-Sheikh (2014) found that higher sympathetic reactivity (i.e., shortened PEP) in response to the Trier Social Stress Test was associated with poorer sleep quality and longer wake episodes. Studies of PEP recovery are notably absent from the current literature. RSA studies generally support positive associations between optimal parasympathetic regulation and positive adjustment outcomes (Berntson, Cacioppo, & Quigley, 1993; Butler, Wilhelm, & Gross, 2006; Calkins et al., 2007; Cipriano, Skowron, & Gatzke-Kopp, 2011; Gentzler, Santucci, Kovacs, & Fox, 2009), and recent studies of RSA recovery suggest that the capacity to return toward resting levels following a stressor is related to fewer behavior problems and positive executive functioning (Cui et al., 2015; Kahle et al., 2016; Miller et al., 2013; Obradović & Finch, 2016; Rudd et al., 2017).

Integrative investigations of both sympathetic and parasympathetic influences on cardiac function are scarce. This gap is particularly notable given that extant theory and research consistently demonstrate the importance of considering relations between systems, in addition to the dynamics of any one system (Flam & Powell, 2009; Gottlieb & Halpern, 2002; Marshall, 2013), and these ideas have been extended to models of ANS regulation (Berntson et al., 1991; Cacioppo, Berntson, Sheridan, & McClintock, 2000; Cacioppo, Gardner, & Berntson, 1997). Moreover, the few studies that have examined both sympathetic and parasympathetic regulation processes have typically measured each branch of the ANS using separate physiological systems. For example, in a study of 132 infants, Hill-Soderlund et al. (2008) found that children classified as having an insecure-avoidant attachment style evidenced higher sympathetic salivary alpha-amylase and higher parasympathetic RSA (i.e., regulatory discoordination) in response to the strange situation attachment assessment (see El-Sheikh et al., 2009; McLaughlin, Sheridan, Alves, & Mendes, 2014; Schmitz, Krämer, Tuschen-Caffier, Heinrichs, & Blechert, 2011 for additional examples of studies that draw on distinct regulatory systems to study sympathetic *and* parasympathetic activity). Although these studies highlight the value of looking at sympathetic and parasympathetic processes in tandem, doing so across systems is problematic because they operate on very different scales of time and measurement.

Only a handful of prior studies have examined PEP and RSA during a cardiac challenge paradigm (Neuhaus, Bernier, & Beauchaine, 2016; Quas, Carrick, Alkon, Goldstein, & Boyce, 2006), and still fewer have considered the meaning of regulatory coordination (Alkon, Boyce, Neilands, & Eskenazi, 2017; Boyce et al., 2001; Salomon, Matthews, & Allen, 2000). In a series of studies using a profile-based conceptualization of ANS coordination, Alkon and colleagues found that children exhibit increasingly coordinated autonomic profiles of reactivity across the first five years of life as the proportion of children with discoordinated profiles of co-activation or co-inhibition gradually declines, and the proportion of children with coordinated patterns of reciprocal activation increases (Alkon et al., 2014; Alkon, Boyce, Davis, & Eskenazi, 2011). Moreover, preliminary findings suggest that children with coherent profiles of ANS regulation (i.e., reciprocal sympathetic and parasympathetic activation patterns) evidence better sleep outcomes and less family conflict than those with incoherent patterns of co-inhibition or co-activation (Alkon et al., 2017; Salomon et al., 2000).

Although there are a number of approaches for considering the coordination of sympathetic and parasympathetic activation (e.g., the aforementioned profile approaches and cardiac autonomic balance/regulation; Bylsma et al., 2015), interactive models are particularly well suited to assess sympathetic and parasympathetic influences along the full continuum of activation and inhibition. For example, using skin conductance and RSA as sympathetic and parasympathetic indicators, respectively, El-Sheikh et al. (2008) found that a coordinated pattern of sympathetic inhibition and parasympathetic activation at rest (i.e., low skin conductance and high RSA) was associated with fewer concurrent delinquency problems among 8-year-olds drawn from homes that were high in marital conflict, whereas a discoordinated resting pattern of sympathetic activation (i.e., high skin conductance) and parasympathetic activation (i.e., high baseline RSA) was associated with higher levels of delinquency. Although El-Sheikh et al. (2008) did not use cardiac indices of PEP and RSA, which would assess these processes in a similar time frame, their interactive analytic approach supported the continuous examination of all four activation types (i.e., co-activation, co-inhibition, reciprocal sympathetic activation, and reciprocal parasympathetic inhibition). Further supporting a continuous interactive analytic approach, a recent study found that infants with discoordinated ANS profiles of cardiac regulation during an emotional audiotaped adult conflict challenge (i.e., sympathetic and parasympathetic co-activation or co-inhibition) were more likely to display heightened physical aggression two years later than were infants who exhibited coordinated ANS profiles (i.e., short PEP and low RSA; long PEP and high RSA; Suurland, van der Heijden, Huijbregts, Van Goozen, & Swaab, 2018). To our knowledge, no studies have examined associations between sympathetic and parasympathetic recovery processes and adaptation.

1.3 | The current study

This investigation employed an interactive analytic paradigm to evaluate the influence of sympathetic and parasympathetic ANS reactivity and recovery patterns on school-aged children's later adjustment. Specifically, we evaluated patterns of PEP and RSA reactivity *and* recovery at age 6 as related to caregiver reports of children's adaptability (i.e., the child's ability to adjust to changes and recover from setbacks) and both caregiver and examiner reports of attention problems (i.e., difficulty focusing on tasks) two years later. We chose to focus on children's adaptability and attention problems for two reasons. First, these adjustment indicators are likely to be influenced by ANS reactivity and recovery processes given their emphasis on capacities to recover from a personal setback, sustain work on a difficult school problem, and redirect attention following a distraction. Second, our focus on the early school years coincides with increasing social and attentional demands in the peer and classroom settings, which may enhance the salience of children's adaptability and attention regulation skills for understanding young children's adjustment.

We hypothesized that, in response to a startling challenge, the optimal regulatory response would entail sympathetic activation via shortening PEP and a reduction in parasympathetic inhibition via decreasing RSA. Following the startle, the optimal recovery pattern would feature both a decrease in sympathetic activation (i.e., PEP elongation) and a facilitative reapplication of parasympathetic inhibition (i.e., RSA augmentation). Thus, we predicted that reciprocal reactivity patterns of sympathetic activation and parasympathetic withdrawal would predict higher adaptability and fewer attention problems over and above potential main effect contributions of either system in isolation. Likewise, we predicted that reciprocal recovery patterns of sympathetic withdrawal and parasympathetic activation would predict higher adaptability and fewer attention problems over and above single-system main recovery effects. Finally, we controlled for family socioeconomic status, child race/ethnicity, and child sex in all analyses, given prior evidence that these covariates are associated with children's adjustment during the early school years (Abidin, Jenkins, & McGaughey, 1992; Pungello, Iruka, Dotterer, Mills-Koonce, & Reznick, 2009).

2 | METHOD

2.1 | Participants

Participants were 198 children (49.5% female, M_{age} = 6 years and 1 month, *SD* = 2.51 months) who completed a laboratory assessment of self-regulation and stress physiology as part of an ongoing longitudinal study of child development. The current sample was ethnically/racially diverse (43.9% Latinx, 18.7% African American/Black, 12.1% European American/White, and 25.3% multiracial) and representative of the surrounding community from which it was drawn (U.S. Census Bureau, 2011). All caregivers were female (91.9% biological mothers, 3.0% foster/adoptive mothers, and 5.0% grandmothers or other female kin caregivers). The majority of caregivers were married (61.6%) or in a committed relationship (18.8%), and just over half were employed (55.6%). Education levels were variable (e.g., 12.4% of caregivers had earned a 4-year degree). The average family SES score using the Hollingshead (1975) Four-Factor Index of Social Status was 33.41 (*SD* = 12.31), which corresponds to semiskilled employment (e.g., sales clerk).

Of the 198 children in these analyses, 184 (92.9%) completed a follow-up assessment two years later (M_{age} = 8 years and 3 months, *SD* = 4.0 months). Dyads who did not return for the follow-up visit did not differ significantly from those who did return on key study variables, including child sex, race/ethnicity, IQ, and SES (all $ps > 0.08$).

2.2 | Procedures

Flyers inviting participation in a "study of children's learning and development" were distributed to local child care centers. Caregivers were screened by phone to ensure the child was (a) between 3.9 and 4.6 years of age at the time the study began, (b) proficient in English, and (c) not diagnosed with a developmental disability. Dyads completed 3-hr laboratory assessments at ages 6 and 8, which consisted of measures with the child, the caregiver, and the caregiver and child interacting. Caregivers were compensated with $25/hour for their participation, and each child received a small gift. Written informed consent was obtained from the legal guardian at the beginning of each laboratory visit, and verbal informed assent was obtained from child participants. All procedures were approved by the University's Human Research Review Board.

2.3 | Measures

Child IQ was assessed at age 6 using the Vocabulary and Block Design subtests of the Wechsler Preschool and Primary Scale of Intelligence—III (Wechsler, 2002). Verbal IQ was measured using the Vocabulary test in which the child verbally explained what orally presented words meant. Performance IQ was assessed using the Block Design subtest in which the child was asked to assemble red and white blocks to match models. Estimated Verbal and Performance IQs were averaged to yield a prorated measure of Full Scale IQ (Sattler, 1988).

Autonomic nervous system regulation was assessed for the first time in this study at age 6 using measures of the child's PEP and RSA during rest, reactivity, and recovery phases of a startle task that we adapted from prior work (Talwar, Lee, Bala, & Lindsay, 2004). After spot electrodes were placed in a Lead II configuration on the child's chest, the child and caregiver were brought into a room where they were told they would be listening to a trained doctoral student examiner read aloud from the children's book, *Where the Wild Things Are* (Sendak & Schickele, 1963). The story task was completed in three consecutive parts to yield resting (i.e., examiner read the first five pages of the story in a neutral voice to the dyad; 2 min), startling challenge (i.e., examiner left and the caregiver followed previously provided instructions to trigger a loud noise that elicited the child's startle; 1 min), and recovery (i.e., examiner returned and read the remaining six pages of the story in a neutral voice; 2 min) episodes (See *author cite* for a full description of task procedures). Examiners were trained to ensure that the story content was presented at the same pace and with consistent and neutral intonation across all participants. Each task administration was behaviorally coded for separate analyses, as well as protocol deviations that undermined the validity of the paradigm (n = 2). The current protocol provided a novel startle challenge to assess ANS reactivity while supporting cognitively and motorically matched rest (pre-startle story listening) and recovery (post-startle story listening) ANS data collection episodes.

ANS data were collected using Mindware MW1000A ambulatory cardiography via Kendall Medi-Trace #133 spot electrodes. A 5-min calibration period after initial placement of the electrodes was included at the start of the ANS protocol. PEP data were extracted and scored using the IMP 3.0.3 analysis program (www.mindware.com) where the d*Z*/d*t* waveforms were used to obtain impedance-derived PEP measures quantified as the time interval in milliseconds from the onset of the ECG Q-wave to the B point of the d*Z*/d*t* wave (Berntson et al., 2004). RSA data were filtered, extracted, and scored using Mindware's HRV 3.0.10 analysis program. This technique utilizes the Mindware software algorithms to calculate the variance in R-R wave intervals. RSA scores were calculated using the interbeat intervals on the ECG reading, respiratory rates derived from the impedance (i.e., d*Z*/d*t*) signal, and a specified RSA bandwidth range for 6-year-olds of 0.15–0.80 Hz (Bar-Haim, Marshall, & Fox, 2000). Further data cleaning procedures for both PEP and RSA included screening for outliers (i.e. >3SD; Alkon et al., 2011) minute-by-minute in relation to each child's data pattern and deleting a child's data if more than 25% of their minutes were not scored. ANS values for all three regulatory phases were extracted in 1-min epochs across the 5-min task, yielding measures of pre-startle rest (the average of 2 min), startle challenge (1 min), and post-startle recovery (the average of 2 min).

Standardized residual ANS scores were analyzed to control for the influence of sample-specific resting baseline and challenge ANS values in measures of ANS reactivity and recovery, respectively. Residual ANS reactivity scores were derived from the regression of PEP and RSA values during the startle challenge task on PEP and RSA values during pre-startle rest, respectively. Residual ANS recovery scores were derived from the regression of PEP and RSA values during the post-startle recovery episode on PEP and RSA startle challenge values, respectively. Although ANS recovery can be indicated by regressing recovery values on resting values to assess the predicted rebound in consideration of the child's initial resting activation, our theoretical focus on children's capacity to recover from the startle context itself led us to evaluate residualized change from the level of activation during the startle episode. Indeed, if a child did not react to the startle, a residual based on resting values would suggest strong recovery, rather than the more accurate absence of a stress response and, by extension, an absence of recovery. Standardized residual scores assessed the extent to which each child's physiological response deviated from the regression line as an index of the child's relative change in PEP and RSA given their previous score as compared to the other children in the sample (Manuck, Kasprowicz, & Muldoon, 1990). Strong PEP and RSA reactivity was indicated by negative residual scores, which reflected a greater-than-expected shortening of the PEP interval (i.e., increased sympathetic activation) and a greater-than-expected reduction in RSA (i.e., decreased parasympathetic inhibition) in response to the challenge. Strong PEP and RSA recovery was indicated by positive residual scores, which reflected a greater-than-expected lengthening of the PEP interval (i.e., decreased sympathetic activation) and a greater-than-expected increase in RSA (i.e., increased parasympathetic inhibition) following the startle challenge.

Caregiver reports of child adaptability and attention problems were collected at age 8 using the Behavior Assessment System for Children, Second Edition (BASC-2; Reynolds & Kamphaus, 2004). The BASC-2 is a standardized measure of caregivers' ratings of children's behaviors, self-esteem, and adjustment abilities in the home and community from ages 2 to 25. Scores range from not true of my child (*0*), to somewhat/sometimes true of my child (*1*), and almost always true of my child (*2*). The Adaptability Scale is comprised of eight items that capture the child's ability to effectively adjust to new environments and unexpected changes (e.g., My child adjusts well to new teachers; My child is easily soothed when angry; α = 0.768). The Attention Problems Scale is comprised of 12 items (e.g., my child has a short attention span; my child is easily distracted; α = 0.867). Raw scores were scaled with respect to child age and sex and then converted to t-scores for all analyses.

Examiner reports of child attention problems were obtained at age 8 by a trained examiner who completed a report of the child's behavior using the Test Observation Form (TOF; McConaughy & Achenbach, 2004) immediately following the 3-hr laboratory assessment. The TOF is a standardized form for rating observations of behavior, affect, and test-taking style during assessments with children aged 2 to 18. Trained examiners rated the child's behavior on 125 problem items using a 4-point scale from no occurrence of the behavior (*0*); to very slight or ambiguous occurrence of the behavior (*1*); to a definite occurrence with mild to moderate intensity and frequency and less than three minutes total duration (*2*); and to a definite occurrence with high intensity, high frequency, or three or more minutes total duration (*3*). Raw scores were scaled with respect to child age and sex and then converted to t-scores for all analyses. Although not available from the single-rater data in this study, Achenbach, Rescorla, & Maruish, (2004) reported interrater reliabilities of r = 0.80 for the attention problems subscale and test–retest reliabilities of r = 0.81 in their validation sample. Moreover, they used a diverse sample to develop and validate the TOF, which has since been used as a single-rater observational report in similarly diverse samples (McConaughy, Ivanova, Antshel, & Eiraldi, 2009; Rettew, Stanger, McKee, Doyle, & Hudziak, 2006; Rudd et al., 2017; Sher-Censor, Khafi, & Yates, 2016).

2.4 | Data preparation

All analyses were performed in SPSS version 24. Data were examined for non-normality to render parametric statistics valid (Afifi, Kotlerman, Ettner, & Cowan, 2007). Follow-up data were missing for caregiver reports of adaptability and attention problems at age 8 (n = 19; 9.5%) and examiner reports of attention problems at age

8 ($n = 14$; 7.1%). We imputed missing values for outcome measures using the expectation-maximization (EM) algorithm as supported by Little's MCAR test; $\chi^2 = 185.714$, $df = 182$, $p = 0.410$. Multiple imputation using the EM algorithm is superior to prior approaches, such as listwise deletion, mean substitution, and imputation approaches with a limited number of iterations, because it estimates expected values from observed values through multiple iterations (up to 100) until the values stabilize to yield the best and most likely pooled estimate (Musil, Warner, Yobas, & Jones, 2002). A multivariate analysis of variance (MANOVA) evaluated group differences in study variables as a function of the child's sex, race/ethnicity, and their interaction. Correlational analyses assessed the bivariate relations among study variables.

Hayes' (2013) PROCESS routine evaluated individual and interactive relations between PEP and RSA as related to children's later attention problems and adaptability ratings. This routine represents an advance over traditional regression techniques because it employs a bootstrapping method to yield 95% confidence intervals for conditional effects while correcting for non-normality of predictors (Hayes, 2012). This correction is particularly important to account for nonignorable skew and kurtosis in the interaction terms. Separate models evaluated the effects of each regulatory phase (i.e., reactivity and recovery) on each of the adaptive outcomes. All data were standardized prior to analyses, which places all reported B values in standard deviation units (i.e., betas) to aid in the interpretation of the magnitude of effects.

3 | RESULTS

3.1 | Preliminary analyses

Paired samples *t* tests supported the validity of the startle paradigm by demonstrating a significant shortening of PEP (i.e., increased sympathetic activation) from pre-startle to startle ($t = 15.082$, $p < 0.001$) and a significant lengthening of PEP from startle to post-startle ($t = -14.081$, $p < 0.001$). Interestingly, there was also a significant difference between pre-startle and post-startle PEP values ($t = 6.467$, $p = 0.007$), suggesting that sympathetic activation did not return fully to pre-startle values following the challenge. Similarly, paired samples *t* tests showed a significant decline in RSA from pre-startle to startle ($t = 5.28$, $p < 0.001$), a significant increase in RSA from startle to post-startle ($t = -7.31$, $p < 0.001$), yet no significant difference between pre-startle and post-startle RSA values ($t = -0.951$, $p = 0.343$).

3.2 | Descriptive and bivariate analyses

As shown in Table 1, a MANOVA revealed no significant differences among study variables by child sex (Wilks' $\lambda = 1.344$, $p = 0.229$), race/ethnicity (Wilks' $\lambda = 0.989$, $p = 0.479$), or their interaction (Wilks' $\lambda = 0.881$, $p = 0.476$). As shown in Table 2, child IQ was positively related to family SES and negatively related to examiner-reported attention problems. Both PEP and RSA measures were

TABLE 1 Descriptive statistics for study variables by child gender and race/ethnicity

		Child Gender		Child Race/Ethnicity			
Variable	Total M (SD)	Male M (SD)	Female M (SD)	White M (SD)	Black M (SD)	Latinx M (SD)	Multi M (SD)
Child IQ	90.37 (12.21)	90.49 (12.01)	90.24 (12.47)	92.68 (11.63)	88.81 (11.32)	89.77 (12.32)	91.45 (13.01)
Family SES	33.41 (12.31)	31.76 (12.07)	35.09 (12.39)	39.00 (15.34)	35.30 (13.35)	31.76 (10.81)	32.20 (11.78)
Startle PEP	94.85 (8.21)	94.74 (8.68)	94.96 (7.75)	95.89 (8.41)	96.43 (7.81)	94.19 (8.26)	94.84 (8.21)
Recovery PEP	99.25 (7.46)	99.11 (7.48)	99.40 (7.48)	99.32 (7.52)	100.09 (7.47)	98.77 (7.26)	99.45 (7.91)
Startle RSA	6.59 (1.10)	6.64 (1.20)	6.53 (1.00)	6.69 (0.92)	6.93 (0.86)	6.79 (0.70)	6.87 (0.90)
Recovery RSA	7.15 (1.05)	7.14 (1.08)	7.16 (1.03)	7.08 (0.77)	6.60 (1.23)	6.58 (1.08)	6.53 (1.21)
Attention Prob—C	50.03 (9.88)	50.77 (9.98)	49.28 (9.77)	51.86 (9.43)	51.58 (10.96)	48.56 (9.17)	50.56 (10.36)
Adaptability—C	54.39 (9.99)	53.95 (9.13)	54.83 (7.72)	53.89 (7.08)	54.44 (9.52)	55.32 (7.83)	52.39 (9.26)
Attention Prob—E	61.49 (6.21)	61.89 (6.91)	61.09 (5.43)	62.39 (6.99)	61.79 (5.99)	61.14 (6.39)	61.76 (5.76)

Note. *F*-values for sex, race, and the interaction are not shown due to nonsignificant omnibus tests.
PEP: pre-ejection period; RSA: respiratory sinus arrhythmia; C: caregiver report; E: examiner report.

TABLE 2 Bivariate correlations among study variables

	M (*SD*)	1	2	3	4	5	6	7	8	9	10	11
1. Child IQ	90.37 (12.21)	–										
2. Family SES	33.41 (12.31)	0.25**	–									
3. Pre-startle PEP	100.83 (7.86)	−0.07	0.03	–								
4. Startle PEP	94.85 (8.21)	−0.03	−0.04	0.76**	–							
5. Post-startle PEP	99.25 (7.46)	−0.01	0.01	90**	0.85**	–-						
6. Pre-startle RSA	7.07 (0.96)	0.10	0.01	−0.03	−0.07	−0.06	–					
7. Startle RSA	6.59 (1.11)	0.07	−0.05	0.07	0.06	0.07	0.25**	–				
8. Post-startle RSA	7.15 (1.05)	−0.02	0.00	0.12	0.27**	0.20**	0.24**	0.50**	–			
9. Attention prob–C	50.03 (9.89)	−0.08	−0.18*	−0.13	−0.12	−0.11	−0.13	−0.06	−0.17*	–		
10. Adaptability–C	54.39 (8.45)	−0.05	0.05	0.21**	0.13	0.14	0.10	−0.00	0.15*	−0.63**	–	
11. Attention prob–E	60.42 (5.98)	−0.18*	−0.31**	−0.07	−0.06	−0.05	−0.04	0.10	0.02	−0.02	0.40**	–

Note. PEP: pre-ejection period; RSA: respiratory sinus arrhythmia; C: caregiver report; E: examiner Report.
*$p < 0.05$, **$p < 0.01$.

correlated within system across pre-startle, startle, and post-startle episodes (e.g., PEP startle was positively related to both pre-startle PEP and post-startle PEP). Pre-startle PEP was positively associated with caregiver reports of the child's adaptability. RSA recovery was positively related to caregiver-reported adaptability and negatively related to caregiver-reported attention problems. Examiner reports of child attention problems were positively related to caregiver reports of attention problems and negatively related to caregiver reports of child adaptability.

3.3 | Regression analyses

As shown in Table 3, the degree of coordination between PEP and RSA during both reactivity and recovery accounted for more variance in children's later adaptability and attention problems than either system in isolation. Specifically, as shown in Figure 1, children with an optimal reactivity pattern of short PEP and low RSA evidenced greater caregiver-reported adaptability and fewer caregiver-reported attention problems, but not examiner-reported attention problems (*not shown*). Conversely, incoherent ANS reactivity (e.g., high or low activation in both systems) was associated with poor adjustment across both domains. Interestingly, RSA reactivity did not evidence significant associations with later child adjustment among children who evidenced long PEP (i.e., low reactivity) during the startle challenge.

As shown in Figure 1, children who evidenced an optimal recovery pattern of long PEP and high RSA following the startle challenge evidenced greater caregiver-reported adaptability, fewer caregiver-reported attention problems, and fewer examiner-reported attention problems (*not shown*). In contrast, children who exhibited incoherent ANS recovery patterns (e.g., high or low activation of both systems) or a total failure to recover (e.g., short PEP and low

TABLE 3 Children's adjustment at age 8 on children's sympathetic and parasympathetic reactivity and recovery at age 6

Effect	Reactivity				Recovery			
	B	Bootstrapped SE	95% CI (bias-corrected) LLCI	ULCI	B	Bootstrapped SE	95% CI (bias-corrected) LLCI	ULCI
Attention Problems—Caregiver Report								
Child Sex (Female =1)	1.33	1.20	−1.03	3.69	1.22	1.19	−1.13	3.57
Child IQ	0.06	0.05	−0.04	0.16	0.04	0.05	−0.06	0.14
Family SES	−0.05	0.05	−0.15	0.05	−0.03	0.05	−0.13	0.06
Race/Ethnicity (Latinx = 1)	1.71	1.20	−0.67	4.08	1.87	1.19	−0.48	4.22
PEP	0.47	0.63	−0.77	1.71	−0.04	0.61	−1.25	1.16
RSA	1.35*	0.63	0.13	2.59	1.73**	0.61	0.52	2.93
RSA * PEP	1.20*	0.58	0.05	2.35	−1.66**	0.60	−2.84	−0.47
	$R^2 = 0.119$**		$F_{1,190} = 4.247$		$R^2 = 0.087$*		$F_{10,239} = 7.566$	
Attention Problems—Examiner Report								
Child sex (Female = 1)	−0.72	0.82	−2.34	0.90	−0.73	0.81	−2.33	0.87
Child IQ	−0.14**	0.03	−0.21	−0.07	−0.14**	0.03	−0.20	−0.07
Family SES	−0.05	0.03	−0.12	0.01	−0.06	0.03	−0.12	0.01
Race/Ethnicity (Latinx = 1)	−0.86	0.83	−2.49	0.76	−0.92	0.81	−2.53	0.68
PEP	−0.13	0.43	−1.08	0.62	0.25	0.42	−0.58	1.08
RSA	−0.23	0.43	−0.97	0.71	−0.75	0.42	−1.58	0.07
RSA * PEP	0.58	0.40	−1.37	0.21	−0.83*	0.41	0.01	1.64
	$R^2 = 0.009$		$F_{1,190} = 2.11$		$R^2 = 0.142$*		$F_{10,239} = 2.933$	
Adaptability—Caregiver Report								
Child Sex (Female = 1)	−1.84	1.36	−4.52	0.08	−1.69	1.39	−4.44	1.05
Child IQ	−0.15	0.06	−0.26	−0.04	−0.13*	0.06	−0.25	−0.02
Family SES	−0.03	0.06	−0.14	0.85	−0.03	0.06	−0.15	0.08
Race/Ethnicity (Latinx = 1)	−2.97**	1.37	−5.67	−0.28	−3.05*	1.39	−5.79	−0.30
PEP	−0.34	0.71	−1.75	1.07	−0.50	0.71	−1.91	0.91
RSA	−1.76**	0.71	−3.16	−0.36	−0.86	0.72	−2.28	0.55
RSA * PEP	−1.77*	0.66	−3.07	−0.46	1.50*	0.70	0.11	2.89
	$R^2 = 0.069$*		$F_{1,190} = 7.099$		$R^2 = 0.082$*		$F_{10,239} = 4.521$	

Note. PEP: pre-ejection period; RSA: respiratory sinus arrhythmia.
*$p < 0.05$, **$p < 0.01$.

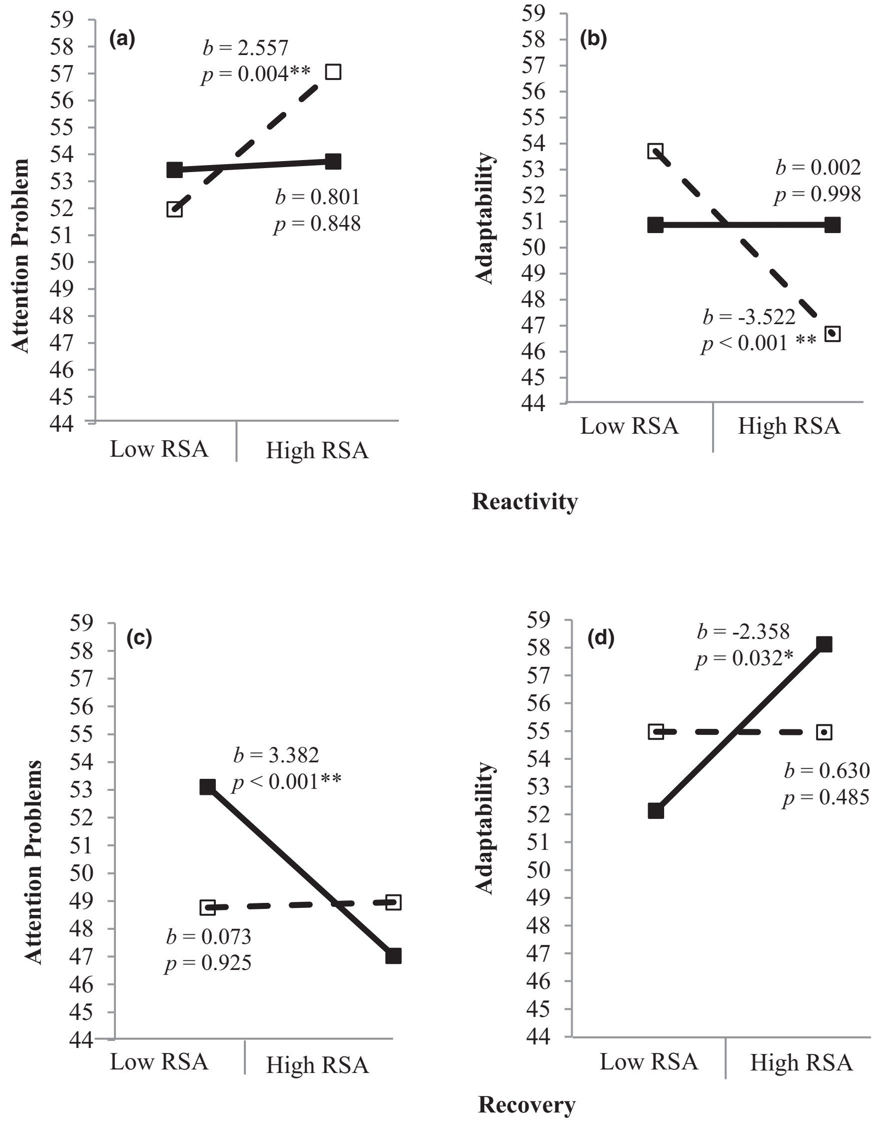

FIGURE 1 Caregiver-reported attention problems reactivity (a), caregiver-reported adaptability reactivity (b), caregiver-reported attention problems recovery (c), and caregiver-reported adaptability recovery (d). – – –, Short PEP (high SNS activation); —, Long PEP (low SNS activation). $^{*}p < 0.05$, $^{**}p < 0.01$

RSA) evidenced poorer adjustment across both domains and both informants. Paralleling the reactivity findings, RSA recovery did not evidence significant associations with later child adjustment among children who evidenced short PEP (i.e., low recovery) during the post-startle period.

4 | DISCUSSION

This investigation evaluated the individual and interactive associations of sympathetic and parasympathetic ANS regulation at age 6 with children's adaptability and attention problems two years later. The obtained results highlight the salience of coordinated ANS regulation between sympathetic and parasympathetic branches for understanding children's adaptability and attention problems. In addition to supporting core tenets of dynamic systems theories of the development (Flam & Powell, 2009; Gottlieb & Halpern, 2002; Thelen, 2005) and doctrines of autonomic space and calibration (Berntson et al., 1994; Del Giudice et al., 2011), these findings are consistent with evidence from prior studies that have examined both sympathetic and parasympathetic ANS reactivity within the same model using either profile (Alkon et al., 2017) or interaction (El-Sheikh et al., 2009) approaches. Importantly, to our knowledge, the current study was the first to examine sympathetic and parasympathetic coordination during ANS recovery. As with ANS reactivity, coordinated recovery responses between PEP and RSA were associated with higher ratings of adaptability and lower reports of attention problems.

In addition to illuminating the unique significance of ANS coordination for understanding children's adaptation, the current findings revealed an interesting pattern wherein sympathetic regulatory processes appeared dominant with regard to the adaptive implications of both ANS reactivity and recovery. Specifically, associations of parasympathetic regulation (i.e., RSA) with children's adaptability and attention problems were not significant among children with maladaptive sympathetic reactivity (i.e., long PEP) or recovery (i.e., short PEP). This pattern suggests that parasympathetic regulation was not related to later adjustment among children who failed to mobilize a sympathetic response to, or recovery from, a startling challenge.

These findings reveal an additional layer of complexity that informs ongoing efforts to elucidate relations between ANS regulation and child adaptation by demonstrating how it may be *both* the coordination of the regulatory response *and* the optimization of the sympathetic response to the nature of the challenge (e.g., a startle should prompt PEP attenuation, followed by elongation during recovery) that supports positive development. This finding runs counter to prior assertions regarding the dominance of the parasympathetic system in ANS regulation (e.g., the emphasis on the parasympathetic "brake" in polyvagal theory; Porges, 1995) by suggesting that the relation between ANS branches is complex and highlighting the salience of sympathetic regulatory processes in the development. Future research should build on these findings and capitalize on longitudinal data to evaluate if and how one ANS branch may drive change in the other branch, whether these dynamics change over developmental time, and how the coordination between ANS branches influences later adaptation.

5 | STRENGTHS AND LIMITATIONS

The current study provides new information about the importance of the coordination between sympathetic and parasympathetic influences during reactivity and recovery phases of stress regulation for understanding children's later adjustment. Notable strengths of this investigation include our use of a large and diverse sample of caregiver–child dyads; multiple methods; multiple informants, including both caregivers and the trained examiners; and a laboratory assessment of ANS regulation with task-inclusive pre-startle rest, startle reactivity, and post-startle recovery periods using both ECG and impedance cardiography. However, several features of this study introduced both strengths and limitations to the interpretation of the obtained data.

First, our novel startle paradigm to assess children's ANS regulation awaits further validation in ongoing and future studies. Although prior investigations with this age group have used a fire alarm to assess ANS responses to startle (Quas, Bauer, & Boyce, 2004), researchers have expressed concern about habituation effects as fire alarms and drills have become commonplace in child care settings (Quas et al., 2006). Moreover, traditional alarm startles fail to address the need to consider task-specific cognitive and physical demands across measures of rest, reactivity, and recovery (Burt & Obradović, 2013). Although the current paradigm begins to address some of these issues, there remained significant variation between the startle episode and the other two episodes that may have limited the validity of our reactivity findings (e.g., the examiner was not present, no story was read during the startle episode, and the story content differed across the rest and recovery episodes). Likewise, children's differential familiarity with the story itself may have influenced its emotional salience and, by extension, physiological patterns of rest and recovery in ways that could not be examined here. Finally, notwithstanding the consistency of findings across the reactivity and recovery episodes in this study, and prior studies with this paradigm (author cite), our capacity to compare the obtained findings with prior studies was necessarily limited.

Second, although the cardiac system represents a substantial advance over prior studies that have evaluated sympathetic and parasympathetic processes across different systems (e.g., salivary alpha-amylase and RSA), even within the cardiac system, PEP and RSA operate on slightly different time scales. Although the current paradigm represents a significant improvement over prior cross-system studies with ~30-min time differentials, PEP generally lags behind RSA up to 20 s and it is not clear how that may have affected the obtained findings (Berntson et al., 1991). For example, it may be that what appeared as an inability of PEP to react and/or rebound in some children may have reflected a slower acting sympathetic system, rather than a completely ineffective one.

Third, alternative analytic approaches, which were not feasible with the current data design, may have allowed for a deeper understanding of the coordination among the ANS regulatory processes examined here. For example, recent studies have adopted multilevel modeling approaches to support inferences about the influence of ANS regulation patterns over time utilizing growth curve modeling (Miller et al., 2013; Obradović & Finch, 2016). Although the nature and timing of the current startle task precluded our ability to adopt these approaches due to limited data points, a recent comparative analysis between residualized and latent change analytic approaches in a study of parenting influences on children's executive functioning found that, though the latent approach provided more detailed information about the sources of change, both procedures revealed the same overall pattern of effects (Blair, Raver, & Berry, 2014). Relatedly, a comparative analysis of shyness and boldness in fearful toddlers indicated that both dynamic indices in growth curve models and more traditional, static change scores offered incremental knowledge to understanding observed relations (Brooker & Buss, 2010). Drawing on studies outside the literature on stress physiology, these methodological comparisons suggest that there may be incremental utility to employing advanced statistical analyses in future research on ANS regulation, while illustrating the enduring value of the conventional analytic approaches that were supported by the current data.

Finally, despite the strengths of our highly reliable and well-validated caregiver reports of children's positive and negative adjustment on the BASC-2 at age 8, our inability to control for prior caregiver reports on this measure limits our ability to draw directional conclusions regarding the relations among ANS coordination and children's adjustment outcomes (Reynolds & Kamphaus, 2004). Still, our findings offer an advance beyond many prior studies, which have used cross-sectional investigations, because the assessments of physiology and adjustment were completely independent, especially given the use of physiological regulation and both caregiver- and examiner-reported outcomes. Looking ahead, a cross-lagged panel model that includes measures of all constructs at all data waves would further clarify the longitudinal associations suggested in this study.

6 | IMPLICATIONS AND FUTURE DIRECTIONS

The current study illustrates the coordinated dynamics of sympathetic and parasympathetic ANS regulatory processes, as well as their salience for understanding children's adjustment. These findings suggest that single-system investigations of either sympathetic or parasympathetic regulation may support erroneous conclusions about the role of ANS regulation in the development. For example, had we examined the main effects of sympathetic or parasympathetic reactivity and recovery in isolation, our investigation would have supported long-held assertions regarding the dominance of parasympathetic processes (i.e., RSA) on adaptation (Porges, 1995). However, in addition to highlighting the importance of coordinated reactivity and recovery across systems, our interactive analyses revealed the special significance of sympathetic processes (i.e., PEP) for understanding children's adaptability and attention problems. With the growing accessibility of cardiac impedance assessments, researchers should direct increased attention to the study of sympathetic regulation processes in the development, especially as they interact with the parasympathetic regulation processes.

Although the interactive analyses employed here captured the continuous relations among both branches of the ANS, alternate analytic approaches may offer additional insights into the joint contributions of sympathetic and parasympathetic regulatory processes to the development. As noted earlier, a few studies have employed person-oriented classifications of regulatory profiles, which delineate clear groups of individuals who may be at differential risk and benefit with regard to specific adaptive outcomes (Alkon et al., 2017). Likewise, cardiac autonomic balance (CAB) and cardiac autonomic regulation (CAR) are relatively new approaches that offer a single metric of relative activation between the ANS branches, and these may be especially beneficial to investigations of ANS flexibility (Berntson, Norman, Hawkley, & Cacioppo, 2008). Although these and other analytic approaches to understanding dynamic systems in the development, such as state–space grid modeling (Hollenstein, 2007), are valuable, newer developments (e.g., a dynamic assessment geared toward stress physiology specifically; Marshall, 2013; Urban, Osgood, & Mabry, 2011) may further advance this field of research.

Importantly, research on ANS regulation, including the current investigation, offers a deeper understanding of the complexities of physiological self-regulation that may aid ongoing efforts to support positive child development. Although biological systems may be difficult to influence via intervention, efforts to aid children in understanding and regulating their physiological responses, such as through mindfulness and relaxation training (Grossman, Niemann, Schmidt, & Walach, 2004), may be cost-effective interventions that have lasting positive effects on adaptation. Supporting the development and implementation of knowledge regarding the mind–body connection in childhood may help efforts to support overall regulatory competence.

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