Received: 18 May 2020 | Revised: 18 November 2020 | Accepted: 19 November 2020

DOI: 10.1111/sode.12498

ORIGINAL MANUSCRIPT

WILEY

Self-regulated behavior and parent-child co-regulation are associated with young children's physiological response to receiving critical adult feedback

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Funding information
Jacobs Foundation; Institute of Education Sciences; U.S. Department of Education; Stanford Data Science Fellowship

Abstract

Using piecewise growth curve trajectory modeling, we investigated kindergartners' physiological responses to receiving critical feedback from an adult during a laboratory drawing task. Further, we tested how children's independent self-regulated behavior, as well as the quality of parent-child co-regulation, related to physiological reactivity to and recovery from this challenge. We used respiratory sinus arrhythmia (RSA) to measure parasympathetic nervous system activity. Participants were 96 children (M_{age} = 5.6 years, 56% female) and their parents. We used observer ratings to capture children's self-regulated behavior during the laboratory visit and state-space grid methodology (an innovative, moment-to-moment behavioral coding method) to index observed parent-child positive co-regulation during four interaction tasks. First, the quality of dyadic parent-child co-regulation was associated significantly with children's RSA reactivity during the dyadic experience of receiving critical feedback from an adult. Specifically, children with higher levels of positive parent-child co-regulation exhibited decreases in RSA while receiving critical feedback, which may indicate active engagement or coping with the challenging situation. Second, children's self-regulated behavior was associated significantly with RSA recovery during a period immediately after the task ended, when children were seated alone. Children with lower levels of observed self-regulated behavior showed sudden RSA decrease after the critical feedback ceased, suggesting that this post-task period was physiologically challenging for them.

KEYWORDS
critical feedback, parasympathetic nervous system, parent-child co-regulation, response trajectories, self-regulation

1 | INTRODUCTION

As young children enter school, they increasingly are expected to persist on challenging learning tasks in the face of critical feedback from adults. For preschoolers, receiving critical feedback from an adult elicits negative emotions (Chaplin et al., 2017; Dennis, 2006), and two studies have suggested that it also elicits physiological response (Kahle et al., 2018; Perry et al., 2013). However, we do not know how school-age children respond to this type of critical feedback, which occurs more frequently in elementary school than in early education settings. Further, examining how individual skills and family processes that support children's self-regulation are linked with variability in children's stress physiology can help researchers contextualize and interpret different physiological response patterns (Blair & Raver, 2012; Klein Velderman et al., 2006; Obradović, 2016). In this study, we examined kindergartners' parasympathetic response (i.e., respiratory sinus arrhythmia; RSA) to receiving persistent critical feedback during a laboratory task that involves adult evaluation of children's drawings. We tested how observations of children's independent self-regulated behavior and the quality of parent-child behavioral co-regulation were associated with trajectories of physiological reactivity to and recovery from this challenge.

1.1 | Young children's physiological response to critical feedback

Young children often encounter critical feedback in school and are expected to persist on frustrating tasks. Yet, receiving critical feedback from an adult can be emotionally taxing. During evaluative drawing tasks, preschoolers have been found to display moderate psychological distress, as indexed by increases in expressions of anger and decreases in expressions of happiness (Chaplin et al., 2017; Dennis, 2006). However, as children grow older, they may learn to mask or suppress displays of their negative emotions (Chaplin et al., 2017). Environmental challenges such as receiving negative feedback from an adult may not elicit observable behavioral changes in most school-age children. Thus, studying only behavioral responses may not provide complete insight into how different children respond to these challenges (Obradović, 2016).

Children's responses to contextual challenges—such as receiving critical feedback and experiencing frustration—also are reflected in changes to their physiological arousal. Because young children's subjective reports may not be reliable due to limited language or cognitive capacities, physiological responses can provide unique insights into children's experiences of environmental challenges. Identifying patterns of physiological response to evaluative laboratory tasks can help researchers to understand how children's bodies may respond to similar challenges in school settings, which increasingly are common during the transition to elementary education.

In particular, children's parasympathetic nervous systems (PNS) have been shown to respond to social and emotional challenges (Porges, 2007). Decrease in PNS activity during challenges reflects increased physiological arousal and is believed to facilitate children's active engagement and coping in the moment (Porges, 2007). Studies of young children demonstrate that PNS activity typically decreases during socially and emotionally challenging laboratory tasks (Beauchaine et al., 2007; Blair & Peters, 2003; Porges, 2007). In addition, a handful of studies have specifically investigated young children's PNS responses to laboratory tasks that involve critical feedback. Perry and colleagues (2013) presented a series of frustrating tasks—including an evaluative drawing activity—to 3- to 5-year-old children. PNS activity decreased during these tasks, suggesting that receiving critical feedback is physiologically arousing for young children. In a smaller study, Kahle and colleagues (2018) modeled preschoolers' PNS responses during the same evaluative drawing task and a 1-min recovery period following the task. This approach revealed that PNS activity not only decreased over the course of the task, but it also continued to decrease *after* the task—suggesting that this period continued to be physiologically challenging for young children (Kahle et al., 2018). We need more research to examine if this pattern of prolonged physiological arousal following critical feedback also is found in children who have started formal schooling and are more likely to experience adult evaluations of their work. Because ongoing physiological adaptations to daily stressors can have both short- and long-term implications for well-being and health (McEwen, 1998), this research can help identify when and how to support young children's physiological recovery.

1.2 | Children's self-regulated behavior as a predictor of physiological response

Identifying factors that explain variability in trajectories of physiological arousal during and after challenges can help researchers to contextualize and interpret different physiological response patterns. Research has linked individual differences in young children's emotional and behavioral self-regulation to their PNS response to challenges (Graziano & Derefinko, 2013; Holzman & Bridgett, 2017). Task-based measures of children's executive functioning—a component of self-regulation—are associated with greater decreases in PNS input concurrently (Becker et al., 2012; Sulik et al., 2015; Utendale et al., 2014). Further, greater decreases in PNS activity during socially and emotionally challenging laboratory tasks have been linked to more positive developmental outcomes, such as parent and teacher reports of children's emotion regulation skills and on-task behavior (Blair & Peters, 2003; Gentzler et al., 2009; Hastings et al., 2008; Kahle et al., 2018; Santucci et al., 2008). Given implications of both young children's physiological and behavioral regulation for broader developmental outcomes (Davis et al., 2020; Doebel, 2020; Obradović & Armstrong-Carter, 2020), it is important to further investigate the extent to which physiological and behavioral regulation are related. Because physiological response is a dynamic and multi-determined process (Davis et al., 2020), studies need to examine how children's self-regulation behavior relates to both physiological reactivity and physiological recovery. Identifying unique profiles of physiological and behavioral regulation can help us understand processes supporting children's adaptation and resilience (Blair & Raver, 2015; Obradović, 2016).

Prior research examining how child behaviors relate to physiological response has relied primarily on executive functioning tasks and parents' and teachers' reports of children's self-regulated behavior. However, executive function tasks do not directly reflect children's self-regulated behavior in daily life (Fuhs et al., 2015; Toplak et al., 2013). Parents and teachers provide an ecologically valid perspective on child behavior; however, their reports could be biased by the quality of their relationship with the child, their current mental state, and the child's demographic characteristics (Berg-Nielsen et al., 2012; Garcia et al., 2019). In addition, global ratings by parents and teachers measure children's trait-like tendencies, and are not sensitive to state factors, such as children's mood that day and level of comfort with unfamiliar adults, which impact children's behavior and physiology (Smith-Donald et al., 2007).

Using trained observers to rate children's self-regulated behavior can provide ecologically valid data while mitigating potential bias from parent and teacher surveys. Yet, studies have not found significant associations between observer ratings of preschoolers' emotion regulation and concurrent PNS responses to critical feedback (Kahle et al., 2018). This finding may be in part due to low variability in children's emotional expressions and behaviors in the moment while they are receiving critical feedback. In contrast, observer ratings of children's behavior throughout the entire laboratory visit can capture more variability in children's self-regulated behavior across a variety of activities (Obradović & Finch, 2017; Smith-Donald et al., 2007).

1.3 | Parent-child co-regulation as a predictor of physiological response

Children's self-regulated behavior emerges from their experiences with parents, who model and socialize patterns of regulation and coping (MacPhee et al., 2015). Several studies demonstrate associations between parenting and young children's PNS response (Miller et al., 2013; Paret et al., 2015; Shih et al., 2018). For example, children who experience more supportive parenting practices during parent-child interaction (as assessed by parent- and observer ratings) exhibit greater decreases in PNS activity during challenge tasks designed to elicit moderate anger, frustration, and sadness (Gilissen et al., 2008; Miller et al., 2013; Paret et al., 2015; Perry et al., 2013).

Beyond parenting behavior, parent-child co-regulation—which reflects reciprocal, bidirectional patterns of parent and child behavior during shared interactions—is uniquely important for children's adjustment (MacPhee et al., 2015). Young children from dyads who show more positive behavioral co-regulation (e.g., sensitive and mutually responsive actions and suggestions, active engagement and cooperation, shared positive affect) display fewer externalizing and aggressive behaviors (Bardack et al., 2017; Lunkenheimer et al., 2020) and more optimal self-regulated behavior (Scholtes et al., 2020; Suveg et al., 2016).

Positive, reciprocal interactions with parents help children to internalize independent self-regulation skills and learn how to interact with others (Sroufe & Waters, 1977). Specifically, attachment theory posits that the quality of co-regulation with a primary caregiver provides children with an inner working model that shapes their responses when interacting with other adults (Groh et al., 2017). Although the quality of parent-child behavioral co-regulation has been linked to children's physiological responses during parent-child interactions (Davis et al., 2018; Skowron et al., 2015), less is known about how parent-child co-regulation relates to children's physiological responses when interacting independently with an unfamiliar adult. It is particularly important to understand how dyadic co-regulation relates to physiological response in 5-year-old children, who are beginning to face new challenges in kindergarten that require independent, self-regulated behavior with their teachers (Calkins, 2011).

1.4 | Current study

The goal of the present study was to characterize children's PNS response (i.e., RSA) during and immediately after receiving adult critical feedback. We conceptualized RSA response as a dynamic process that changes over time and can be modeled via growth curve trajectories (Burt & Obradović, 2013; Kahle et al., 2018; Miller et al., 2013; Obradović & Finch, 2017). Specifically, we used piecewise growth curves to model change in RSA values as: (a) the child engages with the task while receiving critical feedback (reactivity trajectory) and (b) after the child completed the task and critical feedback ceased (recovery trajectory). Next, we examined children's self-regulated behavior and, separately, positive parent-child co-regulation as predictors of reactivity and recovery trajectories. To capture self-regulated behavior, we used observer ratings of children's ability to regulate attention, behavior, and emotions during the entire research study session. To capture positive parent-child co-regulation, we used a second-by-second independent coding of child and parent behavioral states during interaction (Bardack et al., 2017). Based on polyvagal theory (Porges, 2007), we hypothesized that children with relatively higher levels of self-regulated behavior and higher levels of positive co-regulation would exhibit an RSA decrease during the task (i.e., greater reactivity) and subsequent RSA increase after the task (i.e., greater recovery).

2 | METHOD

2.1 | Participants

The participants were 96 kindergarteners (M_{age} = 5.62 years; *SD* = 0.55; 52% females) drawn from a sample of 102 children who participated in a laboratory study with a primary caregiver (M_{age} = 38.92 years; *SD* = 6.82 years; 93% female). Six children were excluded from the current study because they did not complete the physiological protocol. Families were recruited with advertisements at community centers, preschools, elementary schools, and libraries and were eligible if they had a child who was fluent in English and entering kindergarten or first grade. The sample was racially diverse, with caregivers reporting the children as 36% White, 26% Hispanic/Latino, 20% Asian, 4% Black, and 14% Multiracial/Other. Seventeen percent of participating caregivers were single parents. Seventeen percent reported educational attainment of a high school diploma or less whereas 42% had earned a graduate or professional degree. Consistent with this, 23% of the families reported household income less than $50,000 whereas 36% reported household income greater than $200,000.

2.2 | Procedure

Primary caregivers and children visited a university research laboratory to complete a 3-hr protocol. Upon arrival, research assistants greeted and consented the dyad, introduced them to the laboratory setting and the study protocol, and setup equipment for measuring physiological responses. Parents completed an in-person survey with a trained interviewer, which included demographic information. Meanwhile, in a separate room, children completed a series of challenge tasks designed to elicit physiological response with a research assistant. The current study focuses on the Perfect Green Circles Task (Goldsmith & Rothbart, 1999) which was designed to elicit frustration and was completed during the middle of the 2.5-hr session. Toward the end of the session, parents and children reunited to participate in 4 video recorded, structured tasks designed to capture the quality of the parent-child interaction and, specifically, patterns of parent-child behavioral co-regulation. At the end of the session, the research assistant who conducted the study session reported on the child's observed self-regulated behavior during the entire session. All procedures were approved by the Stanford University Institutional Review Board.

2.3 | Measures

2.3.1 | Child self-regulated behavior

At the end of the session, children's self-regulated behavior was assessed using the Preschool Self-Regulation Assessment Assessor Report (Smith-Donald et al., 2007). The original 28-item survey was designed to provide a global index of children's emotions, attention, and behavior as observed across the duration of a proscribed assessor–child interaction. The survey was completed by the research assistant who had run the study session using a 4-point scale that used detailed behavioral markers. The observations were based on the entire laboratory visit, including Perfect Green Circles and the parent-child interaction tasks. The items were rated on a 4-point Likert scale with specific behavioral descriptions associated with each numerical code, which aided in training and establishing good reliability. For example, the item 'sustains concentration; willing to try repetitive tasks' was scored as follows: 0 = Child not able to concentrate or persist on much of the assessment; 1 = Child frequently distracted, requires multiple prompts from assessor; 2 = Child occasionally distracted but generally persistent, and does not require prompt from assessor; and 3 = Child able to concentrate and persist with task, even toward the end of tasks and with distractions. Twenty percent of all cases were double-coded by a master coder using video recordings, yielding high interclass correlations (ICC range: 0.82–1.00). Using a standardized average, we created a composite by averaging 13 items that captured children's attention, inhibitory control, and emotion regulation observed by the assessor during the laboratory visit (Cronbach's α = .96). This measure was consistent with our prior publication (Obradović & Finch, 2017). We selected these 13 items on a conceptual basis, focusing on self-regulated behavior rather than emotional items. The excluded items were not as directly relevant to our conceptualization of self-regulated behavior (e.g., 'shows pleasure in accomplishment', 'confident'). Follow-up confirmatory factor analysis indicated that that these 13 items factored separately from the other items. Data were complete for all 96 children in the analytic sample on this measure.

2.3.2 | Positive parent-child co-regulation

The parent-child interaction protocol lasted for approximately 30 min and was video recorded. It consisted of four structured tasks designed to assess the quality of parental responsiveness and assistance, structure and limit setting, and support of the child's autonomy. During the free play task, the parent and child were asked to play together with provided toys; unbeknownst to the child, the parent had been instructed to enforce a rule disallowing the child from touching certain attractive toys. During the cleanup task, the parent was instructed to read a magazine while asking the child to clean up the toys, but was not prohibited explicitly from helping the child during this task. During the problem-solving discussion, the dyad was asked to try to resolve a salient issue that the parent had chosen from a list of age-appropriate parent-child challenges (e.g., waking up on time, getting along with siblings). During the Tangoes game, the parent was asked to teach and support the child in completing a series of challenging geometric puzzles.

To measure parent-child positive co-regulation, we used an innovative state-space grid (SSG) methodology, which captures observer ratings of moment-to-moment changes in dyadic behavior patterns (Herbers et al., 2014; Hollenstein, 2007). In prior work (Bardack et al., 2017), this measure was shown to independently predict teacher reports of fewer externalizing and inattention/impulsive behaviors in school. Using a 4 × 4 SSG grid, parent and child behaviors were coded on a continuous, second-by-second basis into mutually exclusive and exhaustive categories reflecting the behavioral state of the dyad (Figure 1; see also Bardack et al., 2017). Child behavior was plotted on the *y* axis and was coded as: (a) active on task (e.g., leading play, engaging the parent in join attention); (b) passive on task (e.g., following parent's lead during play, listening to parent); (c) withdrawn/disengaged (e.g., avoiding eye contact, turning away); or (d) defiant/dysregulated (e.g., verbally refusing; expressing emotional distress). Parent behavior was plotted on the *x* axis and was coded as: (a) positive control (e.g., redirecting child's attention to on-task behavior, comforting); (b) following the child's lead (e.g., responding to child's play and verbalizations); (c) disengaged (e.g., ignoring child, appearing distracted or withdrawn); or (d) negative control (e.g., criticizing or showing harsh physical contact). We defined positive co-regulation as temporally co-occurring parent-child behaviors in which the parent guides or maintain children's well-regulated attention and behavior (see Figure 1). In other words, the cells selected from the grid represented parent positive control behaviors when the child was showing positive behaviors (i.e., actively and passively on task) as well as negative behaviors (i.e., withdrawn from the interaction or exhibiting defiant, dysregulated behavior).

Using Gridware 1.5 (Lamey et al., 2004), we derived variables characterizing the tendency of dyadic behavior to occur and maintain within the region of parent-child positive co-regulation: (a) the proportion of time spent in this region relative to the whole grid (M = 0.82, SD = 0.09), (b) average duration (in seconds) per cell (M = 150.54, SD = 23.46) in this region, and (c) average return time (reversed; M = 2.80, SD = 0.67) to this region. We standardized and averaged these three variables to create a composite score for parent-child positive co-regulation (α = .87).

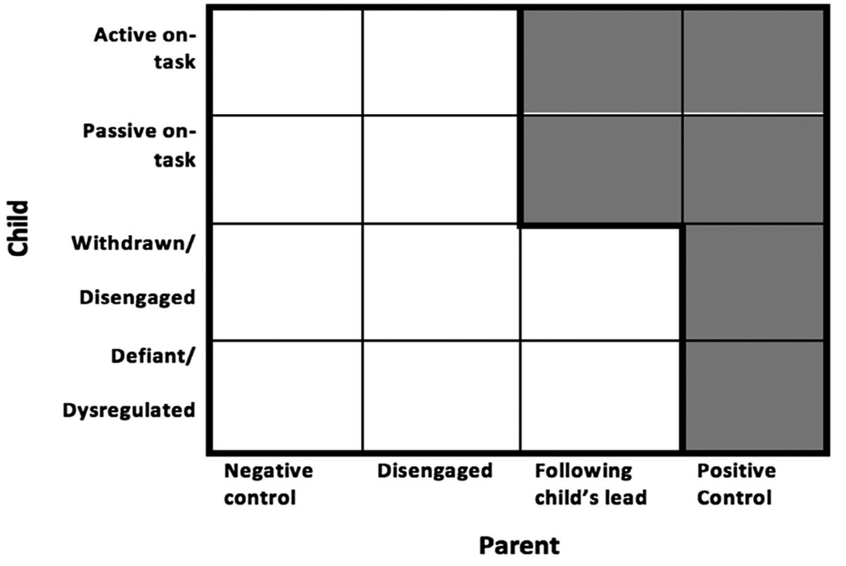

FIGURE 1 State-space grid with positive co-regulation shown in gray

2.3.3 | Physiological response

During the Perfect Green Circles task (Goldsmith & Rothbart, 1999), the child and assessor sat at a small table. The assessor gave the child a marker and asked the child to 'draw a perfect green circle'. After each drawing, the assessor provided critical feedback (e.g., 'that circle is not quite perfect') in a neutral tone of voice and asked the child to try again. The assessor did not explicitly instruct the child how to improve the circle. After 1 min, the assessor said again 'I need the perfect green circle'. The child continued to attempt to draw the perfect green circle for 2 min total. After 2 min, the assessor acknowledged being picky and praised the child's effort and the final circle. The task ended with the assessor suggesting that the child draw a smiley face in his or her favorite circle. This marked the onset of the recovery episode, which lasted 1 min. The assessor said 'I need to get some things ready' and left the table (but not the room) so the child was seated alone. After 30 s, the assessor returned to the table where the child sat and reminded the child that they did a great job and could relax. After another 30 s, the recovery period ended. The assessor praised the child again and gave him or her a sticker.

PNS activity was indexed via respiratory sinus arrhythmia (RSA). RSA response to the socio-cognitive task was measured using a Wireless BioNomadix RSP module (BIOPAC Systems, Goleta, CA). RSA was estimated as the natural logarithm of the variance of heart period within the high-frequency band-pass associated with respiration at this age (i.e., 0.15–0.80; Bar-Haim et al., 2000; Rudolph et al., 2003). Prior to analyses, each waveform was verified, inter-beat intervals were checked visually, and artifacts were removed. Using AcqKnowledge software, RSA values were calculated in 30-s epochs during the reactivity and recovery episodes. Due to variation in the protocol length, 33% of participants had a fifth reactivity epoch. Accordingly, we modeled five reactivity epochs in order to use all available data, and so that there would be no missing gaps of time in individuals' trajectories (i.e., trajectories would not be discontinuous). We modeled two recovery epochs to account for the 1-min recovery period, consistent with prior work (Kahle et al., 2018). Descriptive statistics and valid sample size for all epochs are reported in Table 1.

TABLE 1 Descriptive statistics for RSA by epoch during reactivity and recovery

	N	Mean	*SD*	Min	Max
RSA reactivity epochs					
1	96	7.54	1.02	5.49	9.93
2	96	7.63	1.00	5.40	10.35
3	96	7.61	1.07	5.49	10.09
4	86	7.68	1.08	5.17	9.97
5	32	7.69	1.26	5.37	9.77
RSA recovery epochs					
1	96	7.36	1.11	5.04	9.96
2	73	7.45	1.22	5.22	9.84

2.3.4 | Covariates

Child age was included as a covariate, to account for the negative relation between age and breathing rate, which impacts RSA (Laborde et al., 2017). Child gender and family income were not correlated significantly with RSA, so they were not included as covariates.

2.4 | Analytic plan

All children in the analytic sample ($N = 96$) had complete demographic, parent-child co-regulation, and self-regulated behavior data. Self-regulated behavior and co-regulation were mean centered. We analyzed piece-wise growth curve trajectories using multilevel modeling in R 3.5.2 with the 'lme4' package (Bates et al., 2015). Following the approach of Obradović and Finch (2017) and Kahle et al., (2018), we estimated separate slopes for the reactivity and recovery episodes (together in a single model). This analytic approach allows estimation of random intercepts (i.e., initial values of RSA can vary) and random slopes (i.e., rates of change in RSA reactivity and recovery can vary). In other words, we estimated an intercept corresponding to children's initial RSA, a reactivity slope corresponding to change in RSA during the critical feedback period, and a recovery slope corresponding to change in RSA during the recovery period.

We started with an unconditional model (i.e., a model without any predictors; Model 1) to describe average trajectories of physiological reactivity and recovery in our sample. We then examined child self-regulated behavior (Model 2a) and positive parent-child co-regulation (Model 2b) as predictors of initial intercept, reactivity slope, and recovery slope. Child self-regulated behavior and co-regulation were correlated positively ($r = .38$, $p < .001$), so these two predictors were tested in separate models to understand their independent effects. In models where self-regulated behavior or co-regulation emerged as significant predictors of physiological trajectories, we plotted trajectories at 1 *SD* above and below the mean of self-regulated behavior or co-regulation (Aiken & West, 1991). In addition, we conducted follow-up analysis to test the statistical difference between the reactivity slope estimate and the recovery slope estimate. This helped us understand the statistical significance of the transition between two segments (i.e., reactivity to recovery).

3 | RESULTS

Descriptive statistics and correlations are reported in Table 2. Child age was correlated positively with child self-regulated behavior ($r = .32$, $p < .010$) and was included as a covariate. Mean RSA across all reactivity task epochs and mean RSA across all recovery epochs were correlated positively ($r = .78$, $p < .001$), such that children who had higher RSA during the task also had higher RSA during recovery.

3.1 | Characterizing children's physiological response

Our unconditional model would not converge when random slopes were included for both the reactivity and recovery slopes. Therefore, we removed the random effect for the reactivity episode from the model because it had the smallest variance ($\sigma^2 = 0.00$) among the random effects. Our final unconditional model included random effects for the intercept ($\sigma^2 = 0.91$) and for recovery slope ($\sigma^2 = 0.13$), which were correlated negatively ($r = -.15$). Following expert recommendation, we did not test the significance of this correlation (Bates et al., 2015). In this model, the residual variance estimate of RSA was 0.19. On average, the RSA reactivity slope was not significantly different from zero ($\beta = .00$, $SE = 0.02$, $p = .564$) whereas the recovery slope showed a significant decrease over time ($\beta = -.11$, $SE = 0.05$, $p = .024$).

3.2 | Self-regulated behavior and physiological response

Estimates for Model 2a are presented in Table 3. Self-regulated behavior was not related to the reactivity slope ($\beta = -.02$, $SE = 0.03$, $p = .576$), but it was related significantly to the recovery slope ($\beta = .17$, $SE = 0.08$, $p = .032$). As shown in Figure 2, children with lower levels of self-regulated behavior (1 *SD* below the sample mean) exhibited a significant negative recovery slope ($\beta = -.20$, $SE = 0.07$, $p = .003$) and children with higher levels of self-regulated behavior (1 *SD* above the sample mean) exhibited a recovery slope that was not significantly different from zero ($\beta = -.02$, $SE = 0.07$, $p = .719$). These results revealed that, on average, children with higher levels of self-regulated behavior did not exhibit change in RSA during and after the task. In contrast, children with lower levels of self-regulated behavior did not show significant RSA change during the task, but had an abrupt, significant decrease in RSA following the completion of the task.

TABLE 2 Correlations

	1	2	3	4	5	6	7
1. Family income	–						
2. Age	0.09	–					
3. Parent-child co-regulation	0.27*	0.12	–				
4. Self-regulation	0.23*	0.32**	0.38***	–			
5. Reactivity RSA	0.01	−0.03	−0.11	−0.07	–		
6. Recovery RSA	−0.02	0.14	−0.01	0.11	0.78***	–	
7. Female	−0.02	−0.08	0.03	0.08	−0.04	0.09	
Mean/%	0.00	5.61	0.00	0.00	7.61	7.41	54%
SD	1.01	0.56	0.91	0.65	0.98	1.07	

Note: For correlations, reactivity RSA and recovery RSA were averaged across all 30-s epochs.
***$p < .001$; **$p < .01$; *$p < .05$.

TABLE 3 Piecewise growth-curve models of children's RSA values, moderation by child self-regulation and parent-child co-regulation

	RSA	
	Model 2a	Model 2b
	Self-regulation	Parent-child co-regulation
	B	*B*
Fixed effects	*(SE)*	*(SE)*
Intercept	7.618**	7.617**
	(0.104)	(0.104)
Age	−0.053	−0.075
	(0.197)	(0.188)
Self-regulation	−0.070	
	(0.170)	
Parent-child co-regulation		−0.049
		(0.115)
Linear slope during reactivity		
Reactivity	−0.011	−0.010
	(0.017)	(0.017)
Age	0.020	0.026
	(0.034)	(0.032)
Self-regulation	−0.016	
	(0.029)	
Co-regulation		−0.039**
		(0.020)
Linear slope during recovery		
Recovery	−0.115**	−0.115**
	(0.047)	(0.047)
Age	0.168+	0.210**
	(0.090)	(0.087)
Self-regulation	0.171**	
	(0.079)	
Co-regulation		0.099+*
		(0.053)

Note: ****p* < .001; ** *p* < .01; **p* < .05. +*p* < .10.

3.3 | Parent-child co-regulation and physiological response

Estimates for Model 2b are presented in Table 3. Positive parent-child co-regulation was related significantly to the reactivity slope (β = −.39, *SE* = 0.02, *p* = .044). As shown in Figure 3, children with lower co-regulation (1 *SD* below the sample mean) had a reactivity slope that did not significantly differ from zero (β = .03, *SE* = 0.03, *p* = .303) whereas children with higher co-regulation (1 *SD* above the sample mean) exhibited a marginally negative reactivity slope (β = −.04, *SE* = 0.03, *p* = .061). These results revealed that, on average, children with higher

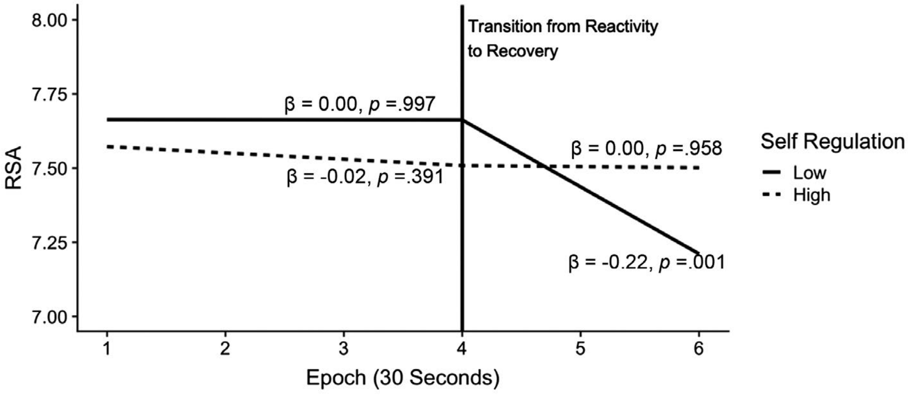

FIGURE 2 Children with high self-regulation (+1 *SD*) tend to have greater RSA decrease (i.e., parasympathetic withdrawal) on average after the critical feedback task during recovery, compared to children with low self-regulation (−1 *SD*). This Figure is based on Model 2a. About 33% of participants had an additional fifth reactivity epoch which is included in the analysis, but not depicted in this Figure. The difference between children with high and low levels of self-regulation was only significant for recovery, and not for reactivity

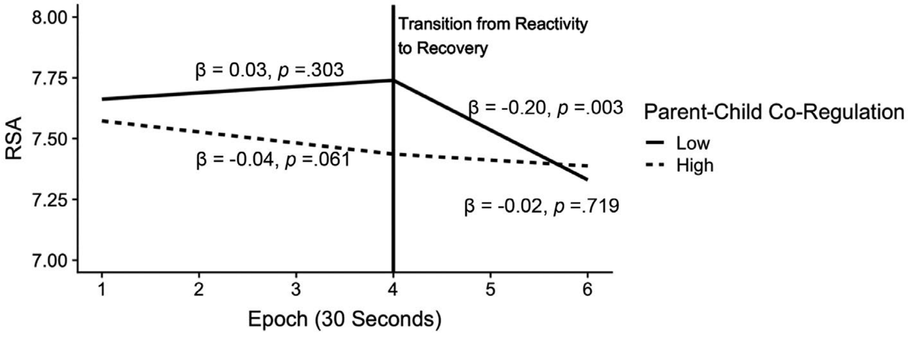

FIGURE 3 Children from dyads with higher levels of positive parent-child co-regulation (+1 *SD*) tend to have greater RSA decrease (i.e., parasympathetic withdrawal) on average during the critical feedback task, compared to children with lower levels of positive parent-child co-regulation (−1 *SD*). This Figure is based on Model 2b. About 33% of participants had an additional fifth reactivity epoch which is included in the analysis, but not depicted in this Figure. The difference between children with high and low levels of Parent-Child Co-Regulation was only significant for reactivity, and not for recovery

co-regulation decreased in RSA during the task. In contrast, children with lower co-regulation did not show significant RSA change during the task. Positive parent-child co-regulation was not related significantly to the recovery slope (β = .10, *SE* = 0.05, *p* = .063).

3.4 | Follow-up analysis

To understand better these trajectories and the transition across segments (i.e., reactivity to recovery), we conducted follow-up analysis to test the difference between the reactivity and the recovery slopes. The difference was significant for children with lower levels of self-regulated behavior (β = −.23, *SE* = 0.08, *p* = .006) and co-regulation (β = −.23, *SE* = 0.08, *p* = .004), suggesting that there was an abrupt change in physiological arousal when these children completed the task and transitioned into recovery. This was not the case for children with higher levels of self-regulated behavior (β = .02, *SE* = 0.08, *p* = .778) or co-regulation (β = .02, *SE* = 0.08, *p* =.773).

We also tested self-regulation and co-regulation together in a single model, to investigate if each were uniquely associated with RSA trajectories. The association between co-regulation and reactivity slope remained significant (β = −.04, *SE* = 0.02, *p* = .048). The association between self-regulation and recovery slope was reduced to marginal significance (β = −.07, *SE* = 0.05, *p* = .098). This result likely is due to limited statistical power.

4 | DISCUSSION

Receiving critical feedback from an adult can be emotionally taxing for young children. Understanding children's physiological response patterns provides unique insight into how they adapt to this type of emotional challenge, which can be encountered in educational settings (Kahle et al., 2018; Perry et al., 2013). We modeled trajectories of kindergartners' parasympathetic nervous system (PNS response, indexed via respiratory sinus arrhythmia, RSA) while receiving critical feedback from an adult and during a recovery period following critical feedback. Further, we investigated how children's self-regulated behavior and the quality of parent-child co-regulation were associated with reactivity to and recovery from this laboratory challenge. Linking physiological response to children's self-regulation skills and dyadic co-regulation experiences with their parents can help researchers to contextualize and interpret different physiological response patterns. Children who experienced higher levels of positive parent-child co-regulation showed mild, gradual PNS decrease during the task, which may indicate active physiological engagement with the challenging situation. However, most of the variability in children's PNS response occurred during the recovery period rather than during the critical feedback phase. During the recovery period, children with lower levels of self-regulated behavior exhibited sudden PNS decrease, suggesting that the time *after* critical feedback was physiologically challenging for them.

4.1 | Positive parent-child co-regulation is associated with physiological reactivity

On average, children did not show change in PNS activation during the challenge while receiving critical feedback from an adult about their drawings. This was unexpected, given that young children's PNS activity usually decreases during socially and emotionally challenging laboratory tasks (Beauchaine et al., 2007; Blair & Peters, 2003; Porges, 2007). It is possible that this task was not very challenging for many children in our study. However, significant individual variability in response patterns revealed that some children did respond physiologically to this challenge. By linking the quality of dyadic parent-child co-regulation with children's physiological response during this challenging dyadic experience with an adult research assistant, we can understand better the variability of children's physiological adaptations to the task.

Specifically, children with higher levels of positive parent-child co-regulation showed PNS decreases while receiving the critical feedback. In contrast, children with lower levels of positive parent-child co-regulation did not exhibit change in PNS activation during the challenge. The gradual lifting of the vagal brake during the challenge—as observed among children who experienced higher levels of positive co-regulation—may reflect focused attention and cognitive engagement during the task (Porges, 2007). Although we do not have insight into these children's subjective experiences, we draw from the attachment theory to suggest that children who experience more responsive parent-child relationships may tend to see the unfamiliar adult (i.e., the assessor) as more responsive and less threatening (Groh et al., 2017). Further, research with adults shows that appraising stressors as challenging rather than threatening is associated with improved cardiac efficiency (i.e., less vasoconstriction and greater cardiac output; Blascovich & Mendes, 2010; Jamieson et al., 2013). Thus, it is feasible that children with more positive parent-child co-regulation may engage more vagal regulation during the critical feedback because they experience the critical feedback as challenging but manageable rather than overwhelming and overly stressful.

The finding that positive parent-child co-regulation is linked to greater PNS decrease during critical feedback is consistent with prior studies showing that parent and observer reports of supportive parenting practices are associated with decreases in PNS activity for young children during social and emotional challenges (Hastings et al., 2008; Miller et al., 2013; Perry et al., 2013). Our study extends understanding of these processes by revealing that the observed quality of parent-child *co-regulation*, based on the moment-to-moment coding of both parent and child behaviors, also is related to greater decrease in PNS activity during critical feedback. As such, our study contributes to a growing body of evidence that quality of the dyadic relationships—reflecting both parent and child behaviors in the context of each other—is relevant for children's response to socially mediated challenges (MacPhee et al., 2015).

4.2 | Self-regulated behavior is associated with physiological recovery

On average, children displayed more physiological change during the period immediately following the challenge task than during the task itself. We observed a pattern of significant PNS decrease (i.e., increasing physiological arousal) immediately after the task ended. This result was consistent with the findings of the only one other study that examined young children's physiological response after the same task (Kahle et al., 2018). The period after receiving critical feedback continued to be physiologically arousing for young children, suggesting a need to reconceptualize what constitutes 'recovery'. Young children may not return immediately to baseline arousal after receiving critical feedback.

Individual differences in self-regulated behavior shed light on which children might be most affected after receiving critical feedback. Children with strong self-regulated behavior followed a stable pattern of PNS activation that did not change during critical feedback or afterward whereas children with poorer self-regulated behavior exhibited a rapid decrease in PNS input (i.e., increased physiological arousal) immediately after the critical feedback ended. An increase in physiological arousal after critical feedback—when the challenge was over—could be indicative of coping with accumulated stress, because prolonged physiological arousal may no longer reflect engagement once the task was complete. The sustained decreases in PNS after the task ended suggest that this recovery period may be psychologically challenging for young children with lower levels of self-regulatory skills.

Previous research indicates that children engage in more self-soothing behaviors after this critical feedback task than during the task (Kahle et al., 2018), suggesting that the need for self-regulation actually increases during the 'recovery' period. This may be because children are no longer attending to the research assistant or the task and could be perseverating or ruminating about their performance on the challenge task. Rumination has been associated with lower PNS activity in older children (Borelli et al., 2014) and with slower autonomic and PNS recovery from stressors among adults (Glynn, 2002; Verkuil et al., 2009). Rumination during the recovery period could explain why children's PNS activity decreased on average after the task, but not during the task. Further, children with lower self-regulation may have been less effective at using self-regulatory strategies such as distraction to reduce their rumination, which could explain why they showed the largest decreases in PNS activity during the recovery period.

Although previous work linked higher levels of self-regulated behavior with PNS decrease *during challenge* (Blair & Peters, 2003; Gentzler et al., 2009; Hastings et al., 2008; Kahle et al., 2018; Miller et al., 2013; Santucci et al., 2008), our findings link lower levels of self-regulated behavior with PNS decrease *after challenge*. This finding supports the notion that PNS decrease may represent different forms of children's adaptation, depending on the timing and context in which it occurs (Ellis et al., 2017). Examining PNS responses across different contexts and in relation to relevant behavioral predictors can help us better understand which PNS response patterns could be adaptive, for whom, and in which contexts.

Our results contribute to a growing body of evidence that children's self-regulation is particularly relevant for physiological recovery. In prior work, lower levels of parent-reported emotion regulation were associated with slower PNS return to baseline in 4- to 7-year-old children (Santucci et al., 2008) and slower sympathetic recovery in 3.5-year-old children (Kahle et al., 2016). However, one study also found that preschoolers' observed emotion regulation strategies measured during the Perfect Green Circles Task and subsequent recovery were unrelated to PNS reactivity and recovery (Kahle et al., 2018). Our study suggests that observing children's self-regulated behavior across activities in the context of the entire laboratory setting—compared to observations limited to only during and immediately after critical feedback—may capture greater variability in self-regulated behavior and relate more strongly to PNS response. Consistent with our current findings, observed self-regulated behavior across the entire laboratory visit was also associated with a slower return to baseline PNS activity after a different socio-evaluative challenge in this sample (i.e., the Trier Social Stress Test; Obradović & Finch, 2017).

4.3 | Limitations

The correlational nature of our study limits any conclusion about directionality. Our study was also limited by a small sample size, similar to other studies linking children's behavioral and PNS functioning (Kahle et al., 2016; Miller et al., 2013). Our small sample size reduces confidence in our observed estimates because of large standard errors, and raises the possibility of false null results (type II errors). For example, we may not have had the statistical power to detect relations between self-regulated behavior and PNS reactivity during the challenge task, or between parent-child co-regulation and PNS recovery. Similarly, our follow-up test, which examined how self-regulated behavior and co-regulation each uniquely related to PNS functioning, was likely underpowered.

Our measure of self-regulated behavior was observed during the entire laboratory session, which included the parent-child interaction tasks. As such, observers' ratings of child self-regulated behavior were partially based on the parent-child interaction tasks. This overlap could have contributed to stronger associations between parent-child co-regulation and children's self-regulated behaviors relative to having completely independent measures. Future research could investigate whether our findings are replicated when using task-based measures of self-regulation (e.g., executive functions tasks). In addition, the laboratory visit was about 2.5 hr long and included many tasks, which could have contributed to fatigue and less well-regulated behavior for parents and children. However, their fatigue could also mirror real-life experiences—particularly in school—where children must regulate their behavior for extended periods of time throughout the day.

4.4 | Conclusion and future directions

Understanding how young children cope with critical feedback is particularly challenging because children lack the metacognitive and language skills to describe their subjective experiences. Studying variability in young children's physiological responses offers valuable insight into how they adapt to environmental stressors in ways that may not be detected by child report or observation. In addition, understanding physiological responses is important because some children who show positive adaptation via cognitive and behavioral measures may exhibit heightened levels of physiological stress response and elevated allostatic load, which contribute to poor health outcomes in adolescence and adulthood (Brody et al., 2014; Hostinar & Miller, 2019). Previous research suggests that PNS withdrawal during mild-moderate challenges is adaptive in terms of task performance (Calkins, 2011), but less research has examined physiological costs of post-task experiences. Adaptation is a relative construct (Ellis et al., 2017), and our study helps to shed light on the adaptive nature of different physiological trajectories by linking them to children's self-regulation skills and experiences of positive parent-child co-regulation, and by examining them during and after the environmental challenge. In the future, a longer recovery period also would clarify how prolonged physiological response continues to be after critical feedback.

Future research should attempt to identify psychological mechanisms linking behavioral regulation to PNS response. Specifically, measuring children's subjective feelings during and after laboratory tasks would reveal how they perceive the challenge (e.g., engaging versus. frustrating) and shed light on which physiological responses are adaptive. Further, future studies should investigate whether young children are able to modulate their physiological arousal effortfully, and whether their physiological arousal can be manipulated by different emotional and behavioral regulation strategies in the face of critical feedback. For example, children randomly assigned to distract or reappraise their emotions during a sad film showed less RSA reactivity (Davis et al., 2016). In young adults, random assignment to use distraction techniques after a stressor also facilitated swifter physiological recovery (Glynn, 2002). Reappraisal strategies—or adult reassurance—may similarly modulate young children's PNS reactivity to and recovery from critical feedback.

More in situ work is needed to examine the extent to which our findings are generalizable across different educational settings (Obradović & Armstrong-Carter, 2020). However, the current findings have real-life implications for children's developmental trajectories of adjustment. Educators working with young children should consider how receiving critical feedback may affect their students physiologically. Our study revealed that the period after critical feedback has ceased may be especially relevant for young students with lower self-regulatory skills. Educators may consider offering these students support vis-a-vis self-regulation strategies or appraisal strategies in order to minimize potential deleterious effects that prolonged stress arousal can have on health and learning (Obradović & Armstrong-Carter, 2020). Research in classrooms could clarify whether behavioral self-regulation and parent-child co-regulation explain variability in children's physiological adaptation to receiving critical feedback in real, daily, and educational settings. Such field work would also facilitate larger and more representative samples. Finally, it is important to extend this work to identify how variability in physiological responses to similar challenges map onto young learners' short-term and long-term achievement and well-being (Brody et al., 2014; Hostinar & Miller, 2019).

ACKNOWLEDGMENTS

The preparation of this article was supported by (a) a Jacobs Foundation Advanced Research Fellowship grant to Dr. Jelena Obradović, (b) a doctoral fellowship to Emma Armstrong-Carter funded by the Institute of Education Sciences, U.S. Department of Education, through Grant R305B140009 to the Board of Trustees of the Leland Stanford Junior University, and (c) the Stanford Data Science Fellowship awarded to Emma Armstrong-Carter.

CONFLICT OF INTEREST

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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How to cite this article: Armstrong-Carter E, Sulik MJ, Obradović J. Self-regulated behavior and parent-child co-regulation are associated with young children's physiological response to receiving critical adult feedback. *Soc Dev*. 2021;30:730–747. https://doi.org/10.1111/sode.12498