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RESEARCH ARTICLE

More than meets the eye: Examining physiological and behavioral regulation during delay of gratification task

Radhika S. Raghunathan[1] | Janet A. DiPietro[2] | Nicole Knudsen[3] | Rashelle J. Musci[4] | Sara B. Johnson[1,2,4]

[1] Department of General Pediatrics, Johns Hopkins School of Medicine, Baltimore, Maryland, USA

[2] Department of Population Family and Reproductive Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA

[3] Krieger School of Arts and Sciences, Johns Hopkins University, Baltimore, Maryland, USA

[4] Department of Mental Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA

Correspondence
Radhika S. Raghunathan, 1620 McElderry Street, Reed Hall Room 201, Baltimore, MD 21205, USA.
Email: rraghun1@jhu.edu

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Abstract

Children continually encounter situations where they must regulate impulsive responses to achieve a goal, requiring both self-control (SC) and delay of gratification. We examined concurrent behavioral SC strategies (fidgeting, vocalizations, anticipation) and physiological regulation (heart rate [HR], respiratory sinus arrhythmia [RSA]) in 126 children (M (SD) = 5.4 (0.29) years) during a standard delay of gratification task. Latent variable models derived latent SC classes and examined the moderating role of HR/RSA on SC and delay ability. Three classes of SC were identified: *passive*: low fidgeting and vocalizations, moderate anticipation; *active*: moderate fidgeting, low vocalizations, and high anticipation; and *disruptive*: moderate fidgeting, high vocalizations, and high anticipation. Children in the *active* class had the lowest odds of delaying full task time, compared to children in the *passive* ($OR = 0.67$, $z = -5.25$, $p < .001$) and *disruptive* classes ($OR = 0.76$, $z = -2.03$, $p = .04$). RSA changes during the task moderated the relationship between SC class and delay ability for children in the *active* class (a$OR = 0.92$, $z = -3.1$, $p < .01$). Within the group who struggled to delay gratification (*active* class), a subset exhibiting appropriate autonomic regulation was able to delay. The findings suggest probing congruency of observed behavioral and unobserved physiological regulation.

KEYWORDS
autonomic regulation, delay of gratification, latent variable analysis, self-control

1 | INTRODUCTION

Self-regulation, the ability to monitor, evaluate, deploy, and inhibit behaviors or emotions to attain a goal or desired environmental response (Blair & Ursache, 2011), plays an essential role in children's emotional and behavioral adjustment. Self-regulatory capacity in early childhood is linked with a range of positive developmental outcomes, including higher academic achievement, lower rates of smoking and/or substance abuse, and better mental health outcomes in adulthood (Moffitt et al., 2011; Robson et al., 2020). Delay of gratification, or the ability to wait for a delayed reward instead of taking the immediate and/or lesser reward, is a central behavioral indicator of self-regulation. Delay of gratification is most often measured by structured laboratory assessments, particularly the delay of gratification task (Mischel et al., 1989). The ability to delay gratification is closely associated with socioemotional competence, prosocial behaviors, and health-related outcomes such as lower rates of obesity and reduced psychopathy (Caleza et al., 2016; Hernandez et al., 2018; Schlam et al., 2013; Supplee et al., 2011; Watts et al., 2018). Research examining the constellation of children's regulatory processes has explored both biological and physiological underpinnings (i.e., temperament, autonomic regulation) and self-control (SC) strategies and skills (i.e., fidgeting, self-distraction), revealing substantial heterogeneity in how and why children delay gratification (Wilson et al., 2009). For example, some children wait calmly while others fidget or are unable to resist the immediate reward, suggesting individual differences in processes underlying SC. In addition, delay of gratification often requires recruitment of volitional or effortful top-down processes (i.e., cognitive control) to modulate emotional and/or impulsive processes (Casey et al., 2011; Neuenschwander & Blair, 2017; Santucci et al., 2008; Wilson et al., 2009). However, despite extant research on factors associated with delay of gratification in childhood, few studies have focused specifically on understanding how children deploy SC strategies along with the physiological changes that modulate emotional/impulsive processes, driving delay of gratification ability. These interactions may have implications for understanding the relationship between children's ability to delay gratification and socioemotional adjustment. Therefore, the current study aims to address gaps in the literature on the interaction between behavioral and physiological processes underpinning delay of gratification in preschool-age children.

1.1 | Self-control strategies and delay of gratification

Observable SC strategies begin as early as infancy. Strategies such as deliberate attention deployment (i.e., directing attention toward or away from reward; Rodriguez et al., 1989; Sethi et al., 2000), self-distraction (i.e., distraction or engaging in other activities; Supplee et al., 2011), verbalizations (e.g., "I am not going to take the reward"; Manfra et al., 2014), and motor activity (i.e., fidgeting; Hong et al., 2017; Neuenschwander & Blair, 2017) have been examined as forms of arousal/anticipation control during tasks requiring SC.

Research on SC behaviors in children can be generally categorized into experimenter-directed and spontaneous/child-directed behaviors. Our focus is on the latter: examining spontaneous/child-directed SC strategies and their relationship with physiological regulation during the delay of gratification task.

Experimenter-directed SC strategies include focusing on fun/abstract thoughts as methods of distraction or providing toys as a distraction (Mischel et al., 1972, 1989), presenting children with a set of SC behaviors to imitate (Corriveau et al., 2016), or conveying the importance of willpower through storybook characters (Haimovitz et al., 2020). On the other hand, spontaneous or child-directed SC strategies are observed in children during a task and then analyzed. For example, Rodriguez et al. (1989) conducted one of the initial studies examining children's spontaneous behaviors during Mischel's delay of gratification task to develop a behavioral coding scheme capturing strategic attention deployment. This coding scheme was adapted by Sethi et al. (2000) to understand differences in coping strategies toddlers use when separated from their mothers and types of attentional strategies during the delay of gratification at age 5. Several other investigators have focused on spontaneous child behaviors related to attention and distraction during tasks that require SC as well (Jahromi et al., 2019; Murray et al., 2016; Supplee et al., 2011).

Fewer studies have examined the role of fidgeting and self-talk as SC strategies. Hong et al. (2017) measured both spontaneous attention deployment strategies (i.e., averting attention to reward) and examined maternal ratings of motor activity levels in 9-year-old children. The findings indicated an interaction between attention deployment strategy and activity levels in children's delay of gratification ability (Hong et al., 2017). For example, among children who used a more effective attention deployment strategy (i.e., averting attention to reward), there was no relationship between activity levels and delay ability; however, higher activity levels were associated with shorter delay time in the group of children who used a less effective behavioral strategy (i.e., directing attention toward reward) during the task. One study examined preschool-aged children's spontaneous motor movement and verbalizations during a resistance-to-temptation task aimed to parse motor and verbal components of SC (Manfra et al., 2014). Children who used motor, verbal, or a combination of strategies were able to resist temptation longer than children who did not (Manfra et al., 2014). Taken together, children who can effectively shift their attention away from the reward use self-distraction techniques such as fidgeting and self-talk and/or a combination of strategies are most often able to delay gratification.

Less is known about the role of anticipation toward the reward during the delay task. An inverted-U relationship between anticipation toward reward and delay ability has been proposed such that moderate levels of anticipation may be beneficial for children's delay of gratification, while high and low levels of anticipation are related to less ability to delay (Neuenschwander & Blair, 2017). In prior work from our research group, 5-year-old children whose level of anticipation was concordant with the level of SC strategies used during the delay task (i.e., moderate or high anticipation and moderate or high levels of fidgeting and vocalizations) were more likely to delay the full task time as compared to children who were driven by anticipation (Raghunathan et al., under review). As such, regulation related to delaying gratification may represent the "tug of war" between underlying anticipation/temptation and SC strategies.

1.2 | Autonomic regulation and SC strategies during delay of gratification

The autonomic nervous system (ANS) is implicated in self-regulation and socioemotional capacity due to its interconnections with limbic brain systems (e.g., amygdala, thalamus, hypothalamus) responsible for emotional and psychological aspects of development (Mulkey & du Plessis, 2019). This interplay between the ANS and the limbic neural network facilitates physical, environmental, and social experiential influences on behavior, emotion/self-regulation, and socioemotional well-being through the course of development.

Changes in autonomic indicators and/or behavioral and emotional regulation strategies over a battery of self-regulatory tasks have been examined (i.e., Coulombe et al., 2019; Manfra et al., 2014; Sacrey et al., 2021), but few have parsed these processes into delay-specific tasks. Most studies examining associations between the ANS and children's regulation ability rely on measures of cardiac parameters as expressions of ANS control, including heart rate (HR) and respiratory sinus arrhythmia (RSA), with greater focus on the latter. In general, the results from this literature indicate that higher levels of basal RSA and increased vagal suppression (or a decrease in RSA relative to baseline or resting values) are moderately associated with better SC and regulatory capabilities. Children with lower basal RSA (indicative of higher arousal at rest), over-suppression of RSA in response to challenge/stressor, or both, may be highly attentive to environmental challenges to an extent that might be detrimental to appropriate coping or adaptation (Hinnant & El-Sheikh, 2009). This relationship between basal RSA/RSA regulation and self-regulatory capacity may also be dependent on social context (i.e., socioeconomic status; Sturge-Apple et al., 2016) and/or the nature of the challenge/task (i.e., executive function vs. emotion regulation task; Sulik et al., 2015) rather than globally indicative of self-regulation and therefore should be considered in such research. RSA modulation also reflects the ability to engage volitional processes such as sustaining one's attention (Skowron et al., 2014), employing effortful control (Taylor et al., 2015) and executive functions (Laborde et al., 2017), and adapting to one's environment (Sturge-Apple et al., 2016). As such, effective RSA regulation may be an antecedent of delay-control ability.

While spontaneous self-regulatory behaviors and physiological regulation during delay of gratification-related tasks have been examined separately (Skowron et al., 2014; Sturge-Apple et al., 2016; Sulik et al., 2015), limited work has evaluated them in tandem. For example, Santucci et al. (2008) assessed the role of vagal tone/regulation (via RSA) and emotional regulation strategies during the delay of gratification tasks in a sample of 54 children aged 4–7 years. Emotion regulation strategies such as active distraction (i.e., singing or dancing), passive waiting, and physical comfort-seeking (i.e., asking to be held) were coded during the delay task, informing three constructs: negative focus on delay, behavioral distraction, and positive reward anticipation (Santucci et al., 2008). RSA at rest (baseline), during the delay task (reactivity), and post-task (recovery) were examined with emotion regulation strategies used by the child and maternal ratings of child temperament. Children with lower vagal recovery and higher mother-reported negative affect had more maladaptive emotional regulation strategies (negative focus on delay) and failed to delay gratification (Santucci et al., 2008). Vagal tone measures and temperament ratings were unrelated to adaptive emotion regulation strategies (behavioral distraction or positive reward anticipation) during the task. Children's level of temptation or anticipation toward the reward, however, was not measured.

Children's concurrent physiological responses and self-regulatory behaviors during a delay task were examined in 91 children aged 8–11 years, but only for children who delayed the full task time (Wilson et al., 2009). Ratings of behaviors indicating difficulty delaying included observations such as boredom, fidgeting, annoyance, facial grimaces, and focusing on the prize during the delay task. In addition to behavioral observations during the delay task, Wilson et al. (2009) also examined emotionality, self-regulation and child adjustment problems using maternal and child self-reported questionnaires. Cluster analysis indicated that children with low electrodermal and HR reactivity had the lowest self-regulation and highest adjustment problems, similar to children who did not delay the full task time; however, cluster analysis was limited to children who delayed the full task time (Wilson et al., 2009).

1.3 | Current study

Despite empirical work examining the autonomic processes underlying self-regulation in general, there is little information regarding physiological associations with behavioral processes underlying delay of gratification per se. Research to date has focused on either behaviorally observable components of delay ability (i.e., attention deployment) or physiological correlates (i.e., RSA) alone, with little focus on the bidirectional interplay between these. Studies that have examined both during a delay task have been limited in their measurement of child behaviors (i.e., not measuring anticipation toward reward or not including fidgeting) or have restricted their analyses to children who only delayed the full task time, thus not tapping into the physiology and behaviors underlying lapses in delay ability. The current study extends the current literature by examining the following questions: (1) are changes in and patterns of autonomic reactivity, specifically, HR, and RSA during a delay of gratification task, different for children who delayed versus did not delay the full task time?; (2) do autonomic indicators moderate the relationship between SC behaviors (fidgeting, vocalizations, anticipation) and delay ability for both children who did and did not delay the full task time?

Based on existing related work (Hinnant & El-Sheikh, 2009; Holzman & Bridgett, 2017), we hypothesize that children who delay the full task time will exhibit high levels of baseline/initial RSA that reach a nadir through the task, coupled with stability in HR during the task, compared to children who do not delay the full task time. Previous research and theory suggest that an interaction between impulsigenic and volitional capacities can explain how anticipatory/attention deployment, non-verbal, and verbal behaviors come together to regulate impulses (Blair, 2002; Blair & Ursache, 2011; Cole et al., 2017, 2019; McGuire & Kable, 2013). As such, we hypothesize that children who can employ behavioral SC strategies to mitigate their level of anticipation toward the reward will be able to delay gratification, compared to children who are driven by their anticipation. Additionally, while data on which to base hypotheses are limited (Wilson et al., 2009), we expect that HR and RSA will dually moderate the relationship between SC and delay ability such that children whose SC strategies helped them delay will have more stability in HR and RSA during the task, compared to children who had ineffective SC strategies as indicated by failing to delay gratification.

2 | METHODS

2.1 | Participants

Participants were 5-year-old children recruited in two different ways. Mothers of Cohort 1 participated in a study that began during the

TABLE 1 Sociodemographic characteristics between Cohorts 1 and 2

Variable	Cohort 1 ($n = 50$) Mean (*SD*)	Cohort 2 ($n = 76$) Mean (*SD*)	t or X^2
Maternal Age (years)	37.5 (4.5)	30.0 (6.9)	7.37***
Maternal Education (years)	18.1 (2.9)	12.6 (2.2)	11.38***
Married (%)	94	17.1	71.49**
Maternal Race and Ethnicity (%)			70.0***
Non-Hispanic White	78	11.3	
Hispanic White	4	0	
Black	12	86	
Other	6.0	2.8	
Child Age (years)	5.4 (0.29)	5.5 (0.27)	−2.79**
Girls (%)	60	52.6	0.66
Child Race and Ethnicity (%)			68.36***
Non-Hispanic White	73.5	8.5	
Hispanic White	4.1	2.8	
Black	16.3	88.7	
Other	6.1	0	
In Pre-K or Kindergarten (%)	66	67	0.02
Child BMI (% overweight/obese)	4	53	32.10***

Note: Child body mass index (BMI) is categorized as underweight/normal weight versus overweight/obese.
$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

prenatal period and required multiple prenatal visits. This group skewed predominantly well-educated and non-Hispanic White (for further details see DiPietro et al., 2010). To provide a more diverse sample for this study, mother–child pairs in Cohort 2 were recruited from a large urban area through community postings and fliers around the city (i.e., community centers, churches, markets) when children were 5 years old (Riis et al., 2015). Table 1 presents and compares sociodemographic characteristics by cohort. Women of children in Cohort 1 were on average older, completed more years of education, and were more likely to be married than women in Cohort 2. Children in Cohort 2 were slightly older than children in Cohort 1, with no differences in child sex or school attendance between the samples. Children's reported race and ethnicity matched mothers' race and ethnicity composition for each respective sample.

A total of 151 children participated in a laboratory visit; 54 (93%) from Cohort 1 and 90 (97%) from Cohort 2 had a useable delay of gratification task data (three children in Cohort 2 had an incomplete visit or did not complete the delay of gratification task, and four children from Cohort 1 had no video data due to protocol error). Eleven children ($n = 9$ boys) ate the snack reward immediately upon presentation and, therefore, did not have audio/video-recorded data to code, resulting in 133 children with usable behavioral data during the delay task. Of the 133 children, seven children did not have usable physiological data due to electrocardiograph pads becoming unstuck ($n = 6$) or high levels of artifact ($n = 1$). Therefore, the final analytic sample was restricted to 126 children ($n = 50$ Cohort 1 and $n = 76$ Cohort 2) with usable physiological and behavioral data.

2.2 | Procedures and measures

2.2.1 | Overview

Study visits were conducted in a dedicated laboratory space. Visits lasted approximately 90 min, during which children engaged in a battery of tasks to assess cognitive and executive functioning and emotional regulation. Among these was the delay of gratification task, central to the results described here. Electrocardiogram (ECG) data were collected throughout the visit. All tasks were audio/video-recorded. While children were being evaluated, mothers completed questionnaires on themselves and their child's behavior and development in a separate room. This study protocol was approved by the Johns Hopkins School of Public Health Institutional Review Board. Women provided informed consent for themselves and their children.

2.3 | Delay of gratification task and SC strategies

The delay of gratification task (delay task) is an assessment of SC, manifested as impulsivity regulation and inhibitory/attentional control (Mischel et al., 1989). For this task, children were given the option to ring a bell and take an immediate reward of one snack (either marshmallow or pretzel based on the child's preference), or if the child waited for the experimenter to return, they would receive two snacks. The child was left alone for 8 min or until they rang the bell.

The current analyses examined data from the instruction period (instruction duration was defined as the period of the time when the research assistant provided task instructions to the child) and task period (task duration was either 8 min or until the child ate the snack reward/rang the bell to bring the research assistant back). Whether a child waited the full 8 min vs. did not wait had been previously recorded for this task.

Fidgeting and vocalization as SC strategies and anticipation toward snack reward were coded to assess individual differences in behavior that contributed to ease or difficulty in delaying (see the Supplemental Materials for coding scheme). The coding of behavioral SC strategies used in this study was influenced by previous behavioral rating systems for inhibitory control tasks (Goldsmith & Rothbart, 1999) and observations of child behavior from delay task videos (i.e., attention deployment, intensity of fidgeting, facial, vocal and bodily expression of emotion). Videotapes were coded by a primary coder, and 20% of videos were double-coded to establish reliability (weighted Cohen's kappa). Partial interval coding was used with a decision rule that only behaviors that occurred for most of the interval (at least 16 s of the 30-s epochs) were recorded for that interval. This captured the most dominant behavior during the interval and accounted for over- and underestimation that often occurs with other methods of discontinuous data collection. Continuous composite scores for fidgeting (inter-rater reliability $\varkappa = 0.78$, $p < .001$) and vocalizations ($\varkappa = 0.88$, $p < .001$), created by averaging the level of fidgeting and vocalization strategies through the delay period (up to 8 min or 16 intervals of 30 s) separately, and a global categorical score for anticipation ($\varkappa = 0\ .78$, $p < .001$) during the delay task.

2.4 | Psychophysiological data acquisition

Children were seated during ECG instrumentation and were instructed to remain seated during the study visit. ECG was collected through three electrodes placed as follows: right clavicle near the sternum, superior to the first rib; near the junction of the transpyloric and midclavicular planes; and upper abdomen near the lower right rib. ECG data were sampled at 1000 Hz and recorded continuously for the duration of the laboratory visit (Mindware Technologies Ltd., BioNex Desktop Platform).

Data were subsequently analyzed using Mindware Technologies Ltd., HR Variability (HRV) Analysis Software version 3.0. Artifact was detected using dual algorithms (IBI Min/Max and MAD/MED) within Mindware based on the detection of values that exceeded predetermined thresholds. R-waves that were identified as potential outliers were marked. ECG data were manually edited based on flagged artifacts by deleting erroneous R-waves, adding missing R-waves, and estimating where R-waves should be if data were not clear. Some degree of data editing was required for 25 cases due to physiological artifacts, outliers/implausible physiologic values, or missing data within Mindware Software. ECG data were visually inspected for each child during the delay of gratification task; 30-s segments with more than 5% estimated R-waves were dropped. ECG data were collected but not usable due to excessive artifacts for one participant (Cohort 2). Sensitivity analyses were performed comparing values from the 25 cases with edited data and treating any outliers/missing values as missing, resulting in no differences in means.

2.5 | Psychophysiological data quantification

Digitized psychophysiological data were extracted and quantified as follows. HR: Interbeat intervals (IBI) were timed (ms) and converted to HR (bpm, beats per minute). Mean values were computed for the duration of the instruction period, for the total task period, and in 30-s intervals (i.e., up to 16 intervals depending on delay time) during the task. RSA: Collecting respiratory data from children is often difficult, especially since respiration data are sensitive to movement or shifts in respiration belt placement. Therefore, investigators often rely on frequency-domain analyses (i.e., heartbeat to beat timing) for examining RSA in children. In our study, respiration was not measured directly, so RSA was calculated based on IBI time series and spectral analysis using high-frequency HRV as follows: RSA = ln (HFPower) within Mindware. RSA calculations used age-adjusted respiratory frequency bands, 0.15–0.8 Hz, as typically done to account for children's faster rates of breathing (Bar-Haim et al., 2000). Mean values were computed for the length of the instruction period, for the total task period and in 30-s intervals during the task.

Two sets of change scores were computed to assess physiological regulation:

<u>HR and RSA response to task</u> (*dMeanHR*, *dMeanRSA*): Mean task HR and RSA values were subtracted from mean instruction HR and RSA separately to assess change in autonomic functioning prechallenge (instruction period) and during the challenge (task); positive values indicate an increase in HR or RSA in the task period compared to the instruction period.

<u>Change in HR and RSA during task</u> (*dDelayHR*, *dDelayRSA*): To characterize changes in HR and RSA *during* the task period, difference scores were calculated for each child by subtracting the mean HR or mean RSA value at the end of the task (i.e., either 16th interval or when the child rang the bell to end the task) from the mean values at the start of the task (Interval 1). For example, if a child waited the full task time, the delta for HR or RSA was calculated as the mean physiological value at Interval 16 minus the mean physiological value at Interval 1; if a child only waited part of the time, the delta reflected the mean physiological value of the last 30-s interval the child waited minus the mean value at Interval 1. This approach was taken to account for the varying number of intervals a child waited. Positive values for this variable indicate lower starting HR or RSA values, compared to values at the respective end of the delay task (increasing HR or RSA during the task period).

2.6 | Maternal and child covariates

Key confounders were informed by the literature on HR/RSA regulation and SC in childhood (Cicchetti & Dawson, 2002; Giuliano et al., 2018; Hinnant & El-Sheikh, 2009; Holochwost et al., 2018). Maternal age, education, marital status, race and ethnicity, and child age, sex, race, ethnicity, and school attendance were all collected through maternal reports. Children's body mass index (BMI) was included as a covariate since the delay task specifically uses a snack as a reward and given the established associations between snack-delay tasks and children's BMI (for review, see Caleza et al., 2016). Children's BMI was also incorporated to control for the impact of body size and composition on physiological reactivity. Child height and weight measured at the study visit were used to compute age- and sex-adjusted BMI based on the Centers for Disease Control and Prevention guidelines for age- and sex-adjusted BMI percentile cutoffs (Centers for Disease Control & Prevention, 2021). Children were classified into two categories (underweight/healthy or overweight/obese) based on age- and sex-adjusted BMI percentile cutoffs.

2.7 | Data analyses

Descriptive and exploratory analyses (*t*-tests, χ^2 analyses, and Pearson correlation coefficients) examined associations between selected maternal and child covariates and children's delay ability. *t*-tests assessed differences in instruction duration between children who delayed the full time versus children who did not delay the full time. Variance inflation factors were evaluated for potential multicollinearity between a cohort indicator (variable indicating whether children were from Cohort 1 or 2 included to account for potential unmeasured/non-measurable differences in samples) and selected maternal demographics (age and education).

Independent measures included HR and RSA during the instruction and task segments and HR and RSA change scores from instruction to task (*dMeanHR* or *dMeanRSA*) and from start of task to end of task (*dDelayHR* or *dDelayRSA*). First, we generated plots of mean HR and RSA during the delay task to examine epoch-by-epoch patterns (Figures 1 and 2). Next, differences in these HR and RSA patterns between children who delayed and did not delay were examined using two sample *t*-tests, Mann–Whitney two-sample tests and variance ratio tests. Then, we fit mixed-effects models, with and without a time by delay ability (delayed full task time, yes vs. no) interaction term, to further quantify patterns in HR and RSA. Bivariate analyses and examination of epoch-by-epoch mean plots were used to inform which independent variable(s) best characterized children's physiological reactivity for the delay task. Finally, separate multivariate logistic models, with stepwise addition of covariates, were used to investigate the adjusted relationship between selected physiological measures and delay ability. Fit statistics and diagnostics (i.e., χ^2 goodness of fit, Akaike information criterion (AIC), Bayesian information criterion (BIC)) were used to evaluate the final model fit.

Mixture modeling, using the Bolck, Croon, & Hagenaars (BCH) method, was employed to examine the joint association of physiological measures and SC strategies/anticipation in predicting children's delay ability. First, the heterogeneity of SC strategies/anticipation that children used during the delay task was modeled using latent class analysis. Indicators to characterize patterns of children's SC strategies for the latent class model included levels of fidgeting, vocalizations, and anticipation. We used several fit statistics (BIC and the Lo–Mendell–Rubin (LMR) test; Nylund et al., 2007) along with the substantive interpretation of classes to select classes. Next, an unconditional model was run to create BCH weights that reflect the measurement error of the latent class variable; using a weighted multiple-group model is advantageous to avoid class shifting in subsequent models (Asparouhov & Muthén, 2014). Finally, using the BCH weights, the moderating role of physiological variables on the relationship between latent SC classes (independent variable) and delay ability (dependent variable) was tested. Here, we modeled the influence of covariates on the latent SC classes and outcome of interest (main effect) as well as interactions between latent SC classes and physiological variables (moderation). Full information maximum likelihood estimation was used to account for missingness.

Analyses were conducted using Stata version 16.1 (StataCorp, 2019) and *Mplus* version 8 (Muthén & Muthén, 1998–2017).

3 | RESULTS

Of the 126 children with usable physiology and behavioral data, 82 (65%) delayed the full task time and 44 did not; exploratory analyses showed a bimodal distribution of continuous delay time; therefore, delay ability remained a dichotomous variable (delayed full task time vs. did not delay full task time). Children who delayed the full task time were more likely to be girls ($\chi 2(1) = 4.19$, $p = .04$) and more likely to be underweight/normal weight than overweight/obese ($\chi 2(1) = 4.47$, $p = .03$), compared to children who did not delay. Post hoc analyses revealed that boys in Cohort 2 were less likely to delay the full task time than girls in Cohort 2 ($\chi 2(1) = 7.40$, $p = .007$); there were no sex differences in delay in Cohort 1 ($\chi 2(1) = 0.15$, $p = .70$). Child age was unrelated to delay ability. Mothers of children who delayed the full task time were somewhat older than mothers of children who did not delay ($M = 34.1$, $SD = 7.2$ vs. $M = 31.0$, $SD = 6.4$; $t(124) = -2.35$, $p < .05$); however, there were no other differences detected in maternal characteristics. Additionally, there was no difference in children's delay ability by cohort (Cohort 1 vs. Cohort 2).

The instruction period was relatively brief ($M = 82.0$ s, $SD = 22.9$), compared to the task period ($M = 367.9$ s, $SD = 175.1$). However, mean HR in the instruction period and task period were highly correlated, $r\ (124) = .82$, $p < .001$, as were mean RSA during the instruction and task periods, $r\ (122) = .76$, $p < .001$, indicative of the intraindividual stability of these measures. Since the task period for some children was as short as 30 s, correlations were recalculated using data from a subset of children with at least 3 min of task data to assess the stability of the

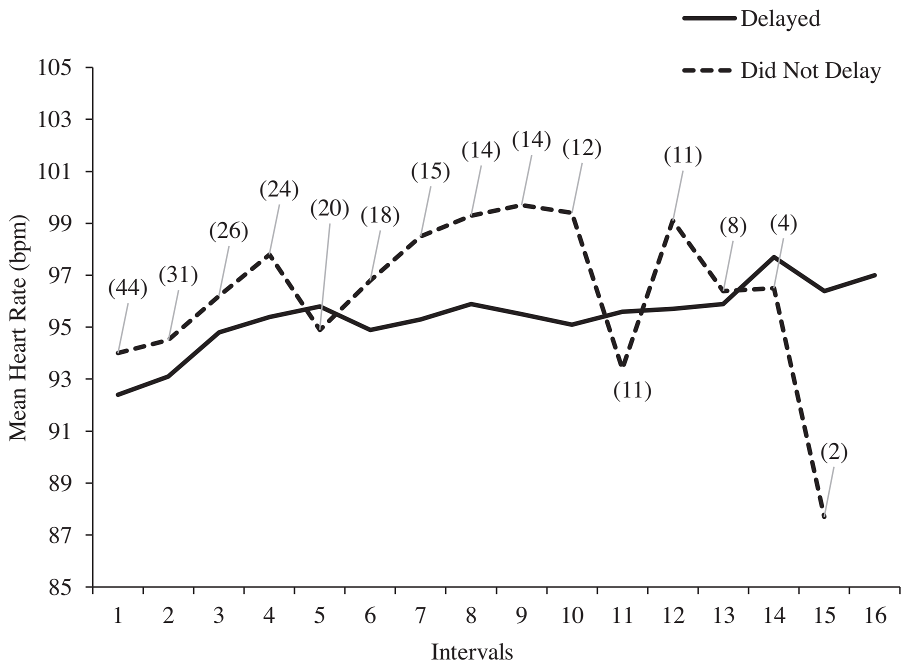
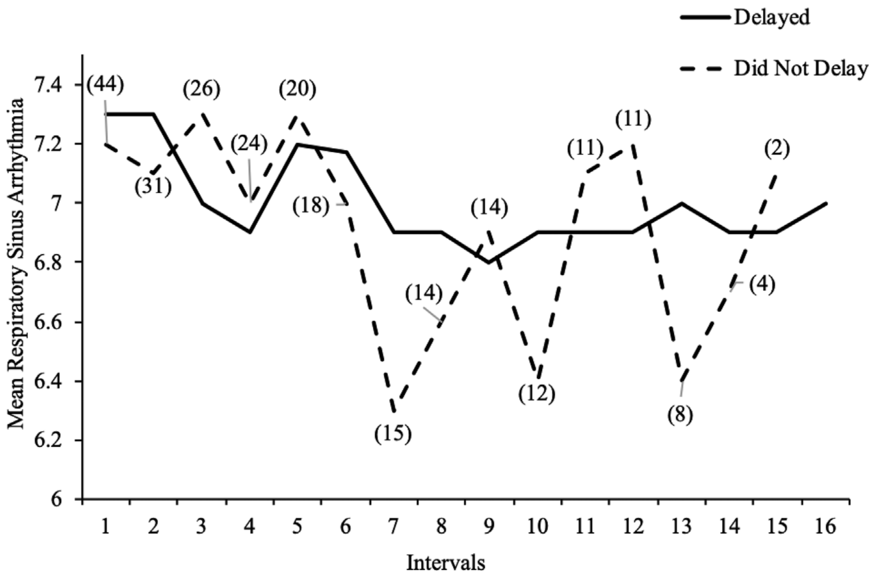


FIGURE 1 Patterns of heart rate (HR) during delay of gratification task comparing children who delayed and did not delay. *Note*: (Value) reflects decreasing sample size for children who did not delay at each respective interval; sample size for children who delayed is $n = 82$ across intervals

FIGURE 2 Patterns of respiratory sinus arrhythmia (RSA) during the delay of gratification task comparing children who delayed and did not delay. *Note*: (Value) reflects decreasing sample size for children who did not delay at each respective interval; sample size for children who delayed is $n = 82$ across intervals



derived RSA and HR measures. The correlation between mean HR and mean RSA for children with at least 3 min of task data, $r(95) = -.55$ $p < .001$, was similar to the correlation with all children, $r(124) = -.51$, $p < .001$, providing confidence in the reliability of the measure regardless of wait time.

There was a trend level association between delay ability and the duration of the instruction period, such that children who delayed the full task time had slightly shorter instruction periods than children who did not ($M = 78.9$ s, $SD = 19.1$ vs. $M = 87.6$ s, $SD = 28.1$; $t(64.8) = 1.82$, $p = .07$); instruction duration, therefore, was considered a covariate and examined with selected physiological measures for confounding.

3.1 | Sociodemographic correlates of cardiac variables

Segment and change scores for HR and RSA did not differ between Cohort 1 and Cohort 2 (all $ps > .20$). There was a trend-level association

TABLE 2 Physiological measures and delay ability

Variable	Delayed ($n = 82$) Mean (SD)	Did not delay ($n = 44$) Mean (SD)	t or X^2
Heart Rate (HR)			
Instruction Period	94.3 (8.4)	93.5 (9.9)	−0.50
Overall Task	95.3 (8.5)	95.6 (11.3)	0.17
Instruction to Task Change	0.93 (4.4)	2.1 (7.1)	0.98
Change during Task	4.7 (6.6)	30.3 (44.8)	3.77***
Respiratory Sinus Arrhythmia (RSA)			
Instruction Period	6.8 (1.3)	7.1 (1.9)	0.81
Overall Task	7.0 (1.3)	7.1 (1.7)	0.42
Instruction to Task Change	0.17 (0.78)	−0.07 (1.4)	−1.0
Change During Task	−0.35 (1.5)	1.8 (3.6)	3.81***

Note: Instruction period duration: $M = 82.0$ s, $SD = 22.9$, task period duration: $M = 367.9$ s, $SD = 175.1$; HR and RSA change during task reflect difference between the end of task and start of the task for each child; positive values indicate greater HR or RSA at end of task as compared to start of task.
***$p < .001$.

between child BMI category and HR during the instruction period only, such that children who were overweight/obese had a faster average HR of ~3 bpm than children who were underweight/normal weight, $t(124) = -1.92$, $p = .06$. No other associations were detected with child covariates (child age and child sex) and the cardiac segment values or change scores. Child sex was associated with mean instruction RSA, such that boys had lower average RSA during the instruction period than girls ($M = 6.6$, $SD = 1.5$ for boys vs. $M = 7.2$, $SD = 1.6$ for girls, $t(122) = -2.31$, $p = .02$). There were no other associations found between child-level covariates and RSA parameters. Maternal age and education were unrelated to the cardiac segment values and the change scores.

3.2 | Cardiac variables and delay ability

Differences in the segment values and change scores comparing children who delayed the full task time and children who did not are presented in Table 2. No differences in mean HR or RSA values during instruction or task periods or for *dMeanHR* and *dMeanRSA* comparing children who delayed to children who did not delay were detected. There were only differences in *dDelayHR* and *dDelayRSA*; children who delayed showed less increase in HR from the start of the task to the end of the task ($M = 4.7$ bpm, $SD = 6.6$ vs. $M = 30.3$ bpm, $SD = 44.8$, $t(44) = 3.8$, $p < .001$) and a greater decrease in RSA ($M = -0.35$, $SD = 1.5$ vs. $M = 1.8$, $SD = 3.6$, $t(51.3) = 3.8$, $p < .001$) from the start of the task to the end of the task, compared to children who did not delay.

Epoch-by-epoch means of HR (Figure 1) and RSA (Figure 2) for children who delayed and children who did not delay were plotted to discern whether children exhibited different temporal patterns of HR or RSA during the task period. Visual examination suggested that children who delayed had stable but somewhat increasing HR during the task, while children who did not delay showed accelerating HR commencing near Interval 6 (3 min into the task) diverging from delayers. However, point-by-point comparisons of mean HRs did not indicate significant differences between children who delayed and did not delay. Differences were likely not detected due to small sample sizes in the group of children who did not delay and the somewhat larger variances when comparing delayers to non-delayers. Children who delayed had a more stable but decreasing trend in RSA during the task period, while non-delayers showed greater variation in epoch-by-epoch means. Again, point-by-point comparison of mean RSA did not indicate significant differences between children who did and did not delay.

Mixed-effects regression models were run to further examine patterns of HR and RSA during the task. Separate models for HR and RSA were run with a random intercept at the subject level to account for expected associations in HR and RSA values within subjects. Mixed-effects models with a time by delay (time x delay) interaction term were considered, and model fit was compared to models without the interaction term. For HR and RSA, likelihood ratio tests indicated that the model with the time x delay interaction term fit better than the model without the interaction term (for HR model $LR\chi2(29) = 98.2$, $p < .001$; for RSA model $LR\chi2(29) = 46.1$, $p < .05$). The results of the models indicated no significant difference in patterns of HR (*coeff* $= -1.63$, $z = -0.86$, $p = .40$) or RSA (*coeff* $= 0.14$, $z = 0.44$, $p = .66$) between delayers and non-delayers. The small sample size likely limited the power to detect interaction effects in these models. These models were considered only for exploratory purposes.

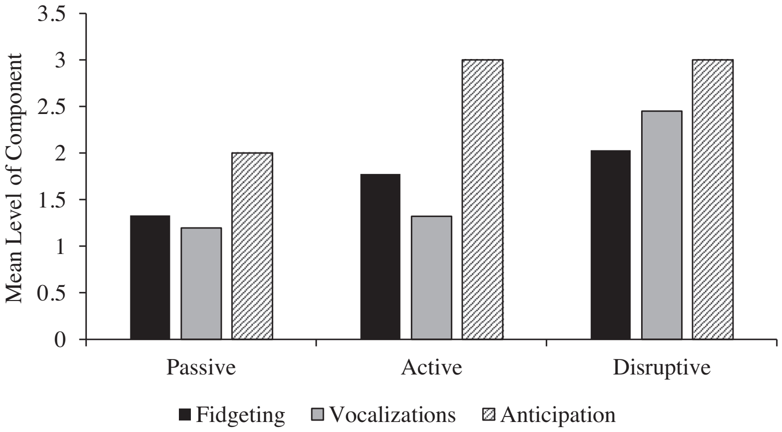
Based on analyses between segment values/change scores and delay ability, while taking into consideration the patterns of HR and RSA during the delay task, only *dDelayHR* and *dDelayRSA* were used in subsequent multivariate analyses, controlling for covariates (maternal age, maternal education, child age, child sex, child BMI category, cohort, and instruction duration). Fit statistics (AIC, BIC, goodness-of-fit) indicated that multivariate logistic regression models accounting for all selected covariates were appropriate for the data.

TABLE 3 Fit statistics for self-control (SC) behaviors latent class enumeration

Fit statistic	1-Class	2-Class	3-Class
Log-likelihood	−335.13	−227.52	−265.25
Akaike information criterion	682.26	577.05	544.49
Bayesian information criterion (BIC)	699.28	608.24	589.87
Sample Size Adjusted-BIC	680.31	573.46	539.27
Entropy	NA	1.00	0.971
Lo–Mendell–Rubin (LMR) adjusted test	NA	110.64	40.86
LMR, *p*-value	NA	< .001***	.05*
Bootstrap Likelihood Ratio Test (BLRT)	NA	−335.13	−277.5
BLRT, *p*-value	NA	< .001***	< .001***

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

FIGURE 3 Composition of child self-control (SC) behavior classes. *Note*. Mean values for fidgeting and vocalizations for each SC class are presented in this figure. The anticipation level presented here is based on odds ratios for class membership. The figure reflects the composition of child SC behaviors for 126 children with psychophysiological and behavioral data



The direction of associations between *dDelayHR* and delay ability (a*OR* = 0.96 (CI: 0.94, 0.98), $z = -3.59$, $p < .001$) and *dDelayRSA* and delay ability, a*OR* = 0.73 (CI: 0.61, 0.88), $z = -3.32$, $p = .001$, found in preliminary analyses remained after adjusting for covariates. None of the covariates in these models reached statistical significance.

3.3 | SC classes and delay ability

A three-class solution was selected to model children's SC strategies; the class enumeration process has been discussed elsewhere (Raghunathan et al., under review). Briefly, 1-, 2-, and 3-class models were fit using fidgeting, vocalizations and anticipation as indicators, and a 3-class model was selected based on BIC values, LMR test statistics, and substantive interpretation of latent classes (see Table 3 for fit statistics). The composition of classes was comparable to our group's prior work (Figure 3): *Passive* class (Class 1, $n = 64$) who had low levels of fidgeting and vocalizations but moderate anticipation, for example, children who sat generally sat calmly and quietly during the task; *active* class (Class 2, $n = 52$) who had moderate levels of fidgeting, low vocalizations but high anticipation, or the children who tended to fidget, engage in some self-talk, and showed frustration during the task; and *disruptive* class (Class 3, $n = 10$) who had moderate fidgeting and high vocalizations and anticipation, such as children who were in and out of their seat through the task, yelled, and fixated on the snack reward; the *disruptive* class had relatively higher levels of all three SC components, compared to *passive* and *active* classes, however, differences were small. There were no shifts in class structure when comparing latent models with and without covariates. Children in the *disruptive* class were more likely to have a longer duration of the instruction period than children in the *Passive* class (Odds Ratio (OR)*OR* = 1.03 (CI: 1.01, 1.06), $z = 2.47$, $p = .013$). Selected maternal and child characteristics and the cohort indicator were unrelated to SC classes.

Children in the *Passive* class were most likely to delay the full task time (85.9%), while delayed children in the *disruptive* and *active* classes were approximately 60% and 40% likely to delay the full task time. Children in the *active* class had the lowest odds of delaying the full task time, compared to children in the *passive* class (*OR* = 0.67 (CI: 0.57, 0.78), $z = -5.25$, $p < .001$) and compared to children in the *disruptive* class (*OR* = 0.76 (CI: 0.59, 0.99), $z = -2.03$, $p = .04$). There were no other differences in delay ability by SC class.

3.4 | Moderating role of HR and RSA reactivity

HR reactivity and RSA reactivity variables were centered at their respective means to test for moderation. Covariates were held constant across classes. The final estimates presented here were obtained

TABLE 4 Interaction of HR and RSA changes during task in the final model predicting delay ability (Model 3)

SC class	Physio variable	Logit[a]	*SE*	Logit/SE	*aOR* [a]
Passive	*HR change During Task*	−0.01	0.01	−1.4	0.99
	RSA change During Task	0.04	0.03	1.4	1.04
Active	*HR change During Task*	0.002	0.002	1.0	1.00
	RSA change During Task	−0.09	0.03	−3.1	.92**
Disruptive	*HR change During Task*	−0.02	0.01	−1.6	0.98
	RSA change During Task	0.09	0.09	1.0	1.09

Note. Model 3 examines the moderating role of HR and RSA changes during tasks on the relationship between latent SC classes and delay ability.

[a] Estimates adjusted for maternal (age, education), child (age, sex, body mass index (underweight/normal weight vs. overweight/obese) characteristics, cohort (Cohort 1 vs. Cohort 2), and instruction duration.

[b] Adjusted odds ratio of delay ability (delaying full task vs. not delaying full task).

**$p < .01$.

from the structural model that accounted for the influence of covariates on class membership and delay ability. The results from the main effects model indicated no relationship among *dDelayHR* (*est.* = −0.003, a*OR* = 1.00, $p = .12$), *dDelayRSA* (*est.* = −0.02, a*OR* = 0.98, $p = .38$) and delay ability after controlling for selected covariates and IC class. Despite non-significant main effects, moderation was still tested to further probe the heterogeneous results seen in preliminary analyses.

Three models for testing moderation effects were run with SC class as the independent variable, *dDelayHR* and/or *dDelayRSA* as the moderator and delay ability as the outcome (*dDelayHR* (Model 1), *dDelayRSA* (Model 2), joint moderating role of dDelayHR and *dDelayRSA* change (Model 3)). The Wald test indicated significant interaction effects in all three models (Model 1: *Wald* (2) = 7.4, $p < .05$; Model 2: *Wald* (2) = 25.3, $p < .001$; Model 3: *Wald* (2) = 9.3, $p < .01$).

Children in the *active* class were less likely to delay the full task time if they had a greater *dDelayHR* than children in the *passive* class, a*OR* = 0.99, $z = -2.6$, $p < .01$; children in the *active* class, compared to the *passive* class, were less likely to delay if their HR was higher at the end of the task than at the start of the task. No other significant associations with covariates or interactions with SC classes were detected in Model 1. Similarly, children in the *active* class were less likely to delay the full task time if they had a *dDelayRSA* change, compared to children in the *passive* class, a*OR* = 0.94, $z = -3.8$, $p < .001$; children in the *active* class were less likely to delay if their RSA was higher at the end of the task, compared to the start of the task. However, in Model 2, children's BMI was also significantly associated with delay ability after controlling for maternal, child, sample, physiological and SC class variables, a*OR* = 0.84, $z = -1.9$, $p = .05$. Here, children who were overweight/obese were less likely to delay the full task time than children who were underweight/normal weight. The results of Model 3 are presented in Table 4 and represented in Figure 4. When the moderating role of *dDelayHR* and *dDelayRSA* were examined together, *dDelayRSA* played a significant role in predicting delay ability; children in the *active* class again were less likely to delay if they had a greater *dDelayRSA*, a*OR* = 0.92, $z = -3.1$, $p < .01$ (see Figure 4). As in Model 2, children who were overweight/obese were less likely to delay the full task time, compared to children who were underweight/normal weight, a*OR* = 0.82, $z = -2.3$, $p < .05$. No other covariates were significant in Models 2 and 3.

4 | DISCUSSION

Our study suggests that preschool-aged children who exhibited physiological flexibility to modulate their anticipation during a delay of gratification task, even children who struggled more with delaying, were able to successfully delay. Using physiological indicators provided a window into differences in regulation that were not evident in behavior alone. Specifically, the findings reveal that (1) changes in HR and RSA during the delay task were associated with children's delay ability and (2) changes in RSA during the delay task moderated the relationship between children's use of SC strategies and children's delay ability, particularly for children who had high levels of anticipation but not the matching level of self-regulatory strategies to quell their anticipation (*active* class). Sociodemographic explorations indicated that child sex and BMI both related to children's autonomic measures and their delay ability; however, there were no differences by study sample.

4.1 | Autonomic regulation and delay of gratification

Autonomic regulation was measured by several derived cardiac regulatory markers, including basal (resting) indicators, task-related indicators, changes between basal and task, and changes during tasks. Most studies to date have focused on basal and/or task-related reactivity (Calkins, 1997; Coulombe et al., 2019; Hinnant & El-Sheikh, 2009; Holzman & Bridgett, 2017; Kahle et al., 2018; Sturge-Apple et al., 2016; Sulik et al., 2015). The current study found no associations between pretask values and physiologic response to task (pretask to task change) and delay ability. Only changes in HR and RSA *during* the task were related to delay ability, even after adjusting for maternal, child, and sample characteristics. Children who delayed showed a smaller increase in HR and a greater decrease in RSA from the start of the task to the end of the task than children who did not delay. Efficient

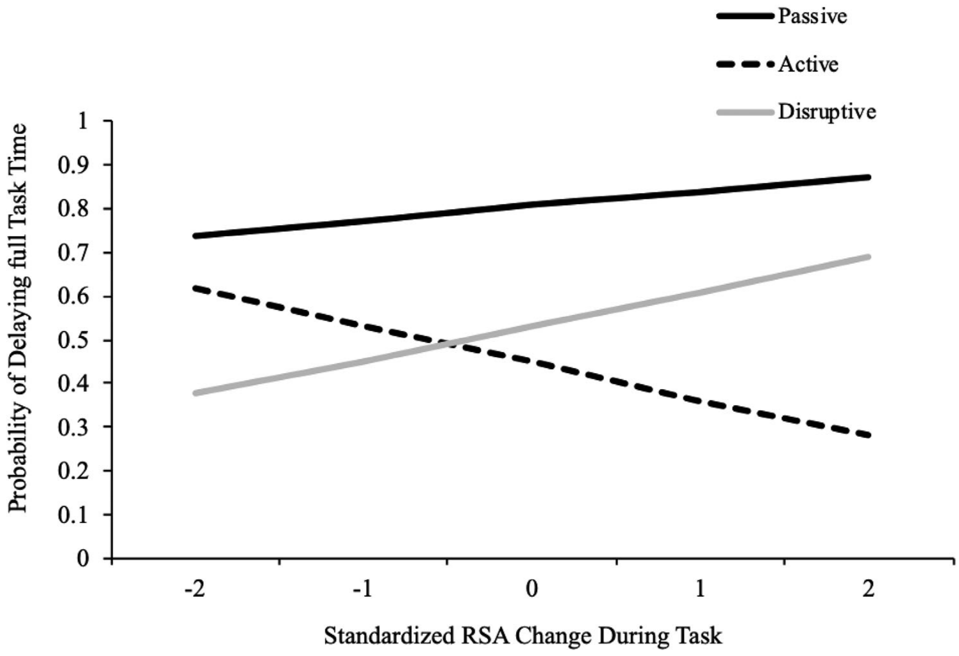


FIGURE 4 SC classes and delay ability: Moderating role of RSA based on Model 3. *Note*. HR and RSA variables were centered at $M = 0$, $SD = 1$. Results reported based on Model 3

suppression of vagal tone is necessary when attention is required for coping with environmental demands, often resulting in a decrease in RSA (and thereby an increase in HR) in response to a challenge (Coulombe et al., 2019; Hinnant & El-Sheikh, 2009; Porges et al., 2007). The association between HR and RSA changes during the task and children's successful delay of gratification is likely an indicator of effective vagal tone suppression in response to adapting to challenging stimuli.

Mixed-effects regression models indicated no differences in point-by-point estimates of HR and RSA means during the delay task. However, after 3 min, children who did not delay the full task time seemed to have more physiological disruption than children who delayed the full task time, who showed more stability in physiologic measures over task time (Figures 1 and 2). Children who delayed the full task time had physiologic patterning that has been reported in the literature as typically characteristic in response to a challenge (Hinnant & El-Sheikh, 2009). The differential physiological patterns of children who did not delay the full task time (e.g., fluctuating during the task), compared to those who did delay the full task time (e.g., relatively stable during the task) may indicate that children who failed to delay the full task time found the task more challenging. The differential patterns seen here might also reflect physiological modulation to adapt (or eventually not adapt) to the task and/or indicative of the balance between anticipation toward the snack reward and resultant modulation of that arousal to complete the task.

Only 35% ($n = 44$) of children did not delay the full task period, with rapid attenuation in the number of children during the task. Although speculative due to the small sample, findings may suggest that pre-task and task-related (overall mean HR or RSA during task) differences between children who do and do not delay alone might miss some of the nuanced variation, or changes, between start and end of task that could be an indicator of physiological flexibility. Further research is needed to confirm this relationship in a larger sample.

4.2 | Moderating role of autonomic regulation during the delay of gratification

By examining biobehavioral processes underlying SC, we gained insight into variation in children's regulatory functioning. Three distinct classes of SC in response to the delay of gratification challenge task were identified based on differing intensities of SC/coping strategies (fidgeting, vocalizations) and anticipation. Children in the *active* SC class had the lowest odds of delaying the full task time compared to children in *passive* and *disruptive* classes. These findings support differential behavioral mechanisms by which children regulate. We see that children who had higher levels of anticipation but who were able to regulate their anticipatory pull by employing regulatory strategies, including a range of behaviors more typically seen as disruptive, such as constant self-talk and fidgeting, were able to delay effectively. Differences in regulatory expression may have implications for classroom behavior management. For example, children in the *disruptive* and *active* classes may benefit from incorporating active breaks during the day to manage their behavior effectively. We caution from overinterpreting results from the *disruptive* class, however, due to only 10 children being in that group.

HR and RSA changes during the task, when examined separately, moderated the role between SC class and delay ability for children in the *active* class (moderate fidgeting, moderate vocalizations, high anticipation). Children in the *active* class were more likely to delay if their HR decreased over the course of the delay task. Similarly, children who effectively suppressed RSA (decrease in RSA over task time) in the *active* class were able to delay the full task time. Visually, children in the *disruptive* class were sensitive to changes in RSA during the delay task, but there were no significant associations detected, likely due to the small sample size for that group. When examining HR and RSA changes during the task together, RSA changes during the task played a greater moderating role. These results are consistent with prior research that suggests that effective vagal suppression aids inhibitory control and delay ability (Hinnant & El-Sheikh, 2009; Holochwost et al., 2018; Holzman & Bridgett, 2017).

The interpretation of increases and decreases in HR with respect to delay and SC tasks is less clear. HRs could be a product of differing levels of children's impulsivity, activation of attentional processes, and/or a result of swift changes in somatic (or motor) activity (Holzman & Bridgett, 2017). However, our study findings were strengthened by the inclusion of RSA, which provides a more robust indicator of parasympathetic contribution to regulation than does HR alone. For children with high anticipation toward the reward (*active* class), vagal (RSA) suppression could help modulate some of the tug of war between SC strategies and impulse-driven processes, enhancing self-regulatory capacity.

Measuring both external (behavioral) manifestations of SC and internal components of SC (e.g., physiological arousal) allows for the examination of congruence between the two. Congruence between external and internal states allows parents, caregivers, and others to rely on children's behaviors as an indication of a child needing support, comfort and/or help (Zantinge et al., 2019). The early development of children's regulation is established and scaffolded through the caregiver environment; caregivers aid in externally modulating their children's response to stressors, which in turn serves to lay the foundation for the development of children's own regulatory capacity (DePasquale, 2020). Incongruence between children's expressed behavior cues and physiological regulation, in contrast, may impact caregivers' ability to decipher their children's behavioral cues, thus impacting caregivers' ability to promote regulatory strategies. As such, incongruence may lead to early developmental vulnerabilities related to self-regulation and social development. While we primarily see incongruence between behaviors and physiological arousal in the *active* class, it is important to consider what incongruence between expressions and internal states signals for children's trajectories related to social and emotional development more generally.

The focus of self-regulation interventions has largely been reducing impulsivity in children (Baker et al., 2019). In our study, we see that it is not just the level of impulse that drives delay ability but also the use of SC strategies. As such, examining the balance between regulation and impulsivity could help direct children into appropriate selective and indicated prevention programs aimed at improving psychosocial well-being. Measuring physiological reactivity to stressors in children is often difficult to scale up. However, with advances in wearable devices (Choi et al., 2017; Schaefer et al., 2014), continuous monitoring of physiological states and changes is somewhat more accessible. This could drive innovation for examining concordance between internal physiological processes and external behavioral and emotional expressions in settings beyond the laboratory. For example, physiological regulation could be used to evaluate the impact of classroom or school-based interventions aimed at improving children's socioemotional well-being and in turn allow for targeting self-regulation on multiple levels.

4.3 | Sociodemographic characteristics relating to delay of gratification

Girls were more likely to delay the full task time than boys. Post hoc analyses showed that boys in Cohort 2 were less likely to delay than girls in Cohort 2, while no sex differences in delay ability were detected in Cohort 1. This is compounded by the observation that nine out of 11 children who did not wait for a single 30-s interval and therefore were not included in the analyses were boys. There has been considerable research examining sex differences in self-regulatory capacity, including delaying gratification (Doidge et al., 2018; Hosseini-Kamkar & Morton, 2014; Silverman, 2003). Some research has suggested that girls tend to delay gratification longer than boys (Silverman, 2003), while other studies have found no sex differences in delay ability alone (Doidge et al., 2018), citing various developmental and evolutionary reasons. The sex differences in delay ability seen in Cohort 2 alone suggest a potential sex-by-sample interaction to be considered to extend this work. In the current study, girls also had higher RSA during the instruction period than boys, suggestive of more activation of a vagal "brake"—slowing down HR to maintain physiologic homeostasis in the absence of threats or challenges for girls in this sample. Boys' low pretask RSA coupled with higher HR could either indicate less self-regulation capacity or higher anticipation toward the snack reward while instructions were presented, both of which could contribute to failure to delay gratification.

Children with BMI indicating overweight status or obesity (35%) were less likely to delay the full task time than those with underweight or normal weight. This relationship remained even after adjusting for maternal, child, sociodemographic, SC strategies, and autonomic indicators. This finding is consistent with that of a systematic review on childhood obesity and delay of gratification behavior that revealed that all studies using a food-based reward in children found a clear relationship between inability to delay gratification and overweight/obese status (Caleza et al., 2016). Several studies included in Caleza and colleagues' review examined relationships between children's BMI and delayed ability using both food and non-food rewards. In general, these studies found that children did not differ in delay ability when the reward was not food-related irrespective of obesity status; however, both obese and non-obese children selected a food-related reward as opposed to a toy when asked for their preference (Caleza et al., 2016). Recent research has implicated the role of self-regulation, particularly delay of gratification and inhibitory control, on children's obesity rates and trajectories of adult BMI outcomes (e.g., Bruce et al., 2011; Hughes et al., 2015; Schlam et al., 2013). Therefore, delay of gratification tasks that rely on food-related rewards, as in this current study, must control for child BMI to measure SC capacity more accurately.

Several studies have found sociodemographic differences in children's autonomic regulation (e.g., Evans & English, 2002; Raver et al., 2011; Sturge-Apple et al., 2016). Socioeconomic context-dependent associations have been seen specifically with respect to vagal tone and delay of gratification: For children in resource-rich settings, high vagal tone was associated with greater delay ability, while high vagal tone for children from families with fewer socioeconomic resources was associated with lower delay of gratification (Sturge-Apple et al., 2016). These researchers proposed that children's functioning and adaptation of stress responses largely vary across socioeconomic risk strata; that is, what is considered adaptive regulation in one risk context may be counterproductive in another. The results of our study suggest no differences in delay ability and autonomic indicators between children from lower social risk (Cohort 1) and higher social risk (Cohort 2) samples. However, further examining contextual factors will be necessary to draw conclusions about context-dependent behavioral and physiological self-regulation.

To our knowledge, this is the first study to provide a detailed examination of physiological, volitional (SC strategies) and impulse-driven/anticipatory processes underlying children's delay of gratification ability using a latent variable approach. A latent variable approach captures heterogeneity in SC capacities and can help elucidate the extent to which physiological regulation buffers lapse in delay ability. We examined behavioral and autonomic regulation for children who delayed and did not delay, extending prior work, which has been limited to children who successfully delayed (Wilson et al., 2009). In addition to the extended behavioral coding scheme employed to capture mechanisms underlying SC, this study examined pretask, task-related, reactivity, and changes in physiologic variables during the delay task to characterize physiological patterns associated with better self-regulation. Finally, autonomic indicators (RSA and HR) allowed for the identification of distinct unobservable processes underlying observable SC strategies in response to a delay task.

Controlling for motor activity/fidgeting and self-soothing /regulatory behaviors is recommended when measuring physiological responses during challenge/stressor tasks (Cicchetti & Dawson, 2002; Porges et al., 2007) to accurately understand the source of regulatory processes (i.e., are increases in HR due to excess movement during the task or the challenging nature of the task?). To address this, we included concurrent levels of motor activity via levels of fidgeting and other SC behaviors such as self-talk and distraction. We also assessed SC processes across two separate groups of participants from a more racially and socioeconomically diverse sample than studies have typically included (Sturge-Apple et al., 2016). In addition, the current study had a larger sample size than previous work that has examined both behavioral and physiological regulation in tandem (Kahle et al., 2018; Santucci et al., 2008; Wilson et al., 2009).

It is important to interpret our findings considering some limitations. Although this study included children from differing social risk strata, the findings may still have limited generalizability and should be considered preliminary. Additionally, the modest sample size, particularly for the non-delayers over the task duration, may have limited the detection of further associations. The delay task captures a short period of time (up to 8 min) of autonomic and behavioral regulation. However, despite its brevity, this delay task has been used extensively in developmental research to predict a multitude of outcomes, such as reward-seeking behaviors, academic achievement, and socioemotional capacity (Hernandez et al., 2018; Supplee et al., 2011; Watts et al., 2018). There were no data collected on hunger/satiety or the time of the last meal; therefore, we cannot determine whether failure to delay the full task time was driven by individual differences in hunger. However, all children had not eaten at least 60 min prior to the delay of gratification task due to the laboratory visit protocol. Furthermore, we did not measure children's desirability of the snack, but children were able to select between a marshmallow or pretzel by themselves.

Developmental models of self-regulation highlight the importance of resisting impulses as a key component of health and well-being. This study elucidated heterogeneity in unobservable processes underlying and accompanying behavioral regulation to provide insight into how physiological and behavioral regulation work in tandem to modulate self-regulation and drive children's socioemotional capacity. It is important to further probe what it means to have incongruency between physiological regulation and observable emotional and behavioral expressions and whether it is a potential index of vulnerability in children's emotional and behavioral development.

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CONFLICT OF INTEREST

The authors have no financial or non-financial conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

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

ORCID

Radhika S. Raghunathan https://orcid.org/0000-0001-8401-0051

REFERENCES

Asparouhov, T., & Muthén, B. (2014). Auxiliary variables in mixture modeling: Three-step approaches using mplus. *Structural Equation Modeling: A Multidisciplinary Journal*, *21*(3), 329–341. https://doi.org/10.1080/10705511.2014.915181

Baker, E. R., Liu, Q., & Huang, R. (2019). A view from the start: A review of inhibitory control training in early childhood. In S. Palermo, & M. Bartoli (Eds.), *Inhibitory control training* (1–13). IntechOpen. https://doi.org/10.5772/intechopen.88700

Bar-Haim, Y., Marshall, P. J., & Fox, N. A. (2000). Developmental changes in heart period and high-frequency heart period variability from 4 months to 4 years of age. *Developmental Psychobiology*, *37*(1), 44–56. https://doi.org/10.1002/1098-2302(200007)37:1⟨44::AID-DEV6⟩3.0.CO;2-7

Blair, C. (2002). School readiness: Integrating cognition and emotion in a neurobiological conceptualization of children's functioning at school entry. *American Psychologist*, *57*(2), 111–127. https://doi.org/10.1037/0003-066X.57.2.111

Blair, C., & Ursache, A. (2011). A bidirectional model of executive functions and self-regulation. In K. D. Vohs, & R. F. Baumeister (Eds.), *Handbook of* *self-regulation: Research, theory, and applications* (2nd ed., pp. 300–320). Guilford Press.

Bruce, A. S., Black, W. R., Bruce, J. M., Daldalian, M., Martin, L. E., & Davis, A. M. (2011). Ability to delay gratification and BMI in preadolescence. *Obesity (Silver Spring)*, *19*(5), 1101–1102. https://doi.org/10.1038/oby.2010.297

Caleza, C., Yañez-Vico, R. M., Mendoza, A., & Iglesias-Linares, A. (2016). Childhood obesity and delayed gratification behavior: A systematic review of experimental studies. *Journal of Pediatrics*, *169*, 201–207e1.e201. https://doi.org/10.1016/j.jpeds.2015.10.008

Calkins, S. D. (1997). Cardiac vagal tone indices of temperamental reactivity and behavioral regulation in young children. *Developmental Psychobiology*, *31*(2), 125–135. https://doi.org/10.1002/(sici)1098-2302(199709)31:2<125::aid-dev5>3.0.co;2-m

Casey, B. J., Somerville, L. H., Gotlib, I. H., Ayduk, O., Franklin, N. T., Askren, M. K., Jonides, J., Berman, M. G., Wilson, N. L., Teslovich, T., Glover, G., Zayas, V., Mischel, W., & Shoda, Y. (2011). Behavioral and neural correlates of delay of gratification 40 years later. *Proceedings of the National Academy of Sciences*, *108*(36), 14998. https://doi.org/10.1073/pnas.1108561108

Centers for Disease Control and Prevention. (2021). *Defining childhood weight status*. https://www.cdc.gov/obesity/childhood/defining.html

Choi, Y., Jeon, Y. M., Wang, L., & Kim, K. (2017). A biological signal-based stress monitoring framework for children using wearable devices. *Sensors (Basel)*, >1936>, *17*(9), https://doi.org/10.3390/s17091936

Cicchetti, D., & Dawson, G. (2002). Multiple levels of analysis. *Development and Psychopathology*, *14*(3), 417–420. https://doi.org/10.1017/s0954579402003012

Cole, P. M., Bendezú, J. J., Ram, N., & Chow, S. -M. (2017). Dynamical systems modeling of early childhood self-regulation. *Emotion (Washington, D.C.)*, *17*(4), 684–699. https://doi.org/10.1037/emo0000268

Cole, P. M., Ram, N., & English, M. S. (2019). Toward a unifying model of self-regulation: A developmental approach. *Child Development Perspectives*, *13*(2), 91–96. https://doi.org/10.1111/cdep.12316

Corriveau, K. H., Min, G., Chin, J., & Doan, S. (2016). Do as I do, not as I say: Actions speak louder than words in preschoolers learning from others. *Journal of Experimental Child Psychology*, *143*, 179–187. https://doi.org/10.1016/j.jecp.2015.10.006

Coulombe, B. R., Rudd, K. L., & Yates, T. M. (2019). Children's physiological reactivity in emotionl contexts and prosocial behavior. *Brain and Behavior*, *9*(10), e01380. https://doi.org/10.1002/brb3.1380

DePasquale, C. E. (2020). A systematic review of caregiver–child physiological synchrony across systems: Associations with behavior and child functioning. *Development and Psychopathology*, *32*(5), 1754–1777. https://doi.org/10.1017/S0954579420001236

DiPietro, J. A., Kivlighan, K. T., Costigan, K. A., Rubin, S. E., Shiffler, D. E., Henderson, J. L., & Pillion, J. P. (2010). Prenatal antecedents of newborn neurological maturation. *Child Development*, *81*(1), 115–130. https://doi.org/10.1111/j.1467-8624.2009.01384.x

Doidge, J. L., Flora, D. B., & Toplak, M. E. (2018). A meta-analytic review of sex differences on delay of gratification and temporal discounting tasks in ADHD and typically developing samples. *Journal of Attention Disorders*, *25*, 540. https://doi.org/10.1177/1087054718815588

Evans, G. W., & English, K. (2002). The environment of poverty: Multiple stressor exposure, psychophysiological stress, and socioemotional adjustment. *Child Development*, *73*(4), 1238–1248. https://doi.org/10.1111/1467-8624.00469

Giuliano, R. J., Roos, L. E., Farrar, J. D., & Skowron, E. A. (2018). Cumulative risk exposure moderates the association between parasympathetic reactivity and inhibitory control in preschool-age children. *Developmental Psychobiology*, *60*(3), 324–332. https://doi.org/10.1002/dev.21608

Goldsmith, H. H., & Rothbart, M. K. (1999). The Laboratory Temperament Assessment Battery (LAB-TAB): Locomotor; Version 3.0; Technical Report; Psychology Department, University of Wisconsin: Madison, WI, USA. https://goldsmithtwins.waisman.wisc.edu/instruments/

Haimovitz, K., Dweck, C. S., & Walton, G. M. (2020). Preschoolers find ways to resist temptation after learning that willpower can be energizing. *Developmental Science*, *23*(3), e12905. https://doi.org/10.1111/desc.12905

Hernandez, E., Smith, C. L., Day, K. L., Neal, A., & Dunsmore, J. C. (2018). Patterns of parental emotion-related discourse and links with children's problem behaviors: A person-centered approach. *Developmental Psychology*, *54*(11), 2077–2089. https://doi.org/10.1037/dev0000602

Hinnant, J. B., & El-Sheikh, M. (2009). Children's externalizing and internalizing symptoms over time: The role of individual differences in patterns of RSA responding. *Journal of Abnormal Child Psychology*, *37*(8), 1049–1061. https://doi.org/10.1007/s10802-009-9341-1

Holochwost, S. J., Volpe, V. V., Gueron-Sela, N., Propper, C. B., & Mills-Koonce, W. R. (2018). Sociodemographic risk, parenting, and inhibitory control in early childhood: The role of respiratory sinus arrhythmia. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *59*(9), 973–981. https://doi.org/10.1111/jcpp.12889

Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. *Neuroscience and Biobehavioral Reviews*, *74*(PtA), 233–255. https://doi.org/10.1016/j.neubiorev.2016.12.032

Hong, F., Doan, S. N., Lopez, A., & Evans, G. W. (2017). Relations among temperament, self-regulatory strategies and gender in predicting delay of gratification. *Frontiers in Psychology*, *8*, >1925>. https://doi.org/10.3389/fpsyg.2017.01925

Hosseini-Kamkar, N., & Morton, J. B. (2014). Sex differences in self-regulation: An evolutionary perspective. *Frontiers in Neuroscience*, *8*, >233>. https://doi.org/10.3389/fnins.2014.00233

Hughes, S. O., Power, T. G., O'Connor, T. M., & Orlet Fisher, J. (2015). Executive functioning, emotion regulation, eating self-regulation, and weight status in low-income preschool children: How do they relate? *Appetite*, *89*, 1–9. https://doi.org/10.1016/j.appet.2015.01.009

Jahromi, L. B., Chen, Y., Dakopolos, A. J., & Chorneau, A. (2019). Delay of gratification in preschoolers with and without autism spectrum disorder: Individual differences and links to executive function, emotion regulation, and joint attention. *Autism*, *23*(7), 1720–1731. https://doi.org/10.1177/1362361319828678

Kahle, S., Miller, J. G., Helm, J. L., & Hastings, P. D. (2018). Linking autonomic physiology and emotion regulation in preschoolers: The role of reactivity and recovery. *Developmental Psychobiology*, *60*(7), 775–788. https://doi.org/10.1002/dev.21746

Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research–recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, *8*, >213>. https://doi.org/10.3389/fpsyg.2017.00213

Manfra, L., Davis, K. D., Ducenne, L., & Winsler, A. (2014). Preschoolers' motor and verbal self-control strategies during a resistance-to-temptation task. *Journal of Genetic Psychology*, *175*(3-4), 332–345. https://doi.org/10.1080/00221325.2014.917067

McGuire, J. T., & Kable, J. W. (2013). Rational temporal predictions can underlie apparent failures to delay gratification. *Psychological Review*, *120*(2), 395–410. https://doi.org/10.1037/a0031910

Mischel, W., Shoda, Y., & Rodriguez, M. I. (1989). Delay of gratification in children. *Science*, *244*(4907), 933–938. https://doi.org/10.1126/science.2658056

Mischel, W., Ebbesen, E. B., & Zeiss, A. R. (1972). Cognitive and attentional mechanisms in delay of gratification. *Journal of Personality and Social Psychology*, *21*(2), 204–218. https://doi.org/10.1037/h0032198

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., Houts, R., Poulton, R., Roberts, B. W., Ross, S., Sears, M. R., Thomson, W. M., & Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2693–2698. https://doi.org/10.1073/pnas.1010076108

Mulkey, S. B., & du Plessis, A. J. (2019). Autonomic nervous system development and its impact on neuropsychiatric outcome. *Pediatric Research*, *85*(2), 120–126. https://doi.org/10.1038/s41390-018-0155-0

Murray, J., Theakston, A., & Wells, A. (2016). Can the attention training technique turn one marshmallow into two? Improving children's ability to delay gratification. *Behavior Research and Therapy*, *77*, 34–39. https://doi.org/10.1016/j.brat.2015.11.009

Muthén, L. K., & Muthén, B. O. (1998–2017). *Mplus user's guide* (8th ed.). Muthén & Muthén.

Neuenschwander, R., & Blair, C. (2017). Zooming in on children's behavior during delay of gratification: Disentangling impulsigenic and volitional processes underlying self-regulation. *Journal of Experimental Child Psychology*, *154*, 46–63. https://doi.org/10.1016/j.jecp.2016.09.007

Nylund, K. L., Asparouhov, T., & Muthén, B. O. (2007). Deciding on the number of classes in latent class analysis and growth mixture modeling: A Monte Carlo simulation study. *Structural Equation Modeling: A Multidisciplinary Journal*, *14*(4), 535–569. https://doi.org/10.1080/10705510701575396

Porges, S. W., Heilman, K. J., Bazhenova, O. V., Bal, E., Doussard-Roosevelt, J. A., & Koledin, M. (2007). Does motor activity during psychophysiological paradigms confound the quantification and interpretation of heart rate and heart rate variability measures in young children? *Developmental Psychobiology*, *49*(5), 485–494. https://doi.org/10.1002/dev.20228

Raver, C. C., Jones, S. M., Li-Grining, C., Zhai, F., Bub, K., & Pressler, E. (2011). CSRP's impact on low-income preschoolers' preacademic skills: Self-regulation as a mediating mechanism. *Child Development*, *82*(1), 362–378. https://doi.org/10.1111/j.1467-8624.2010.01561.x

Riis, J. L., Granger, D. A., DiPietro, J. A., Bandeen-Roche, K., & Johnson, S. B. (2015). Salivary cytokines as a minimally invasive measure of immune functioning in young children: Correlates of individual differences and sensitivity to laboratory stress. *Developmental Psychobiology*, *57*(2), 153–167. https://doi.org/10.1002/dev.21271

Robson, D. A., Allen, M. S., & Howard, S. J. (2020). Self-regulation in childhood as a predictor of future outcomes: A meta-analytic review. *Psychological Bulletin*, *146*(4), 324–354. https://doi.org/10.1037/bul0000227

Rodriguez, M. L., Mischel, W., & Shoda, Y. (1989). Cognitive person variables in the delay of gratification of older children at risk. *Journal of Personality and Social Psychology*, *57*(2), 358–367. https://doi.org/10.1037//0022-3514.57.2.358

Sacrey, L. R., Raza, S., Armstrong, V., Brian, J. A., Kushki, A., Smith, I. M., & Zwaigenbaum, L. (2021). Physiological measurement of emotion from infancy to preschool: A systematic review and meta-analysis. *Brain and Behavior*, *11*(2), e01989. https://doi.org/10.1002/brb3.1989

Santucci, A. K., Silk, J. S., Shaw, D. S., Gentzler, A., Fox, N. A., & Kovacs, M. (2008). Vagal tone and temperament as predictors of emotion regulation strategies in young children. *Developmental Psychobiology*, *50*(3), 205–216. https://doi.org/10.1002/dev.20283

Schaefer, S. E., Van Loan, M., & German, J. B. (2014). A feasibility study of wearable activity monitors for pre-adolescent school-age children. *Preventing Chronic Disease [Electronic Resource]*, *11*, E85. https://doi.org/10.5888/pcd11.130262

Schlam, T. R., Wilson, N. L., Shoda, Y., Mischel, W., & Ayduk, O. (2013). Preschoolers' delay of gratification predicts their body mass 30 years later. *Journal of Pediatrics*, *162*(1), 90–93. https://doi.org/10.1016/j.jpeds.2012.06.049

Sethi, A., Mischel, W., Aber, J. L., Shoda, Y., & Rodriguez, M. L. (2000). The role of strategic attention deployment in development of self-regulation: Predicting preschoolers' delay of gratification from mother-toddler interactions. *Developmental Psychology*, *36*(6), 767–777. https://doi.org/10.1037/0012-1649.36.6.767

Silverman, I. W. (2003). Gender differences in delay of gratification: A meta-analysis. *Sex Roles*, *49*(9), 451–463. https://doi.org/10.1023/A:1025872421115

Skowron, E. A., Cipriano-Essel, E., Gatzke-Kopp, L. M., Teti, D. M., & Ammerman, R. T. (2014). Early adversity, RSA, and inhibitory control: Evidence of children's neurobiological sensitivity to social context. *Developmental Psychobiology*, *56*(5), 964–978. https://doi.org/10.1002/dev.21175

StataCorp. (2019). *Stata statistical software: Release 16*. StataCorp LLC.

Sturge-Apple, M. L., Suor, J. H., Davies, P. T., Cicchetti, D., Skibo, M. A., & Rogosch, F. A. (2016). Vagal tone and children's delay of gratification: Differential sensitivity in resource-poor and resource-rich environments. *Psychological Science*, *27*(6), 885–893. https://doi.org/10.1177/0956797616640269

Sulik, M. J., Eisenberg, N., Spinrad, T. L., & Silva, K. M. (2015). Associations between respiratory sinus arrhythmia (RSA) reactivity and effortful control in preschool-age children. *Developmental Psychobiology*, *57*(5), 596–606. https://doi.org/10.1002/dev.21315

Supplee, L. H., Skuban, E. M., Trentacosta, C. J., Shaw, D. S., & Stoltz, E. (2011). Preschool boys' development of emotional self-regulation strategies in a sample at risk for behavior problems. *Journal of Genetic Psychology*, *172*(2), 95–120. https://doi.org/10.1080/00221325.2010.510545

Taylor, Z. E., Eisenberg, N., & Spinrad, T. L. (2015). Respiratory sinus arrhythmia, effortful control, and parenting as predictors of children's sympathy across early childhood. *Developmental Psychology*, *51*(1), 17–25. https://doi.org/10.1037/a0038189

Watts, T. W., Duncan, G. J., & Quan, H. (2018). Revisiting the marshmallow test: A conceptual replication investigating links between early delay of gratification and later outcomes. *Psychological Science*, *29*(7), 1159–1177. https://doi.org/10.1177/0956797618761661

Wilson, A. C., Lengua, L. J., Tininenko, J., Taylor, A., & Trancik, A. (2009). Physiological profiles during delay of gratification: associations with emotionality, self-regulation, and adjustment problems. *Journal of Applied Developmental Psychology*, *30*(6), 780–790. https://doi.org/10.1016/j.appdev.2009.05.002

Zantinge, G., van Rijn, S., Stockmann, L., & Swaab, H. (2019). Concordance between physiological arousal and emotion expression during fear in young children with autism spectrum disorders. *Autism: The International Journal of Research and Practice*, *23*(3), 629–638. https://doi.org/10.1177/1362361318766439

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