READY OR NOT: PARASYMPATHETIC NERVOUS SYSTEM ACTIVITY DURING SELF-REGULATORY TASKS PREDICTS SCHOOL READINESS

Lindsay A. Gomes

A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Arts in the Department of Psychology and Neuroscience in the College of Arts and Sciences.

Chapel Hill
2021

Approved by:
Jean-Louis Gariépy
Cathi Propper
Roger Mills-Koonce
ABSTRACT

Lindsay A. Gomes:
Ready or Not: Parasympathetic Nervous System Activity During Self-Regulatory Tasks Predicts School Readiness
(Under the direction of Jean-Louis Gariépy and Cathi Propper)

This study examined how parasympathetic resources are recruited during situations in which children must employ volitional self-regulation and explored associations with subsequent school readiness. At the beginning of the preschool year, children participated in hot gift-wrap (GW) and cool executive functions (EF) tasks of self-regulation. Cardiac data were collected during each task to measure parasympathetic nervous system (PNS) activity through changes in respiratory sinus arrhythmia (RSA) from baseline. Hypotheses stated that RSA suppression during both tasks would predict school readiness at the end of the year, but RSA change during GW would drive more change in school readiness scores. Results revealed higher school readiness scores for children experiencing RSA suppression during GW ($B = 3.38, CI = [0.25, 6.51], p = .033$) and augmentation during EF ($B = -4.05, CI = [-9.04, 0.94], p = .108$). These results situate self-regulation in its developmental stage and corresponding context.
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<tr>
<td>ACC</td>
<td>Anterior cingulate cortex</td>
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<td>ANS</td>
<td>Autonomic nervous system</td>
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<td>BSRA</td>
<td>Bracken School Readiness Assessment</td>
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<td>CAN</td>
<td>Central autonomic network</td>
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<td>ECE</td>
<td>Early care and education</td>
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<td>EF</td>
<td>Executive functions</td>
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<td>ESL</td>
<td>English as a second language</td>
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<td>GW</td>
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<tr>
<td>HPA</td>
<td>Hypothalamic-pituitary-adrenal</td>
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<td>HPV</td>
<td>Heart period variability</td>
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<td>HS</td>
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<td>LEAPS</td>
<td>Learning, Emotion and Play in School</td>
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<td>PFC</td>
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SES  Socioeconomic status
SNS  Sympathetic nervous system
SRS  Stress response system
TSST  Trier Social Stress Test
B  Beta coefficient
CI  Confidence interval
M  Mean
N  Sample size
p  Probability value
r  Correlation coefficient
SD  Standard deviation
α  Cronbach's alpha
*  Significance level
INTRODUCTION

Teachers and parents alike have a general understanding of the concept of readiness to formal schooling. In the United States, preparedness to formal schooling as provided by the family and by society in the form of Head Start and pre-kindergarten education is seen as essential for adjustment to formal schooling and adequate scores on formal school performance tests. School readiness was initially conceived of as content proficiency, with an exclusive focus on basic literacy and numeracy knowledge at school entry. What constitutes school readiness has recently expanded in the community of scholars interested in child development to include the ability to regulate emotions and behaviors in the classroom. Numerous studies have shown in this vein that complying to disciplinary requests in the classroom and being able to follow instructional directions in large part rests on the ability to regulate emotions, behaviors, and thought processes (Mashburn & Pianta, 2006; Silva et al., 2011; Allen et al., 2015).

Given the age range of preschool students, the types of activities that take place in the preschool classroom require behavior and emotion regulation more so than regulation of cognitive processes (Williford et al., 2013b). For instance, the abilities to comply with instructions, repress disruptive behaviors, and coordinate activities in conjunction with other children fall under the umbrella of emotional and behavioral regulation. Accordingly, to benefit from a curriculum aimed at promoting basic literacy and numeracy knowledge prior to formal schooling, a child must be able to regulate the expression of emotions and behavioral organization in ways that are aligned with the teacher’s educational goals and contribute positively to a classroom climate conducive to their attainment.
Research focused on self-regulation typically uses specific tasks that measure one’s ability to regulate in two distinct domains: emotional and cognitive control, referred to as hot and cool tasks of self-regulation, respectively. Studies have demonstrated that the ability to perform well on both types of tasks requires recruiting physiological processes that are capable of supporting their activity in the prefrontal cortex (PFC) and related areas. In current literature, the ability to regulate heart rate via the parasympathetic nervous system (PNS) is considered a key physiological substrate of performance on both hot and cool self-regulatory tasks (Eisenberg & Sulik, 2012; Geisler et al., 2013).

In the present study, PNS activity was measured at the beginning of the school year in the context of hot and cool tasks that jointly require regulative abilities in the behavioral, emotional, and cognitive domains. By the logic outlined above, PNS activity measured during both types of tasks were used in statistical analyses as predictors of basic numeracy and literacy knowledge by the end of the school year. Actual performances on those tasks were not used as predictors in the current study, as its main focus was to test the idea that physiological support for self-regulation at school entry might be, by itself, a significant predictor of knowledge acquisition in this age range. We further hypothesized that in the educational context in which the current study was conducted, PNS regulation during tasks that challenge emotional and behavioral responses should be more predictive of school readiness than performance on tasks designed to challenge cognitive abilities.

**Self-Regulation: Effortful Control and Executive Functions**

Self-regulation is a broad term that encompasses a number of mechanisms by which individuals control their emotions, cognitive processes, and actions (Rueda et al., 2005). With origins in earlier research on the structure of temperament, the concept of effortful control was
introduced by Rothbart and colleagues (1985) as a regulatory aspect of temperament whereby reactive tendencies are brought under volitional control. In most instances, regulating reactive tendencies involves suppressing a dominant response to enact a subdominant one in the service of goal achievement (Zhou et al., 2012; Blair, 2016; Bierman et al., 2008; Rothbart & Rueda, 2005). The majority of tasks designed to measure effortful control abilities have challenged the capacity to regulate emotion and behavior. More recently, research on self-regulation shifted from behavior and emotion to appraise how pure cognitive processes like those involved in problem-solving are themselves regulated. This new tradition has its roots in modern neuroscience and retains from the earlier one a central component of self-regulation: inhibitory control, defined as the ability to suppress a dominant response in the service of goal attainment. To this central component, current research on executive functions adds two other dimensions: working memory, the ability to keep in mind all aspects of a task, and attention flexibility, which allows for shifting among different aspects of the task (Blair & Razza, 2007). The literature asserts that these components are mutually dependent and highly correlated in early childhood, suggesting that in this age range the average performance on tasks designed to assess performance on each may be used to derive an overall score of the ability to recruit executive functions (Wiebe et al., 2008; Willoughby et al., 2012b).

**The Physiological Substrates of Self-Regulation**

The endogenous substrates of self-regulation implicate several physiological systems, including the stress response system (SRS) in its sympathetic and neuroendocrine branches, their secretagogues, including local concentrations and density of their receptors, the GABAergic and the immune systems; the list is not exhaustive. As part of the autonomic nervous system (ANS), the PNS, keeping homeostatic balance in check, counteracts sympathetic nervous system (SNS)
activation whenever possible. In this role, the PNS also provides physiological support for self-regulation. Specifically, the PNS modulates the flow of SNS and hypothalamic-pituitary-adrenal (HPA) axis secretagogues to brain regions that regulate the volitional control of self-regulatory processes. In the most adaptive case, mechanisms of self-regulation are enacted volitionally in a “top-down” fashion via higher brain regions, including the anterior cingulate cortex (ACC) and PFC, where effortful control and, more broadly, executive functions are recruited to take control over automatic and reactive responses that have their source in lower limbic structures (Posner & Rothbart 2000; Rothbart et al., 2003). When volitional control fails, however, bottom-up processes take over the organization of emotional, behavioral, and cognitive activity, giving control to automatic, impulsive, or reactive responses to external challenges. Top-down and bottom-up processes of self-regulation maintain a bidirectional dialogue as the organism responds to varying conditions of environmental stress.

As explained by Blair (2016), dynamic shifts between top-down and bottom-up processes are regimented by the relative saturation of glucocorticoid and adrenergic receptors in the ACC and PFC whose ligands are secreted respectively by the SNS and the HPA. The first system is typically recruited in response to acute stress in the service of fight-flight responses, whereas the HPA is activated under conditions that signal unpredictability and lack of control. Blair (2016) further explains that activity in the ACC and PFC rests on an optimal level of ligand occupancy of stress receptors such that activity in those regions follows an inverse U-shaped curve. Specifically, at a low level of arousal, and thus at low levels of SNS and HPA activity, stress receptors are poorly saturated, signaling that there is no need to engage in the metabolic effort of recruiting higher brain functions. At the high end of arousal level, activity in those same areas shuts down as stress receptors are saturated and organization of action is relegated to limbic
control. It is only under optimal occupancy of these receptors that volitional, top-down processes remain in control of self-regulation. Given the age range considered in this study, it is important to emphasize that the effectiveness of top-down inhibitory processes also depends on the organization of cortico-limbic connections whose functional development is protracted and highly sensitive to the quality of the environment of early care (Gunnar & Quevedo, 2007).

So, what role does the PNS play in the recruitment of volitional efforts to self-regulate? The primary function of the PNS is to operate in the service of maintaining homeostasis. It does so primarily by regulating heart rate and its variability in ways that reduce the need for costly SNS and HPA recruitment when possible. In this function, the PNS also plays a critical role in volitional self-regulation by promoting the maintenance of an optimal level of stress receptor occupancy in the ACC and PFC (Blair, 2016; Porges, 2009).

**PNS Activity Supports Volitional Self-Regulation**

Polyvagal theory, as proposed by Porges (1995; 1997; 2007), states that among mammalian species, the myelinated branch of the PNS (a recent phylogenetic acquisition) allows for an economic way of regulating metabolic demands imposed by external challenges. Porges explains that in mammals the myelinated vagus controls heart rate and its variability using a mechanism called a “vagal brake” that may be applied to the heart or removed. The myelinated vagus synapses onto the sino-atrial node of the heart, which serves as the heart’s pacemaker. Left to its intrinsic mode the sino-atrial node would keep the heart beating around 100 times per minute. With input from the myelinated vagus, however, heart rate is lowered to 60-80 beats per minute, leaving its natural variability under the influence of inhalation and expiration. This input is referred to as the vagal brake, normally kept on in the absence of environmental challenges. The vagal brake is removed when environmental changes threaten homeostatic balance and
require diverting attention from physiological needs to external conditions that may compromise internal equilibrium. The removal of the vagal brake allows for an augmented and regular flow of blood transporting oxygen and glucose to brain regions involved in evaluation, decision making, and action taking. While removal of the vagal brake suffices under manageable conditions to restore control, its effect on visceral functions also opens the possibility of SNS and HPA contributions to the effort.

In highly social species, where survival depends upon supportive relations with meaningful others, the PNS contributes a calm state of engagement in social interactions by reducing heart rate and augmenting its variability. This natural variability at rest has an amplitude that can be measured and which is commonly referred to as vagal tone (Porges, 1992). In the current literature, vagal tone is estimated via respiratory sinus arrhythmia (RSA), a measure of heart rate variability when under the influence of respiration alone. The difference between variability at rest and variability under challenge is estimated as delta RSA (ΔRSA).

Polyvagal theory was initially formulated to highlight the role of the mammalian vagus in the maintenance of calm states of engagement with others, conditions essential to the fabric of our social systems, the cohesion of the family unit, and its role in childcare (Porges, 1998; Porges, 2003). Subsequent literature in developmental science also showed that high levels of resting PNS activity and flexible withdrawal of this input in challenging contexts, early in development, predicted better regulation of attention and affect and more optimal social functioning (Beauchaine, 2001; Beauchaine, 2015; Boyce et al., 2001; Calkins & Keane, 2004; Graziano & Derefinko, 2013).

**Regulating Emotions and Cognitive Processes**

In the recent literature on self-regulation, we see the coexistence of two traditions that
have examined self-regulatory abilities during different challenging contexts: hot and cool tasks (Zelazo & Müller, 2002; Zhou et al., 2012). Hot self-regulatory tasks typically involve emotional responses and require regulation of those emotions during the task. Cool tasks of self-regulation, on the other hand, are not meant to require emotional control specifically; rather, they aim at measuring purely cognitive modes of control over memory, attention, and means-to-end strategies. During hot tasks of self-regulation, young children normally show a substantial suppression of RSA as they become emotionally aroused and following the directives of the task is made more difficult (Calkins & Keane, 2004; Calkins, 2007; Doussard-Roosevelt et al., 2003; El-Sheikh, 2005). A similar pattern of PNS activity was observed during cool tasks of self-regulation in children (Blandon et al., 2008; Marcovitch et al., 2010; Suess et al., 1994) that predicted better academic outcomes, such as greater reading achievement (Becker et al., 2012) and higher teacher ratings of on-task behavior (Blair & Peters, 2003). There are a few notable inconsistencies in the literature; for instance, a study by Staton and colleagues (2009) found that RSA suppression during a cool task marginally predicted better reaction time, and research conducted by Utendale and colleagues (2014) found that greater RSA augmentation was associated with better performance on a cool task of inhibitory control. Comparing PNS activity under hot and cool tasks, however, remains difficult because different age ranges were sampled in the studies that examined this activity under either condition.

In addition, few studies have examined PNS activity during hot and cool tasks together (Wass, 2018). One exception includes research conducted by Sulik and colleagues (2015), who examined changes in RSA within and between these two types of tasks. They found that RSA decreased during a cool task of self-regulation, the knock-tap task, while remaining stable during a hot task of self-regulation, the gift-wrap task. With some exceptions, the literature appears to
support the notion that both tasks of self-regulation require RSA suppression and that a PNS contribution to the effort is linked to better child outcomes. In this study, we explore the possibility that PNS regulation during these two types of tasks may differentially relate to school readiness, defined in the preschool environment as acquisition of basic content knowledge.

**Current Study**

The current study examines associations between PNS activity during a hot task of inhibitory control and a cool task of executive functions and school readiness at the end of the preschool year. Based on the extant literature on self-regulation and the supportive role the PNS brings to this capacity, we hypothesized that RSA suppression during both hot and cool tasks of self-regulation at the beginning of the preschool year would predict subsequent school readiness at the end of the year. However, we hypothesized that RSA suppression during the hot task would be a stronger predictor of school readiness, measured as rote memory knowledge of letters, numbers, and colors. The preschool environment is naturally arousing for young children whose regulatory abilities are still developing while being immersed in a context where conscious control of emotional responses is of paramount importance. It stands to reason that children more capable in biobehavioral self-regulation should gain more from the preschool curriculum than children less so equipped at school entry. As an expansion of this reasoning, relative acquisition of academic content knowledge such as literacy and numeracy should also be best predicted by RSA suppression during a hot task. While the outcome variable used in this study, focusing as it does on numeracy and literacy, is linked to an early conception of school preparedness, it remains relevant to the educational goals pursued in preschool curricula. Importantly, the knowledge content measured in this study does not probe any aspect of executive functions. However, it is important not to discount the contribution of executive
functions to children’s ability to regulate emotions and arousal in the preschool context, and thus while the hot task is hypothesized to be more predictive, RSA changes from baseline during the cool task may, but to a lesser extent, also predict school readiness.

The hot and cool tasks used in this study are comprised of distinct episodes. The hot task measures participants’ inhibitory control during two episodes, the “wrapping time” and the “waiting-for-bow” segments. RSA values were computed at the beginning and the end of these two episodes with the goal of capturing physiological effects of arousal change through the task. The cool tasks were constructed to tap successively into different aspects of executive functions, including inhibitory control, working memory, and attention flexibility. Thus, it will be important to examine correlations among heart rate variability estimates measured both within and between the episodes of the hot and cool tasks to determine whether changes in PNS activity detected in those different contexts warrant attention in analyses. If not, composite ΔRSA scores averaged separately over hot and cool tasks will be computed. The issue is relevant given research asserting that executive function is a unitary construct in early childhood (Wiebe et al., 2008; Willoughby et al., 2012a). Although research on executive functions typically examines the distinct abilities of inhibitory control, attention flexibility, and working memory, the studies referenced above assert that these aspects of executive function together form a single dimension in this age range. Preliminary analyses will inform how measures of PNS activity will be computed within hot and cool tasks for the purpose of model testing in statistical analyses.
METHODS

Participants

Participants were recruited from 12 center-based care settings located in central North Carolina for participation in the Learning, Emotion and Play in School (LEAPS) study. Data were collected from 102 children (n = 54 of whom were female) enrolled in 15 preschool classrooms. Children’s mean age at the time of enrollment in the study was 4.82 (SD = 0.47) years. The majority of the sample identified as Caucasian (51.0%), and it also included children whose families identified them as African American (22.5%), Latinx/Hispanic (16.7%), biracial (7.8%) and Asian (2.0%). Approximately one-quarter of children (26.5%) were eligible for Head Start (HS). Sixteen children (15.7% of the sample) had an English as a second language (ESL) classification, and one child was classified as developmentally delayed. The child classified as delayed was excluded from analyses.

Procedures

Data were collected at the beginning and end of the preschool year by trained research assistants. Collection of data occurred during “pull-out” sessions where the child was taken out of the classroom for testing. Cardiac data were collected using a pair of contact electrodes connected to portable monitors (the Actiwave Cardio monitor, CamNtech, Cambridge, UK). After fitting the monitor to the child, baseline RSA was collected while the child colored quietly for 5 minutes. Next, the children completed the executive functions (EF) tasks, comprised of four computerized measures of executive functions drawn from the EF Touch battery (Willoughby et al., 2010). The tasks that the children completed, in order, were a stroop task, a go/no-go task, a
working memory span task, and a flexible item selection task. In addition, research assistants administered the gift-wrap (GW) task, comprised of two episodes (Kochanska et al., 2000). Cardiac data were collected continuously during both the GW and EF tasks. At the end of the school year, children completed the Bracken School Readiness Assessment (BSRA-3 Third Edition; Bracken, 2007).

**Measures**

**School Readiness**

The BSRA is an assessment that measures children’s knowledge of colors, letters, numbers and counting, sizes, and shapes. Children’s knowledge of colors is assessed by asking children to name and identify primary and secondary colors as well as color absolutes like black and white. Next, children are asked about upper-case and lower-case letters to assess their knowledge of letters. The next domain of numbers and counting is assessed by identification of single-digit and double-digit numbers. In the size and comparisons domain, children need to use comparative words based on characteristics such as height, length, and size. Lastly, the shapes domain is assessed by asking children to identify shapes by name. The BSRA takes approximately 10-15 minutes to administer and can be used with children ranging from 3:0-6:11 years old. The BSRA has demonstrated acceptable test-retest reliability and discriminant and predictive validity (Bracken, 2007; Panter & Bracken, 2009). Following the guidelines pertaining to scoring, a single composite score was calculated as the mean of the five content-area assessments (α = .73).

**Self-Regulatory Tasks**

*Gift-wrap (GW) task*. The gift-wrap (GW) task is commonly used to assess hot self-regulation (Kochanska et al., 2000). During this task, a trained research assistant enters the room
with a gift and wrapping supplies. The child is instructed to turn around so that their back faces the research assistant, and they are told not to turn around or look while the research assistant is wrapping the gift. This “wrapping time” episode lasts 60 seconds. The next episode, called the “waiting-for-bow time,” is 180 seconds long and involves the research assistant telling the child they need to leave the room to get a bow to place on the gift. The child is instructed not to touch the gift while the research assistant is out of the room. This task provides us with a measure of inhibitory control, requiring a child to abstain from touching or unwrapping a gift when left alone.

During the wrapping time episode, children were scored on the extent to which they peeked/turned around; the scale ranges from 1 (turns around and continues to peek) to 3 (peeks over shoulder) to 5 (does not peek). Latencies to peek and turn around were also assessed, with 60 seconds being assigned to a child who did not peek or turn at all during the episode. During the waiting-for-bow time, children were scored on the extent to which they touched the gift; the scale ranges from 1 (opens gift) to 4 (does not touch). Latencies to touch, lift, and open the gift were also examined. These measures were not included in the current analytic plan, as only physiological variations were tested for their relation to our outcome of interest.

Executive functions (EF) tasks. Participants completed four computerized measures of executive functions drawn from the Executive Function Touch (EF Touch) battery (Willoughby et al., 2010). These tasks included a stroop task, a go/no-go task, a working memory span task, and a flexible item selection task. The stroop task is a measure of inhibitory control, where participants need to inhibit a prepotent response to produce a different response according to predetermined rules. In the EF Touch, the stroop task is called the silly sounds task, where children are asked to make the sound a dog makes when viewing a picture of a cat, and they are
asked to make the sound a cat makes when viewing a picture of a dog. The go/no-go task is a task where the child must only respond to one item in a set of stimuli that is presented infrequently. In this battery it is called the animal GNG, where children are presented with a number of images of animals and are asked to press a button whenever they see an animal except when that animal is a pig. The working memory span task requires children to name two objects, picture them briefly in their mind, and name one of the objects and inhibit the other object while both are hidden from view. In this study, the children are presented with a line drawing of a house, inside of which is a line drawing of an animal and a colored dot. Next, the child is presented with just the drawing of the house and asked to remember what animal they saw in the house. Lastly, the flexible item selection task requires that the child attend to three items and first focus on one way in which two of the three items are similar. Next, the child is asked to identify a second way in which two of the three items are similar.

**Respiratory Sinus Arrhythmia**

Cardiac data were edited for artifacts due to movement, and files in which more than 10% of the data required editing were excluded from analyses. Values of RSA were calculated for every 30 seconds using Porges’ methods (1985). Change in RSA, otherwise referred to as delta RSA (ΔRSA), was calculated for each episode of the GW task and the four EF Touch tasks by subtracting the mean RSA during each episode or task from the mean RSA during the 5-minute coloring period (RSAB). The methods utilized here align with Moore and Calkins’ (2004) approach, such that positive values of ΔRSA will indicate a decrease or suppression of RSA relative to baseline, and negative values of ΔRSA will indicate an increase or augmentation of RSA compared to baseline. Composite ΔRSA scores were also calculated as the mean of RSA values across the episodes of the GW task (α = .93) and the EF Touch tasks (α = .95).
Data Analysis

In preliminary analyses we computed bivariate correlations among ΔRSA during each of the four GW episodes and among the four EF tasks. The goal was to determine whether episodes or a global score averaged over each task domain should be used in model testing. In the first of these models, scores on the BSRA were regressed on ΔRSA during the GW task. The second model regressed scores on the BSRA on ΔRSA during the EF tasks. Next, we inspected descriptive statistics for key variables to be included as potential covariates for inclusion in statistical models. The specified models were estimated using the COMPLEX and CLUSTER procedures in Mplus 8.0 (Asparouhov & Muthén, 2014; Muthén & Muthén, 2010). Within the present sample, children were nested within classroom and therefore shared teachers, classroom and school conditions, and other factors, necessitating the analytical procedures outlined thus far for the models. Full-information maximum likelihood (FIML) estimation was used to impute missing data. This procedure has been shown to provide less biased parameter estimates than other approaches used to address missing data, such as listwise deletion (Enders & Bandalos, 2001).
RESULTS

Preliminary Analysis

Table 1 displays bivariate correlations among RSA change during the four GW episodes, showing that all four episodes of this task were highly correlated. Similarly, Table 2, which displays those correlations among RSA change during the four EF Touch tasks, shows that all four tasks of the EF tasks were also highly correlated. Given that RSA values were highly correlated within each task (exceeding 0.70 in all but two cases) with respect to RSA change, composite RSA scores within each task were used in model testing. These findings provide additional evidence in support of prior research asserting that executive functions as measured in its three domains forms a unitary construct in early childhood (Willoughby et al., 2012a), and that the GW task episodes jointly measure inhibitory control. Thus, prior literature supports the notion that using composite scores for those hot and cool tasks is appropriate in the age range of the present study.

In order to determine which demographic characteristics should be included in subsequent models as covariates, correlations were computed among gender, race (a binary variable with codes designating European American and non-European American participants), age, Head Start (HS) enrollment status, English as a second language (ESL) status, ΔRSA during the GW task, ΔRSA during the EF tasks, and composite scores on the BSRA. These correlations and descriptive statistics for each of these variables can be seen in Table 3. We found that HS enrollment ($r (87) = -.56, p < .001$) and ESL classification ($r (87) = -.47, p < .001$) by themselves were strong predictors of BRSA scores. We also found that European American race was
associated with BSRA scores at a level approaching statistical significance ($r (87) = .19, p = .083$). Based on these findings, we decided that HS enrollment, ESL classification, and race should be included in subsequent models regressing BSRA scores on $\Delta$RSA.

Table 1 also provides important information about average patterns of RSA change during both tasks. The mean value of $\Delta$RSA during the GW task was positive ($M = .85, SD = .78$), indicating that, on average, children’s RSA levels were lower during the task compared to baseline. However, the mean value of $\Delta$RSA during the EF Touch was negative ($M = -.70, SD = 0.65$), indicating that, on average, children’s RSA levels were higher during the task compared to baseline. Figure 1 displays the number of participants that showed RSA suppression, no change in RSA (quantified as +/-5% from zero), and RSA augmentation from baseline during each task. The left panel of the figure, which corresponds to $\Delta$RSA during the GW task, shows that a majority of children (85%) experienced RSA suppression during the task. The right panel of the figure, which corresponds to $\Delta$RSA during the EF Touch, shows that a majority of children (90%) experienced RSA augmentation during the task.

**Model Specification and Testing**

Two regression models were specified and the results are reported in Table 4. In the first model, scores on the BSRA were regressed on race, HS enrollment, ESL classification, and $\Delta$RSA during the GW task; in the second model, scores on the BSRA were regressed on the same covariates and $\Delta$RSA during the EF Touch. Model 1 results showed that there was a significant effect of $\Delta$RSA during the GW task on subsequent BSRA scores ($B = 3.38, CI = [0.25, 6.51], p = .033$), demonstrating that children who experienced RSA suppression during the GW task scored higher on the BSRA one year later. Model 2 results showed the opposite trend where children who experienced RSA augmentation during the EF Touch scored higher on the
BSRA one year later ($B = -4.05$, $CI = [-9.04, 0.94]$, $p = .108$), although this association did not reach statistical significance.
DISCUSSION

This study examined associations between PNS activity during hot and cool tasks of volitional self-regulation measured at school entry and school readiness, evaluated at the end of the school year as basic knowledge of numeracy and literacy. Analyzing data gathered by the LEAPS research project, we found that RSA suppression during the hot GW task was significantly associated with children’s content knowledge. This result is consistent with our first hypothesis, which proposed that it is primarily the regulation of arousal, emotions, and behavior at school entry, more so than regulation of cool cognitive processes, that prepares the child to benefit most from a curriculum which in this age range places a premium on attention, compliance, and participation. This result, however, must be interpreted in light of the fact that children’s observed regulation of arousal and behavior during the tasks, or the teaching context for that matter, were not considered in the present study. Instead, a physiological substrate, PNS engagement and disengagement, was used as a biological proxy of the capacity to regulate.

Findings from the second model that examined the effect of ΔRSA during the EF tasks on BSRA scores were nonsignificant and therefore should be interpreted with caution. Nonetheless, they revealed an unexpected trend in which an augmentation of RSA from baseline, as opposed to suppression, showed an association to the BSRA scores. Interpreting this effect within the framework of Cumming’s (2014) new statistics, we find it close to reaching significance. Cumming emphasizes that statistical effects should be interpreted based on degrees of confidence, that is their odds of being replicated. Table 4 model results indicated that while the GW task displays a larger confidence interval (CI) than the EF tasks, the comparable interval for
the latter suggests that neither finding is manifestly off the mark. The current study was exploratory in nature on this question. Replications with larger samples and diverse populations will have to be completed to support the proposal that opposite effects of RSA activity in hot and cool tasks of self-regulation are the norm in the preschool setting.

Opposing effects on PNS activity during hot and cool tasks, if replicated, are informative given conflicting evidence in the current literature on the topic. In the meanwhile, polyvagal theory offers some hints. This theory posits that high PNS activity supports calm cognitive and behavioral states of social engagement. We currently live in a techno-cultural environment in which, often from a very young age, social engagement is replaced or supplemented by an interactive machine the child soon learns to control. Earlier experiments have shown that high interest in a task is normally accompanied by a reduction in heart rate. Is it possible that a corresponding augmentation of RSA during our computer-administered EF battery simply reflects, in this age range, the enjoyment of engaging the machine? Or is it also possible that enjoying this interaction be shown, by itself, to predict knowledge acquisition in the preschool environment?

This unexpected result can also be considered in the larger context of the neurobiological substrates of self-regulation that includes the central autonomic network (CAN). Thayer and Lane (2000) proposed the model of neurovisceral integration in the context of emotion regulation and dysregulation. Their neurovisceral integration model of adaptive functioning links the CAN to the ANS. The CAN system has been tied to inhibitory skills, shown to fail during bouts of anxiety (Friedman, 2007). Further, research participants with diagnosed generalized anxiety disorder have experienced stable decrements in heart period variability (HPV) across trials, indexing a loss of vagal tone. The researchers attributed this pattern of HPV to a “lack of
behavioral flexibility” and an inability to respond to “changing environmental demands” appropriately (Thayer & Lane, 2000). In light of this model, it may be worth investigating whether environmental demands in the age range of interest to us recruit CAN when the necessity of regulating emotions gains salience.

We know from the literature that RSA suppression during EF tasks is a strong predictor of academic performance during formal schooling (e.g., Becker et al., 2012). School-age children learn more beyond simple numeracy and literacy as assessed by tests like the BSRA; for instance, fractions require an understanding of numerical relations that goes beyond knowing how to count from one to 10. According to Piaget’s theory, children in preschool are still in the preoperational stage, when the basic elements of logical thinking are not yet in place. It is only by the time of formal schooling that logical thinking truly emerges with entry in the concrete operational stage (Huit & Hummel, 2003). Advances from preoperational to concrete operational and formal Piagetian stages of cognitive development may serve as useful markers to examine how hot and cool processes respectively weigh in as contributors to school preparedness at all stages of schooling.

Limitations and Future Directions

The methods employed in this study to challenge executive functions regulation, the EF Touch task in particular, warrant a look at the medium used to administer them. The EF Touch is a computerized battery of tasks, that has inherent strengths regarding feasibility and standardization (Willoughby et al., 2019). However, a potential limitation of this instrument is the possibility that its tasks may be perceived as just another computer game by children in this age range. We probably cannot expect four-year-old children to understand that through this game we aim at evaluating some capacity they may or may not have. To a four-year-old a
computerized assessment battery may be plainly experienced as a potentially pleasurable game to engage in. If so, that could explain why we see a trend toward RSA augmentation during the EF Touch task. Future research should utilize the original administration of the EF Touch using pencil and paper to test whether RSA measures during a naturalistic task compare to similar ones obtained through a computerized assessment.

Another aspect to consider when assessing executive functions is how aware the subjects are of being “evaluated.” For a young child who thinks the EF Touch task is just another video game, performance may matter less, making it less likely that errors on the task arouse concerns of self-worth. Based on the literature on stress, challenging the integrity of the self is a potent condition for bringing in the SRS to the rescue (Dickerson & Kemeny, 2004). The Trier Social Stress Test (TSST), a widely used test that was conceived to put self-worth in the public eye, capitalizes on this potent stressor to produce a physiological response. Having one’s self-worth in the public eye (or not) may shed light on the overall lack of RSA suppression during the EF tasks observed in the present study. As explained above, it is unlikely that four-year-old children perceived our computer-administered EF tasks as an attempt to measure their cognitive abilities; therefore, what was left to inform a physiological response was the relative enjoyment experienced during the task. A TSST-like response should be expected, however, when the evaluative aspect of the task gains salience with experience in formal schooling where similar tests are routinely conducted. By late childhood, this response may be measured in part through RSA suppression during cool tasks. Indeed, this is what the extant literature reports, showing abundant evidence that RSA suppression during EF tasks is a strong predictor of social adjustment and academic success over the years of formal schooling and even beyond.
It would be worthwhile in future research to examine how, over development and transitions to more complex learning environments, capacities to regulate emotions and/or pure cognitive processes play out as predictors of concurrent and subsequent academic success. If we were to extend this study longitudinally beyond the preschool years, we may see a change in the relative contribution of hot and cool processes of regulation to academic performance as children enter more complex contexts that increasingly bring to salience the ability to regulate purely cognitive processes.

While this study employed a variable-oriented approach to analyzing the data, future research could utilize a person-centered approach to look at patterning of RSA suppression across tasks using cluster analysis. Cluster analysis has traditionally been used in research on temperament, specifically to identify temperament types (Gartstein et al., 2017), and it has recently been used to identify clusters of physiological activity in the framework of the adaptive calibration model of stress responsivity (Kolacz et al., 2016). This method of analysis could determine the optimal number of groupings that best capture the total variance to extract from the data; in this case, the groupings would be based on RSA suppression patterns measured during hot and cool self-regulatory tasks. Such an analysis could identify, for instance, one group of children that augments during both the hot and cool tasks, another that suppresses during both tasks, and another group that augments during one task and suppresses during the other. The next step would be to examine the extent to which the groupings so obtained are predictive of BSRA scores. Using cluster analysis future research would allow us to evaluate the extent to which it is the patterning of individual differences in RSA responses across hot and cool tasks that is best predictive of school readiness, or a variable-oriented approach in which hot and cool tasks are treated separately in predictive analyses.
Sampling was a limitation in this study, as this convenience sample was small and not as diverse as desirable. A larger sample would give us more power to examine predictor-outcome associations with closer attention to socioeconomic status (SES) and related similar factors. Based on the extant literature, it is well known that children living in poverty face significant challenges in terms of school readiness (Howse et al., 2003). This early exposure to poverty can exert its influence on school readiness through multiple pathways, one highly relevant pathway being through executive functions (Perry et al., 2018). Other research has shown that chronic poverty and experiences of household chaos hinder children’s emotional adjustment and regulation (Raver et al., 2015). Future research should examine more specifically the role of SES; as it stands, the present study only partially captures SES differences within its sample using Head Start enrollment as a proxy. Findings from such studies could inform policies and interventions aimed at improving children’s school readiness outcomes in conjunction with programs implemented to improve children’s self-regulatory capacities in the classroom context (Raver et al., 2011).

Considerations regarding the sample additionally raise questions about children’s level of skills prior to entry into preschool. Depending on a variety of factors, including the family context, it is possible that many preschoolers begin learning concepts such as colors, numbers, and ABCs before stepping foot into a preschool classroom. For these children, this entry-level knowledge, especially when coupled to age-expected regulatory capacities, could set them up to benefit most from the preschool curriculum. Studies have shown that parents living in poverty may have less involvement and engagement in their children’s school and academic activities and may not provide them with as many resources that could help develop cognitive skills (Cooper et al., 2010). Parental involvement in education can be lower for poor parents for a
number of reasons, largely including exclusion in school environments and in social circles (Van der Berg, 2008). While this study did not consider entry level skills, future research should consider initial levels of executive functions along with estimates of parental involvement in providing a ‘head start’ in numeracy and literacy knowledge prior to entry into preschool. Differences among families in the capacity to provide this scaffold could moderate or mediate the findings presented here.

The considerations outlined above pave the way for meaningful interventions in early care and education (ECE). Often, especially in the early education classroom, self-regulation can only be seen from the outside by observing child behavior. As in the present study, examining what is happening “under the skin” via PNS activity during arousing tasks can provide a useful new window of information to parents, teachers, and policymakers that can then help implement policies or programs to aid in promoting calm engagement in the classroom. Focusing on the malleable factors that have the capacity to improve children’s neurophysiological functioning over time provides feasible opportunities for professional practices to change and improve. Harkening back to poverty, increasing community support for poor parents may aid in improving parental involvement in children’s education. Teacher and classroom-level factors, including but not limited to teacher sensitivity (Gerber et al., 2007), teacher beliefs (Hamre et al., 2012; Hoy et al., 2006), and teachers’ interactions with students (Williford et al., 2013a; Heller et al., 2012), have been demonstrated to be indicative of children’s success and are malleable factors that can be improved or adapted in light of the current research on children’s functioning. By implementing changes across the board, we have an opportunity to help improve children’s self-regulatory capacities and promote optimal adjustment punctually, and for their future.
APPENDIX 1: TABLES

Table 1

*Bivariate correlations among RSA change during the four GW episodes*

<table>
<thead>
<tr>
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<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
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<tbody>
<tr>
<td>1. ΔRSA during GW1</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. ΔRSA during GW2</td>
<td>.85**</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. ΔRSA during GW3</td>
<td>.93**</td>
<td>.73**</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>4. ΔRSA during GW4</td>
<td>.80**</td>
<td>.69**</td>
<td>.67**</td>
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</tbody>
</table>

| N   | 71  | 67  | 68  | 68  |
| M   | -.83 | -.93 | -1.07 | -.45 |
| SD  | 1.08 | .89 | .86 | .97 |

Note: GW1-4 refer to each of the four episodes of the gift-wrap task; *p < .05, **p < .01, ***p < .001.

Table 2

*Bivariate correlations among RSA change during the four EF tasks*

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1. ΔRSA during EF1</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. ΔRSA during EF2</td>
<td>.80**</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3. ΔRSA during EF3</td>
<td>.78**</td>
<td>.78**</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>4. ΔRSA during EF4</td>
<td>.84**</td>
<td>.81**</td>
<td>.84**</td>
<td>---</td>
</tr>
</tbody>
</table>

| N   | 73  | 72  | 72  | 75  |
| M   | -.96 | -.81 | -.55 | -.62 |
| SD  | .74 | .66 | .72 | .71 |

Note: EF1 = stroop task, EF2 = go/no-go task, EF3 = working memory span task, EF4 = flexible item selection task; *p < .05, **p < .01, ***p < .001.
Table 3

*Bivariate correlations among and descriptive statistics for ΔRSA, BSRA scores and potential covariates*

<table>
<thead>
<tr>
<th></th>
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<th>5.</th>
<th>6.</th>
<th>7.</th>
<th>8.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gender (1=male)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>2. Race (1=EA)</td>
<td>-.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3. Age (years)</td>
<td>.12</td>
<td>-.16</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4. HS enrollment (1=yes)</td>
<td>-.09</td>
<td>-.39***</td>
<td>.31**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. ESL classification (1=yes)</td>
<td>-.003</td>
<td>-.35***</td>
<td>.25*</td>
<td>.73***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. ΔRSA during GW task</td>
<td>.13</td>
<td>-.13</td>
<td>.26*</td>
<td>.03</td>
<td>.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. ΔRSA during EF tasks</td>
<td>.01</td>
<td>-.002</td>
<td>-.21</td>
<td>-.04</td>
<td>.14</td>
<td>-.77***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. BSRA score</td>
<td>.04</td>
<td>.19</td>
<td>-.08</td>
<td>-.56***</td>
<td>-.47***</td>
<td>-.23</td>
<td>.22</td>
<td></td>
</tr>
</tbody>
</table>

N: 101 102 87 102 102 74 79 87

M: 0.53 0.51 4.82 0.26 0.34 0.85 -0.70 67.34

SD: 0.50 0.50 0.47 0.44 0.79 0.78 0.65 12.05

Note: EA = European American; HS = Head Start; ESL = English as a second language; GW = Gift-wrap; EF = Executive Functions. * p < .05, ** p < .01, *** p < .001.

Table 4

*Regressions of BSRA scores on ΔRSA during the GW and EF tasks*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model 1: GW</th>
<th></th>
<th>Model 2: EF</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>95% CI</td>
<td>B</td>
<td>95% CI</td>
</tr>
<tr>
<td>HS enrollment (1=Yes)</td>
<td>-13.86***</td>
<td>[-19.84, -7.88]</td>
<td>-15.75***</td>
<td>[-21.06, -10.44]</td>
</tr>
<tr>
<td>Race (1=EA)</td>
<td>0.62</td>
<td>[-2.81, 4.05]</td>
<td>0.08</td>
<td>[-4.61, 4.45]</td>
</tr>
<tr>
<td>ESL Classification (1=Yes)</td>
<td>-4.09**</td>
<td>[-6.92, -1.26]</td>
<td>-2.83*</td>
<td>[-5.42, -0.24]</td>
</tr>
<tr>
<td>ΔRSA During Task</td>
<td>3.38*</td>
<td>[0.25, 6.51]</td>
<td>-4.05</td>
<td>[-9.04, 0.94]</td>
</tr>
</tbody>
</table>

Note: EA = European American; HS = Head Start; ESL = English as a second language; GW = Gift-wrap; EF = Executive Functions; CI = Confidence Interval; * p < .05, ** p < .01, *** p < .001; all parameter estimates are unstandardized.
Figure 1. Number of participants who experienced RSA suppression, no change, and RSA augmentation during the gift-wrap (GW) task (left panel) and number of participants who experienced RSA suppression, no change, and RSA augmentation during the EF touch (right panel).
REFERENCES


