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PAPER

Linking executive function skills and physiological challenge response: Piecewise growth curve modeling

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Abstract

This study employed piecewise growth curve modeling to examine how children's executive function (EF) skills relate to different components of children's physiological response trajectory – initial arousal, reactivity, and recovery. The sample included 102 ethnically diverse kindergarteners, whose EF skills were measured using standard tasks and observer ratings. Physiological response was measured via changes in respiratory sinus arrhythmia (RSA) in response to a laboratory socio-cognitive challenge. Children's cool and hot EF skills were differentially related to both linear and quadratic components of RSA response during the challenge. Greater hot EF skills and assessor report of EF skills during laboratory visit were related to quicker RSA recovery after the challenge. These findings demonstrate that children's physiological response is a dynamic process that encompasses physiological recovery and relates to children's self-regulation abilities.

Research highlights

- Children's physiological response is a dynamic process that includes distinct reactivity and recovery trajectories.
- Discrepancies in how cool and hot EF skills relate to RSA response to the challenge task may index different utilization of these skills during social and cognitive task demands.
- Higher executive function skills in emotionally demanding situations were uniquely related to physiological recovery, as indexed by faster RSA augmentation following the challenge.
- Findings are consistent with the polyvagal perspective of social engagement and highlight the importance of studying the interplay between physiological and behavioral regulation.

Introduction

Numerous empirical studies have identified physiological stress response as an important factor in children's adaption to various life experiences (Del Giudice, Ellis & Shirtcliff, 2011; Ellis & Boyce, 2011; Obradović, 2012). However, these studies have focused primarily on how early life experiences contribute to physiological profiles and whether individual differences in physiological reactivity predict certain behaviors or moderate the effect of contextual influences on children's adaptation. This work overlooks how children's capacity for self-regulation relates to their physiological arousal during challenging situations. Although a few studies of young children link higher executive function (EF) skills to physiological response during concurrent EF assessment (Marcovitch, Leigh, Calkins, Leerks, O'Brien *et al*., 2010) and other laboratory challenges (Skowron, Cipriano-Essel, Gatzke-Kopp, Teti & Ammerman, 2014), no study has examined how EF skills relate to children's physiological arousal before, during, and after exposure to a developmentally normative challenge. Moreover, most research represents physiological reactivity as a simplistic, single-score index that obscures the known complexities in physiological response (Berntson, Cacioppo & Grossman, 2007; Burt & Obradović, 2013; Porges, 2007). Using growth curve modeling to analyze physiological response as a *process*, the current study examines how various measures of EF skills relate to

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distinct components of children's continuous physiological response trajectory: initial arousal, reactivity, and recovery.

Physiological responsivity as a process

Activity of the parasympathetic nervous system (PNS), which influences sympathetic input to the heart, regulates recovery, and restores autonomic homeostasis, has been linked to children's ability to engage and cope with everyday challenges (Obradović & Boyce, 2012). Respiratory sinus arrhythmia (RSA), a measure of PNS activity, reflects high frequency heart rate variation controlled by efferent fibers of the vagus nerve during the respiratory cycle. Vagal regulation, as measured by change in RSA values, has been regarded as an indicator of children's capacity to regulate emotional arousal (Beauchaine, Gatzke-Kopp & Mead, 2007; Blandon, Calkins, Keane & O'Brien, 2010; Porges, 2007). Polyvagal theory posits that vagal regulation has evolved to allow for more rapid and flexible physiological responses to both positive and negative environmental demands (Porges, 2003). Accordingly, high baseline RSA and/or low RSA withdrawal enable a child to remain calm and focused in response to safe and positive experiences, whereas moderate RSA withdrawal produces temporary arousal that can promote increased engagement and sustained attention in response to mildly stressful or challenging experiences. In contrast, potentially threatening experiences may result in greater RSA withdrawal and activation of a sympathetic nervous system response, which is metabolically more costly. Porges (2003) further proposed that vagal regulation plays a critical role in promoting social engagement via integration of the vagus nerve with the neural systems that control eye gaze, facial expressions, and vocalizations.

Empirical studies link higher basal RSA with various measures of adaptive functioning, including greater social competence, emotion regulation, and cognitive abilities in early childhood (Beauchaine, 2001; Blair & Peters, 2003; Fabes, Eisenberg & Eisenbud, 1993). Furthermore, greater RSA withdrawal in response to various laboratory challenges has been associated with sustained attention, engagement during challenge tasks, on-task behaviors in the classroom, and cognitive functioning, as well as more adaptive emotion regulation strategies (Blair & Peters, 2003; Calkins, Blandon, Williford & Keane, 2007a; Calkins & Keane, 2004; Doussard-Roosevelt, Montgomery & Porges, 2003; Staton, El-Sheikh & Buckhalt, 2009; Suess, Porges & Plude, 1994). However, RSA withdrawal has also been associated with vigilance, anxiety, poor emotion regulation strategies, and behavioral problems (Beauchaine, 2012; Calkins, Graziano & Keane, 2007b; Santucci, Silk, Shaw, Gentzler, Fox *et al.*, 2008; Utendale, Nuselovici, Saint-Pierre, Hubert, Chochol *et al.*, 2014). Motivated by inconsistent results across individual studies, Graziano and Derefinko (2013) conducted a meta-analysis of 44 studies which revealed that RSA withdrawal was associated with better cognitive and academic performance and fewer externalizing problems. In healthy, community samples, RSA withdrawal was also related to more competent social functioning. However, the effect sizes for cognitive and social outcomes were not as robust as for behavioral problems, highlighting the need for more research examining the relation of RSA withdrawal with indices of positive adaptation.

Most of this work uses a single score to represent average RSA withdrawal, obscuring meaningful changes in RSA regulation as the child encounters, engages with, and completes a challenge, or responds to and recovers from a stressor. Yet, repeated measurement of RSA response during challenge tasks reveal distinct processes of physiological reactivity and recovery (Schmitz, Krämer, Tuschen-Caffier, Heinrichs & Blechert, 2011). Consequently, researchers have called for more dynamic analytic approaches to investigating individual differences in physiological response trajectories (Burt & Obradović, 2013; Fortunato, Gatzke-Kopp & Ram, 2013; Hastings & Miller, 2014). For example, Brooker and Buss (2010) showed that both static and dynamic measures of RSA change during a fear-inducing challenge were related to toddlers' affect and behaviors. This study demonstrates the importance of understanding the timing of RSA withdrawal rather than simply measuring average RSA change. Miller, Chocol, Nuselovici, Utendale, Simard *et al.* (2013) used latent growth curve modeling to show that 4- to 6-year-olds reacted to an anger-inducing video with initial RSA withdrawal followed by recovery to baseline. Further, the quadratic slope of the RSA withdrawal varied as a function of the child's temperament and parenting practices. There is a need to extend this work by investigating whether different child-level characteristics might be associated with reactivity and recovery processes.

Executive functioning and physiological responsivity

Developing EF skills is considered a major milestone of early childhood, as children's ability to use these higher-order cognitive skills to regulate their attention, behavior, and emotions has been linked to better school readiness, social skills, conduct, and academic achievement (Diamond, 2013; Obradović, Portilla & Boyce, 2012). In early childhood, differences emerge between applying EF skills in emotionally neutral contexts (i.e.

cool EF skills) and in motivational and emotionally laden contexts (i.e. hot EF skills) (Zelazo & Carlson, 2012). Further, cool and hot EF skills have a unique brain bases (Zelazo & Müller, 2010), operate independently (Eslinger, Flaherty-Craig & Benton, 2004), and have different developmental trajectories (Prencipe, Kesek, Cohen, Lamm, Lewis *et al.*, 2011; Zelazo & Carlson, 2012). Cool EF skills are more robustly related to cognitive outcomes, whereas hot EF skills are more strongly related to socioemotional behavior problems (Kim, Nordling, Yoon, Boldt & Kochanska, 2013; Willoughby, Kupersmidt, Voegler-Lee & Bryant, 2011). As such, cool and hot EF skills may uniquely relate to how children physiologically respond to challenges that include both cognitive and social demands. For example, cool EF skills may relate to physiological response via cognitive engagement that is supported by focused attention and efficient working memory, whereas hot EF skills may relate to physiological response via social engagement that is supported by adaptive emotion regulation. However, prior psychophysiological research has mostly employed aggregate or single measures of EF skills and has not explicitly examined whether various EF components differentially relate to patterns of RSA regulation.

EF skills have been associated with higher baseline RSA in children and adolescents (Marcovitch *et al.*, 2010; Mezzacappa, Tremblay, Saul, Seguin, Pihl *et al.*, 1997; Staton *et al.*, 2009; Sulik, Eisenberg, Spinrad & Silva, 2015); although some studies have failed to find a significant association (Blair & Peters, 2003) or reported it only in subgroups of shy children (Sulik, Eisenberg, Silva, Spinrad & Kupfer, 2013). Young children's EFs have also been studied in relation to RSA withdrawal, primarily during EF assessments, with inconsistent results. Corroborating the adult literature, Becker, Carrere, Siler, Jones, Bowie *et al.* (2012) reported that better performance on an EF task was associated with greater RSA withdrawal among elementary school students. Marcovitch and colleagues (2010) showed a curvilinear association between EF performance and concurrent RSA regulation, such that the highest EF skills were observed in preschoolers with moderate levels of RSA withdrawal. In contrast, Utendale and colleagues (2014) found that greater EF skills were associated with lower RSA withdrawal among 5- and 6-year-olds, but this relation was further moderated by children's externalizing problems. Better performance on EF tasks was linked to mild RSA withdrawal in children with low levels of externalizing, while the opposite was true for children with high levels of externalizing. Finally, Sulik and colleagues (2015) reported that while RSA withdrawal was linked to better EF performance, the associations between changes in RSA levels and EF skills varied across three different EF tasks. Their work provided preliminary evidence that RSA reactivity may relate differently to cool and hot EF skills.

Studies that examine how direct assessments of EF skills relate to RSA responses during other types of challenges are less common in young children. In a recent study of 78 dyads, higher EF skills in non-maltreated preschoolers were linked to greater RSA withdrawal during a joint parent–child challenge that focused on building a block model with parental guidance (Skowron *et al.*, 2014). However, the opposite was true for preschoolers who had been maltreated. Higher EF skills were related to greater RSA augmentation during the joint challenge, which may have helped maltreated children stay calm during an emotionally taxing interaction with their parent.

Parent report of self-regulation skills offers a broader view of how children apply EF skills in a naturalistic setting. Parent report of observed EF skills, including measures of effortful control, has been associated with higher baseline RSA (Beauchaine, Gatzke-Kopp, Neuhaus, Chipman, Reid *et al.*, 2013; Chapman, Woltering, Lamm & Lewis, 2010; Taylor, Eisenberg & Spinrad, 2015). A few studies have also linked adult report of EF skills to RSA reactivity in small samples of children at risk for mental health problems. For example, greater RSA withdrawal was associated with lower levels of parent-rated EF skills in preschoolers diagnosed with ADHD (Beauchaine *et al.*, 2013) and teacher-reported emotion regulation in highly aggressive kindergarteners (Gatzke-Kopp, Greenberg & Bierman, 2015). In contrast, greater RSA during a sad film was associated with more adaptive emotion regulation strategies in children at risk for mood disorders (Gentzler, Santucci, Kovacs & Fox, 2009). In community samples, RSA withdrawal in response to social challenge was related to higher levels of parent-rated EF skills (Hastings, Nuselovici, Utendale, Coutya, McShane *et al.*, 2008), whereas RSA withdrawal during EF tasks was related to teacher reports of greater on-task classroom behaviors, but lower social competence in preschoolers (Blair & Peters, 2003). However, RSA withdrawal was not related to a latent measure of parent, teacher, and observer report of EF skills in kindergarteners (Taylor *et al.*, 2015). There is a need for more research that investigates how adult report of applied EF skills, rather than dysregulated behaviors (e.g. externalizing symptoms), relates to RSA regulation in young children who are not at risk for psychopathology.

Research assistants who spend significant time observing and assessing children in a laboratory setting can offer a unique perspective on children's ability to apply EF skills in a structured and emotionally taxing situation. For example, the Preschool Self-Regulation Assessment-Assessor Report (PSRA-AR; Smith-Donald, Raver, Hayes & Richardson, 2007) has been shown to relate to direct assessments of cool and hot EF skills and predict adult report of behavior problems and social competence (Bailey, Denham, Curby & Bassett, 2016; McCoy & Raver, 2011; Smith-Donald *et al*., 2007). Further, it has been conceptualized as an index of emotion regulation that captures how well children regulate their behavior during laboratory procedures that may elicit emotions such as frustration, anger, disappointment, excitement, and pride (Bailey *et al*., 2016; McCoy & Raver, 2011). Future research should examine whether assessor ratings of global behavioral and emotional regulation during standardized laboratory procedures relate to children's physiological regulation over and above parent and teacher reports of EF skills in home and school settings.

By focusing on RSA reactivity as indexed by a difference or residual score (Burt & Obradović, 2013), extant work limits our understanding of how EF skills may differentially relate to RSA response before, during, and after the challenge. Recently, Ursache and colleagues reported that preschoolers who displayed high levels of both emotional reactivity and regulation in infancy had high EF skills, whereas children who showed high emotional reactivity but low regulation had poor EF skills (Ursache, Blair, Stifter, Voegtline & The Family Life Project Investigators, 2013). The authors further suggest that the underlying mechanism linking well-regulated or poorly regulated emotional reactivity to subsequent EF development may operate through the modulation of physiological arousal. Relatedly, Santucci and colleagues (2008) found that children who engaged in maladaptive emotion regulation strategies displayed lower RSA recovery after a delay-of-gratification task, an index of hot EF skills. In contrast, RSA recovery was unrelated to emotion regulation in a small sample of children at risk for depression (Gentzler *et al*., 2009). Finally, Kahle, Miller, Lopez and Hastings (2016) reported a nonlinear change in RSA in response to frustration and found that parent-rated emotion regulation was associated with sympathetic recovery. It is crucial to extend this work to better understand how young children's EF skills, especially in an emotionally laden context, relate to regulation of physiological response after the challenge is over (Obradović, 2016).

Current study

We used piecewise growth curve analyses to examine how young children's EF skills explain variability in their dynamic physiological response. We focused on RSA as an index of physiological response because it has been conceptualized as a measure of children's attention, engagement, and emotion regulation capacities and can be reliably measured in short epochs that represent various response trajectory components. We used a multi-method, multi-informant approach to assess EFs, including direct measures of both emotionally neutral and emotionally laden EF skills as well as parent and assessor reports of EF skills at home and in the lab. Since assessors observed both behavioral and emotional regulation skills during a three-hour laboratory visit that included numerous emotional challenges, the assessor report captured a greater proportion of hot EF skills than the parent report. We conceptualized a priori two models, each focusing on a different assessment method (tasks vs. questionnaires). Each model included indices of emotionally neutral and emotionally laden EF skills, with the goal of identifying their unique associations with different aspects of the RSA regulation trajectory (see Analytic Plan for more details).

Given the limited research linking young children's EFs to dynamic measures of physiological response during laboratory challenges, this study is largely an exploratory effort to better understand how various measures of EF skills relate to children's RSA regulation in response to a socio-cognitive challenge. Nevertheless, extant studies suggest that higher levels of cool and adult-reported EF skills may relate to higher initial RSA levels (Chapman *et al*., 2010; Marcovitch *et al*., 2010; Mezzacappa *et al*., 1997; Staton *et al*., 2009; Taylor *et al*., 2015). In contrast, the link between EF skills and RSA reactivity is more tenuous – possibly curvilinear, qualified by sample characteristics or contextual experiences (Becker *et al*., 2012; Marcovitch *et al*., 2010; Skowron *et al*., 2014; Utendale *et al*., 2014). As a result, we examined how EF skills relate to both linear and quadratic RSA change during the challenge. Finally, limited research suggests that indices of emotionally laden EF skills may promote greater physiological recovery via better emotion regulation strategies (Santucci *et al*., 2008).

Methods

Participants

The participants were 96 kindergarteners (*M* age = 5.6 years; *SD* = 0.6; 52% females) drawn from a sample of 102 children who participated in a laboratory study along with a primary caregiver (*M* age = 38.9 years; *SD* = 6.8; 93% females). Six children were excluded from the current study as they did not complete the physiological protocol. Families were recruited with advertisements at community centers, preschools, elementary schools, and libraries and were eligible if they had a child who was fluent in English and entering kindergarten or first grade. The sample was racially diverse, with caregivers reporting the children as 36% White, 26% Hispanic/Latino, 20% Asian, 4% Black, and 14% Multiracial/Other. Seventeen percent of participating caregivers were single parents. Seventeen percent reported educational attainment of a high school diploma or less, while 42% had earned a graduate or professional degree. Consistent with this, 23% of the families reported household income less than $50,000, while 36% reported household income greater than $200,000.

Procedure

Primary caregivers (hereafter referred to as parents) and their children visited a university research laboratory to complete a three-hour protocol. Upon arrival, research assistants (RAs) greeted and consented the dyad, introduced them to the laboratory setting and the study protocol, and set up the equipment for measuring their physiological responses. Parents completed an in-person survey with a trained interviewer, which assessed demographic information, family functioning, parenting strategies, and child functioning. The parent survey was administered in English or Spanish, depending on parent preference. Meanwhile, in a separate room, children first completed a battery of EF tasks and a vocabulary test. Halfway through the session (approximately 90 minutes after arrival), children completed a series of challenge tasks designed to elicit physiological response. The current study focuses on the first socio-cognitive challenge task. At the end of the session, children and parents reunited to complete a set of five interaction tasks. Detailed descriptions of the stress reactivity protocol and parent–child interaction tasks are presented in supplemental materials.

Measures

Socio-cognitive challenge task

Parasympathetic response was assessed using the Storytelling task from the Laboratory Temperament Assessment Battery: Middle Childhood Version (Lab-TAB; Goldsmith, Reilly, Lemery, Longley & Prescott, 2012). The research assistant (RA) who conducted the child assessment was joined by a second RA, unfamiliar to the child, and the child was asked to stand in front of the two seated RAs. The unfamiliar RA introduced the task and asked the child to talk about her day. If the child did not respond initially or stopped talking before 2.5 minutes were over, the unfamiliar RA asked a series of questions (e.g. 'What did you have for breakfast/lunch?') after a designated period of silence. The two RAs did not provide any verbal or facial feedback to the child. After completing the task, the child was asked to sit and rest for 60 seconds as the child assessor prepared the next task. The RAs followed a script and with specific procedures for asking follow-up questions to ensure that the experience was standardized across the sample. Still, as expected, children varied in how much they spoke and how many questions they received. We controlled for total speaking time (M = 49.61 seconds, SD = 40.71) in the follow-up analyses. We conceptualized the Storytelling task as a socio-cognitive challenge because it relies on the child's ability to recall and report events (cognitive challenge) as well as ability to answer questions posed by an unfamiliar person in front of two adults who are providing no feedback (social challenge). The task was designed to approximate normative challenges that kindergarteners may encounter in their daily lives.

Physiological response

RSA response to the socio-cognitive task was measured using a Wireless BioNomadix RSP module (BIOPAC Systems, Goleta, CA). RSA was estimated as the natural logarithm of the variance of heart period within the high frequency bandpass associated with respiration at this age (i.e. 0.15–0.80; Bar-Haim, Marshall & Fox, 2000; Rudolph, Rudolph, Hostetter, Lister & Siegel, 2003). Prior to analyses, each waveform was verified, interbeat intervals (IBIs) were visually checked, and artifacts were removed. Using AcqKnowledge software, RSA values were calculated across eight 30-second epochs. The introduction to the task occurred during epoch 1, the task occurred during epochs 2–6, and the recovery occurred during epochs 7–8. We created a difference score (i.e. Sit-Stand variable) using baseline sitting and baseline standing RSA values (each an average of two 30-second epochs) to quantify the effect of postural change on RSA response (Bush, Alkon, Obradović, Stamperdahl & Boyce, 2011; Dietrich, Riese, Sondeijker, Graces-Lord, van Roon *et al*., 2007). Descriptives and valid sample size for all epochs are reported in Table 1, and missing data are discussed below.

Direct assessment of EF skills

Working memory was assessed using the Backward Digit Span task (Flanagan & Kaufman, 2009). Children were verbally presented with digit strings that increased in length by one digit and were asked to repeat the digit

Table 1 *Descriptive statistics and correlations among primary observed variables*

	M	(*SD*)	*N*	1	2	3	4	5	6	7	8	9	10
1. Child age	5.60	(0.57)	102	–									
2. Child female	0.52	(0.50)	102	−.09	–								
3. Child ethnic minority	0.14	(0.48)	102	−.01	−.03	–							
4. Child PPVT	112.68	(16.69)	101	.15	−.02	−.67***	–						
5. Time speaking	50.04	(41.20)	99	.27**	.03	−.04	−.05	–					
6. RSA sit-stand	0.96	(0.77)	95	.16	.01	.01	.01	.01	–				
7. Working memory	3.90	(2.22)	102	.34***	.00	−.35***	.46***	.05	−.04	–			
8. Delay of gratification	0.01	(0.92)	99	.22*	−.06	−.26*	.35***	−.10	.04	.32**	–		
9. Parent-rated EFs	4.97	(0.71)	101	.06	.09	−.22*	.31**	.05	−.02	.36***	.03	–	
10. Assessor-rated EFs	3.33	(0.67)	102	.33***	.06	−.17†	.38***	.07	.18†	.50***	.43***	.28**	–
11. RSA epoch 1	6.75	(1.13)	92	.06	−.24*	−.05	.05	.26*	−.16	.10	−.04	.02	−.15
12. RSA epoch 2	6.63	(1.20)	96	.08	−.15	−.01	.10	.23*	−.34***	.15	−.03	−.06	−.14
13. RSA epoch 3	6.66	(1.08)	96	.00	−.10	−.07	.13	.08	−.31**	.04	.00	−.14	−.21*
14. RSA epoch 4	6.84	(1.10)	94	.03	−.02	−.06	.10	.18†	−.27*	−.05	.09	−.23*	−.13
15. RSA epoch 5	6.62	(1.05)	91	.05	−.03	.07	.02	.13	−.27**	−.04	−.08	−.17	−.22*
16. RSA epoch 6	6.66	(1.12)	82	.04	−.01	.01	−.03	.08	−.32**	.03	−.06	−.21†	−.18
17. RSA epoch 7	7.49	(1.09)	89	.14	−.04	.01	.02	.25*	−.11	.05	.14	−.20†	.06
18. RSA epoch 8	7.47	(1.04)	85	.12	−.15	.08	.02	.21†	−.15	−.05	.11	−.15	−.01

Note: †$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$. RSA epochs intercorrelations ranged from .52 to .87, $p < .001$. EFs = executive functions, PPVT= Peabody Picture Vocabulary Test, RSA = respiratory sinus arrhythmia.

series in reverse. Each level consisted of two trials of equal length, and the task continued until the child failed both trials within a level. The total score was a sum of all correct trials. *Delay-of-gratification skills*, an index of inhibitory control in an emotionally laden context of immediate reward, was assessed using the Gift Wrap task (Kochanska, Murray, Jacques, Koenig & Vandegeest, 1996). The child was instructed to sit facing away from a table and refrain from peeking while the assessor noisily wrapped a gift for 60 seconds. Afterward, the child was left alone with the gift for 180 seconds and told not to peek. Two independent coders rated transgressions (0 = none, 1 = peeks by turning just head, 2 = turns body) during 180 seconds to yield three separate indices: (1) worst transgression ($M = 0.56$, $SD = 0.84$), (2) total number of peeks and turns ($M = 2.75$, $SD = 2.26$), and (3) latency to the first transgression ($M = 64.21$, $SD = 73.36$). Thirty-two percent of cases were double coded with excellent reliability (kappa: 1.00; ICCs = .94–.97). The total number of transgressions was reversed; and then the three behavioral indices were standardized and averaged to create a composite score ($\alpha = .89$).

Observed EF skills

Parent-rated EF skills were measured using the Inhibitory Control and Attention Focusing subscales from the Child Behavior Questionnaire (CBQ; Putnam & Rothbart, 2006). Sample items included: 'good at following instructions', 'can wait before entering into new activities if asked to', 'when drawing or coloring in a book, shows strong concentration', and 'moves from one task to another without completing any of them' (reversed). Eleven items were rated on a 7-point Likert scale, ranging from 1 = extremely untrue of your child, to 7 = extremely true of your child. Items were standardized and averaged to create a composite score ($\alpha = .69$).

Assessor-rated EF skills were measured using the Preschool Self-Regulation Assessment Assessor Report (PSRA; Smith-Donald *et al.*, 2007). At the end of the laboratory visit, the child assessors, who were trained graduate and undergraduate students, rated children's attention, inhibitory control, and emotion regulation skills observed during the entire laboratory visit (see Procedures for details). Sample items included: 'pays attention during instructions', 'distracted by sights and sounds', 'remains in seat appropriately during test', and 'modulates and regulates arousal level in self'. The items were rated on a 4-point Likert scale with specific behavioral descriptions associated with each numerical code, which aided in training and establishing good reliability. For example, the item 'sustains concentration; willing to try repetitive tasks' was scored as follows: 0 = Child not able to concentrate or persist on much of the assessment, 1 = Child frequently distracted, requires multiple prompts from assessor, 2 = Child occasionally distracted but generally persistent, and does not require prompt from assessor, and 3 = Child able to concentrate and persist with task, even toward the end of tasks and with distractions. Twenty percent of all cases were double-coded by a master coder using video recordings, yielding high interclass correlations (ICC range: .82–

1.00). A composite score was created using a standardized average of 13 items (α = .96). Since assessors observed EF skills during the entire lab visit, which included several tasks designed to elicit various emotions, we propose that this measure captures a mix of cool and hot EF skills including emotion regulation.

Covariates

Child *age*, *sex*, and *minority status* were reported by the primary caregiver as part of the demographic questionnaire completed during the laboratory visit. *Receptive vocabulary* was measured using the Peabody Picture Vocabulary Test IV to assess children's English language ability (Dunn & Dunn, 2007). *Time speaking* was coded as the total number of seconds children spoke during the 150-second socio-cognitive challenge task. The *sit-stand RSA difference score* was used to control for the effect of postural change between epochs 1–6 (standing) and epochs 7–8 (sitting).

Missing data

The number of valid observations across all analysis variables is reported in Table 1. The rate of missing cases varied across eight individual RSA epochs (range: 0%–15%; M = 6%). Consistent with other physiological studies of young children, movement artifacts (e.g. fidgeting, stretching, slouching) were a reason for missing data, and more movement was observed at the onset and after the completion of the task. In regard to other variables, two children (2%) were missing the DG score and behavioral data during the socio-cognitive task, due to missing video recordings, and one parent (1%) did not complete the CBQ due to an abbreviated session. Results of the Grubbs test (Grubbs, 1969) across all variables used in our analyses revealed only one outlier at the 95% significance level for the Sit-Stand variable, which was truncated to the nearest high value. All available data were analyzed using a full-information, maximum-likelihood estimator (see below).

Analytic plan

To examine how various measures of children's EF skills are linked to physiological response trajectories, we used piecewise linear growth curves. Growth curve models allow for both random intercepts (e.g. initial RSA values can vary) and random slopes (e.g. rate of RSA change can vary). Children's arousal during the task introduction was indexed by initial RSA value at epoch 1. We used two splines with one knot fixed at epoch 6 to represent children's RSA reactivity to the challenge (epochs 1–6) and recovery after the completion of the challenge (epochs 6–8). Since the extant research points to the significance of quadratic RSA change during a challenge (Brooker & Buss, 2010; Miller *et al*., 2013), the first spline slope included both linear and quadratic RSA terms.

Due to our small sample size and limited power, we were unable to test all four EF measures in a single model (i.e. a model with 20 parameters did not converge). Thus, we conceptualized two parallel models, each focusing on a different type of assessment. This approach enabled us to control for the shared method variance (e.g. tasks vs. questionnaires) and to isolate the unique contribution of each EF aspect (hot vs. cool) or context (home vs. laboratory). The two models also provided a possible replication of findings across two distinct assessment methods. Model 1 tested the effect of working memory (*WM*) and delay of gratification (*DG*) skills, whereas Model 2 tested parent (*Parent_EF*) and assessor (*Assessor_EF*) report of EF skills. Model 1 can be expressed as:

$$\begin{aligned} RSA_{it} = {} & \beta_0 + \zeta_{0i} + \beta_1(React_{it}) + \beta_2(React_{it}^2) \\ & + \beta_3(Recov_{it}) + \beta_4(WM_i) \\ & + \beta_5(WM_i x React_{it}) + \beta 6(WM_i x React_{it}^2) \\ & + \beta_7(WM_i x Recov_{it}) + \beta 8(DG_i) \\ & + \beta_9(DG_i x React_{it}) + \beta_{10}(DG_i x React_{it}^2) \\ & + \beta_{11}(DG_i x Recov_{it}) + \zeta_{2i} + \epsilon_{it} \end{aligned}$$

RSA_{it} is the estimated RSA value for child i at time t. The value $\beta_0 + \zeta_{0i}$ represents the child-specific intercept. The parameter ζ_{2i} represents the child-specific error component, which remains constant across epochs. The parameter ε_{it} represents the epoch-specific error component, which varies across epochs. In Model 2, WM_i and DG_i are replaced with $Parent\_EF_i$ and $Assessor\_EF_i$ as the key independent predictors for Model 2. The interaction terms between EF measures and reactivity ($React_{it}^2$) test whether the quadratic rate of RSA change during the task differs by children's EFs, whereas the interaction terms between EF measures and recovery ($Recov_{it}$) test whether the linear rate of RSA change after the task differs by children's EFs. A first set of follow-up analyses examined the robustness of findings by including the following covariates: child's age, gender, ethnic minority status, vocabulary, and total speaking time during the challenge. A second set of follow-up analyses controlled for the effect of postural change on RSA response at the beginning of the task (i.e. intercept) when children were standing and during the recovery phase (i.e. recovery slope) when children were sitting.

The multi-level models were estimated with Stata 13's *xtmixed* command using a full-information, maximum-likelihood estimator, which employs all available data (Rabe-Hesketh & Skrondal, 2012). The covariance matrix was unstructured, and we allowed the residual variance to vary by epoch, as it significantly improved fit in the final models ($\chi^2(7) = 38.86$, $p < .001$ for directly assessed EF skills and $\chi^2(7) = 35.72$, $p < .001$ for adult rated EF skills). To probe the significant interaction effects, we plotted the points at one standard deviation above and below the mean for each measure of children's EF skills.

Results

Descriptive statistics

Descriptive statistics for all observed variables are presented along with bivariate, zero-order correlations in Table 1. The four EF measures were correlated in the expected direction, although parent-rated EF skills were not significantly related to performance on the DG task. Individual epoch RSA values were highly intercorrelated (range = .52–.87, $p < .001$), with the correlation magnitude decreasing as a function of temporal proximity. Older children had significantly higher WM, DG, and assessor reports of EFs and spent more time speaking. Child gender was not correlated with any measures of EFs. Minority children had significantly lower EFs across all domains. Children's vocabulary was highly correlated with all measures of EFs. Females had lower initial RSA levels, and children who spent more time speaking during the task had higher RSA levels across multiple epochs. There were no significant zero-order correlations between direct assessments of EF skills and individual RSA epochs. Parent and assessor reports of EF skills were negatively related, albeit weakly, to RSA levels during epochs 3 to 7.

Unconditional model

The likelihood ratio test for the multi-level model versus an OLS regression model ($\chi^2(2) = 482.92$, $p < .0001$) and the interclass correlation of .67 support the use of a multi-level model. We found that the piecewise model, which estimated a quadratic slope for the reactivity component and a linear slope for recovery components, fit the data better than the single linear model ($\chi^2(1) = 79.88$, $p < .001$). The unconditional, multi-level piecewise growth curve model had an overall Wald statistic of $\chi^2(3) = 166.02$, $p < .0001$. The model revealed that the average initial RSA level (epoch 1) was 6.684 ($p < .001$), the average linear rate of RSA change increased by 0.010 ($p = .859$) and the average quadratic rate of RSA change decreased by 0.001 ($p = .931$) during the reactivity phase (epochs 1–6), and the RSA values increased by 0.503 ($p < .001$) during the recovery phase (epochs 6–8).

Conditional models

Results for two conditional models are presented in Table 2. Model 1 shows that children's WM skills predicted both linear ($\beta = -0.183$, $p = .004$) and quadratic ($\beta = 0.025$, $p = .022$) change in RSA levels during the challenge task (i.e. reactivity component). Children with higher WM showed a gradual decrease in RSA during the challenge task that leveled off after epoch 4, whereas children with lower WM showed a gradual increase in RSA during the challenge task that peaked after epoch 4 (see Figure 1a). Further, children's DG skills predicted both linear ($\beta = 0.134$, $p = .028$) and quadratic ($\beta = -0.023$, $p = .031$) change in RSA levels during the challenge task. Children with higher DG showed a gradual increase in RSA levels followed by a slight decrease after epoch 4, whereas children with lower DG showed a gradual decrease in RSA levels followed by a slight increase after epoch 4 (see Figure 1b). In addition, DG skills predicted linear change ($\beta = 0.140$, $p = .003$) in RSA following the challenge task (i.e. recovery component). As shown in Figure 1b, children with higher DG skills had significantly greater RSA augmentation ($\beta = 0.636$, $p < .001$), than children with lower DG skills ($\beta = 0.357$, $p < .001$).

Model 2 results were analogous. Parent report of EFs predicted linear change in RSA levels during the challenge task ($\beta = -0.138$, $p = .025$). There was a trend-level quadratic association between parent-rated EFs and children's reactivity ($\beta = 0.018$, $p = .094$). Given our small sample size and the number of covariates in the final model, we feel it is warranted to report the trend-level quadratic association that corroborates Model 1 results. As shown in Figure 2a, children with higher levels of parent-rated EF skills showed a gradual RSA decrease during the challenge, compared to children with lower EF skills who showed a gradual RSA increase. Further, assessor report of EF skills predicted children's lower initial RSA ($\beta = -0.266$, $p = .045$) values and recovery after the task, although this effect became marginal after inclusion of the sit-stand covariate ($\beta = 0.098$, $p = .080$). Consistent with Model 1 results, children with higher assessor-rated EF skills showed steeper RSA increase after the task ($\beta = 0.598$, $p < .001$) than children with lower EF skills ($\beta = 0.404$, $p < .001$; see Figure 2b).

Table 2 *Piecewise growth-curve models of children's RSA values, moderation by EF skills*

Model 1 Direct assessments of EF				Model 2 Parent and assessor reports of EF			
	β/(*SE*)	*β*/(*SE*)	*β*/(*SE*)		*β*/(*SE*)	*β*/(*SE*)	*β*/(*SE*)
Inter	6.680***	6.507***	6.492***	Inter	6.699***	6.459***	6.454***
	(0.124)	(0.205)	(0.196)		(0.122)	(0.198)	(0.191)
React	0.013	0.012	−0.008	React	0.006	0.008	−0.010
	(0.059)	(0.059)	(0.058)		(0.058)	(0.059)	(0.058)
$React^2$	−0.001	−0.001	0.002	$React^2$	−0.0001	−0.001	0.002
	(0.010)	(0.010)	(0.010)		(0.010)	(0.010)	(0.010)
Recov	0.508***	0.509***	0.496***	Recov	0.497***	0.511***	0.501***
	(0.045)	(0.045)	(0.045)		(0.046)	(0.046)	(0.047)
WM × Inter	0.283*	0.235	0.172	PREF × Inter	0.102	0.053	0.032
	(0.134)	(0.143)	(0.136)		(0.131)	(0.127)	(0.120)
WM × React	−0.174**	−0.173**	−0.183**	PREF × React	−0.151*	−0.152*	−0.138*
	(0.065)	(0.065)	(0.064)		(0.062)	(0.063)	(0.062)
WM × $React^2$	0.024*	0.024*	0.025*	PREF × $React^2$	$0.020^{\dagger}$	$0.020^{\dagger}$	$0.018^{\dagger}$
	(0.011)	(0.011)	(0.011)		(0.011)	(0.011)	(0.011)
WM × Recov	−0.034	−0.034	−0.032	PREF × Recov	−0.008	−0.015	−0.004
	(0.049)	(0.049)	(0.049)		(0.047)	(0.047)	(0.047)
DG × Inter	−0.154	−0.148	−0.144	AREF × Inter	−0.194	−0.307*	−0.266*
	(0.130)	(0.131)	(0.123)		(0.137)	(0.139)	(0.133)
DG × React	0.126*	0.126*	0.134*	AREF × React	0.016	0.020	0.020
	(0.062)	(0.062)	(0.061)		(0.066)	(0.067)	(0.066)
DG × $React^2$	−0.022*	−0.021*	−0.023*	AREF × $React^2$	−0.001	−0.002	−0.002
	(0.011)	(0.011)	(0.011)		(0.012)	(0.012)	(0.012)
DG × Recov	0.139**	0.139**	0.140**	AREF × Recov	0.103†	0.118*	$0.098^{\dagger}$
	(0.047)	(0.047)	(0.046)		(0.055)	(0.055)	(0.056)
Child age		−0.068	−0.032	Child age		−0.070	−0.047
		(0.125)	(0.120)			(0.119)	(0.114)
Child PPVT		0.123	0.182	Child PPVT		$0.287^{\dagger}$	0.303*
		(0.155)	(0.147)			(0.151)	(0.142)
Ethnic minority		0.056	0.059	Ethnic minority		0.106	0.113
		(0.269)	(0.252)			(0.256)	(0.241)
Child female		−0.117	−0.081	Child female		−0.043	−0.025
		(0.192)	(0.182)			(0.186)	(0.176)
Time speaking		$0.005^{\dagger}$	0.005*	Time speaking		0.005*	0.005*
		(0.002)	(0.002)			(0.002)	(0.002)
SitStand × Inter			−0.309**	SitStand × Inter			−0.277**
			(0.096)				(0.093)
SitStand × Recov			0.115**	SitStand × Recov			0.097*
			(0.038)				(0.041)
Log likelihood	−789.134	−787.090	−764.213	Log likelihood	−798.565	−779.717	−760.008
AIC	1624.267	1630.179	1588.426	AIC	1643.129	1615.433	1580.017
BIC	1729.236	1757.967	1725.001	BIC	1748.452	1743.023	1716.377

Note: $^{\dagger}p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. Inter = Intercept, React = Reactivity, Recov = Recovery, WM = Working memory, DG = Delay of gratification, PPVT = Peabody Picture Vocabulary Test, PREF = parent-rated executive functioning skills, AREF = assessor-rated executive functioning skills.

Children who spent greater time speaking during the task had higher initial RSA values across both models ($\beta = 0.005$, $p = .035$, $\beta = 0.005$, $p = .021$, respectively), whereas greater receptive vocabulary was linked to higher initial RSA values only in Model 2 ($\beta = 0.303$, $p = .034$). Across both models, children with higher sit-stand difference scores had lower initial RSA values ($\beta = -0.309$, $p = .001$, $\beta = -0.277$, $p = .003$, respectively) and demonstrated greater RSA augmentation after the task ($\beta = 0.115$, $p = .003$, $\beta = 0.097$, $p = .017$, respectively).

Discussion

The current study represents a unique attempt to examine whether young children's EF skills explain the variability in different components of their physiological response trajectory. Using a piecewise growth curve modeling approach, we were able to investigate the interplay between behavioral and physiological self-regulation processes. We found analogous results across both direct assessments and both adult reports of EF skills, suggesting that children's abilities to regulate their

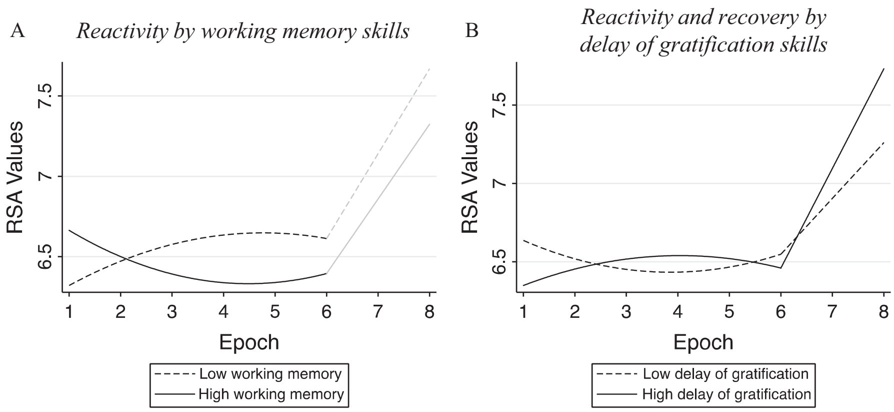

Figure 1 Trajectories of physiological reactivity and recovery are moderated by direct assessment of EF skills.
Note*: RSA = respiratory sinus arrhythmia. Black lines signify interactions that are statistically significant at the 95% confidence level, grey lines signify interactions that are not statistically significant.*

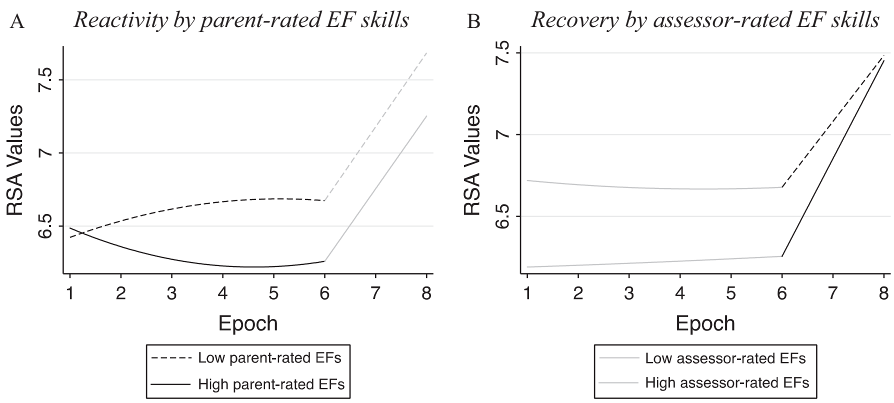

Figure 2 Trajectories of physiological reactivity and recovery are moderated by adult report of EF skills.
Note*: RSA = respiratory sinus arrhythmia. Black lines signify interactions that are statistically significant at the 90% confidence level, grey lines signify interactions that are not statistically significant. Intercept is significantly moderated by assessor-rated EF skills* ($\beta = -0.266$, $p = .045$).

own attention, behavior, and emotions were related to how their bodies responded physiologically during and after a socio-cognitive challenge in a laboratory context. Further, we found that emotionally neutral and emotionally laden measures of EF skills are uniquely associated with different components of the RSA response trajectory.

Physiological reactivity

Both direct assessment of cool EF skills and parent report of EF skills were associated with the trajectory of children's physiological reactivity. Children with higher levels of cool EF skills, as indexed by their performance on a working memory task, displayed a gradual, curvilinear RSA withdrawal during the challenge. In contrast, children with lower levels of cool EF skills displayed a gradual, curvilinear RSA augmentation during the challenge. Analogous results emerged for parent-rated EF skills. Children with high EF skills showed gradual RSA withdrawal during the challenge, whereas those with low EF skills showed gradual RSA augmentation. However, parent-rated EF skills only marginally predicted quadratic RSA change, possibly due to the limited sample size and large number of covariates.

Gradual lifting of the vagal brake during the first part of the challenge followed by a leveling off during the second part of the challenge may reflect focused attention and cognitive engagement with the challenge and subsequent maintenance of an optimal arousal. This interpretation is consistent with polyvagal theory (Porges, 2003) and studies showing that RSA withdrawal is related to greater sustained attention, engagement during challenge tasks, and on-task classroom behaviors (Blair & Peters, 2003; Calkins *et al.*, 2007a; Calkins & Keane, 2004; Doussard-Roosevelt *et al.*, 2003; Staton *et al.*, 2009; Suess *et al.*, 1994). Our results also corroborate previous studies that link a single-score measure of RSA withdrawal to greater EF skills in low-risk groups of young children (Becker *et al.*, 2012; Marcovitch *et al.*, 2010; Skowron *et al.*, 2014; Sulik *et al.*, 2015; Utendale *et al.*, 2014) and higher levels of parent-rated EF skills (Hastings *et al.*, 2008).

Motivated by a growing literature that points to the unique predictive validity of cool and hot EF skills (Kim *et al.*, 2013; Willoughby *et al.*, 2011), we also examined how hot EF skills, as indexed by children's performance on a delay-of-gratification task, relate to the physiological response trajectory, independent of the effect of cool EF skills. Interestingly, hot and cool EF skills were related to both linear and quadratic RSA change in opposing fashion. Children with higher levels of hot EF skills displayed an inverted U-shaped trajectory of RSA reactivity (i.e. gradual, curvilinear RSA augmentation followed by mild RSA withdrawal), whereas those with lower hot EF skills displayed a U-shaped trajectory of RSA reactivity (i.e. gradual, curvilinear RSA withdrawal followed by mild RSA augmentation). In addition, children who exhibited greater behavioral and emotional regulation in the laboratory context, as rated by assessors, displayed lower RSA levels at the onset of the challenge.

Discrepancies in how cool and hot EF skills related to RSA response to the challenge could reflect differences in the timing of measured RSA trajectory response as well as different utilization of these skills during initial social task demands (i.e. being asked to stand and talk in front of two adults) versus latter cognitive task demands (i.e. remembering events, delivering a focused narrative, answering questions). First, it appears that we measured initial RSA levels too late, as the absolute RSA levels at the end of the task were much higher than at its onset and many children's recovery 'overshot' their initial arousal. Further, children's postural change between reactivity and recovery phases may have contributed to exaggerated recovery, even though we controlled for RSA difference between baseline sitting and standing. Despite these caveats, the fact that greater observed EF skills were related to lower initial arousal may indicate a quicker RSA response to the preparation phase of the task by lifting the vagal break before the measurement window started. In other words, children who displayed greater EF skills in the laboratory context may have felt more comfortable and thus engaged faster with the social demands of the challenge. Consequently, the link between greater hot EF skills and initial RSA augmentation may reflect an earlier start to the recovery process, which continued after the challenge was over (see below for further discussion). In contrast, the link between greater cool EF skills and initial RSA withdrawal may reflect a lagging engagement with cognitive components of the task.

However, we were unable to examine how these patterns of physiological responsivity relate to concurrent behavior during the challenge. Thus, the question remains whether the different patterns of RSA response associated with greater EF skills are also indicative of more adaptive behavior during the socio-cognitive challenge. For example, we found that active speaking time during the challenge related to initial RSA levels over and above the effect of children's receptive vocabulary. However, this measure does not necessarily capture the most adaptive behavioral response. Future studies that examine this question should employ a challenge task that is designed to systematically evaluate the adaptive nature of the behavioral response to both social and cognitive task demands.

The unique relations of cool and hot EF skills to children's arousal may also have implications for why studies report a non-significant link between a composite measure of EF skills and RSA withdrawal (Taylor *et al.*, 2015) and why the relation of RSA withdrawal to social and cognitive outcomes was deemed unstable in a recent meta-analysis (Graziano & Derefinko, 2013). Since cool and hot EF skills are related constructs, their contrasting effect may account for the non-significant average reactivity trajectory in our sample. However, our findings must be replicated before drawing any conclusion regarding the differential role of distinct EF constructs.

As researchers continue to employ dynamic measures of RSA change, it will be important to address how the nature of the tasks used to elicit physiological arousal affects variability in response trajectories. Some challenges may seem immediately threatening (e.g. speaking to unfamiliar adults), whereas others produce an emotional response that builds over time (e.g. completing an impossible puzzle or drawing tasks). In our study, change in RSA was more pronounced during the first half of the challenge and then plateaued during the second half of the challenge. This contrasts with work by Hastings and colleagues which reported nonlinear RSA change during a frustration task: initially flat followed by a gradual decrease that continued during the recovery period (Hastings, Kahle & Han, 2014). Although a recent meta-analysis indicates that associations between the point estimate of RSA withdrawal and adaptive functioning do not vary with the nature of the task used to elicit physiological change (Graziano & Derefinko, 2013), future research needs to address how the nature of the challenge task affects dynamic measures of RSA response.

Physiological recovery

Another innovative aspect of our study was measuring children's physiological response after the challenge was completed. This enabled us to extend the work on correlates of children's physiological recovery (Gentzler *et al*., 2009; Schmitz *et al*., 2011). Our findings suggest that children with greater abilities to regulate their attention and behavior in emotionally demanding situations, as indexed by direct assessment of hot EF skills and assessor ratings of EF skills, showed faster RSA augmentation after the stressor had passed. The analogous findings across two separate models corroborate the notion that assessor report of children's EF skills in a laboratory context partly reflects hot EF skills. Although we controlled for the effect of postural change between the reactivity and recovery phases, we interpret these findings with caution. The results are consistent with a study showing lower RSA recovery in young children who displayed negative emotions or focused on the delay object during delay-of-gratification tasks (Santucci *et al*., 2008). It is also related to work by Kahle and colleagues that links parent report of preschoolers' emotion regulation to faster sympathetic recovery after a frustrating task (Kahle *et al*., 2016).

Our study reveals significant interplay between behavioral and physiological regulation in young children. It also points to emerging specificity in how different types of EF skills relate to separate components of physiological response trajectory. Only measures of EF skills in emotionally laden contexts predicted physiological recovery. This finding builds on a recent report that high emotional reactivity and regulation in infancy predicted greater EFs in preschoolers, whereas high reactivity in the context of low regulation predicted poor EFs (Ursache *et al*., 2013). In our sample, children with greater delay-of-gratification as well as assessor-rated EF skills displayed more efficient and swift physiological recovery. It is feasible that these emotionally laden EF skills are uniquely relevant to behavioral processes that promote a state of emotional and physiological calmness. Future research needs to examine whether state anxiety and rumination may mediate the relation between hot EF skills and RSA recovery.

As our study cannot identify the direction of the association between behavioral and physiological regulation, future studies should investigate whether young children are able to effortfully modulate their physiological arousal. In college students, Butler and colleagues have experimentally demonstrated that self-regulation of emotional response, either through suppression or reappraisal, can cause an increase in RSA levels (Butler, Wilhelm & Gross, 2006). Furthermore, the ability to reappraise emotions has been linked to better EF skills in college students (McRae, Jacobs, Ray, John & Gross, 2012; Schmeichel, Volokhov & Demaree, 2008). Although these studies highlight the important role of EFs in controlling emotional and physiological arousal in young adults, less is known about these processes in young children. Studies often imply that children have no control of their physiological response, as if it is solely an unconscious response or even a personal trait.

In turn, physiological arousal can facilitate or hinder cognitive performance, including direct assessment of EF skills (Blair, 2010). Recently, Utendale and colleagues (2014) have suggested that adaptability of RSA regulation may depend on children's perception of situational demands as challenging or threatening. Children who find the laboratory task to be easy may have RSA regulation that promotes their cognitive and social engagement, whereas children who find the task to be more threatening may activate more defensive RSA responses that ultimately undermine their performance. Further, studies of college students show that both experimentally induced reappraisal of heightened physiological arousal as well as naturally occurring performance anxiety can moderate the association between heightened arousal and achievement on cognitive tests (Jamieson, Mendes, Blackstock & Schmader, 2010; Mattarella-Micke, Mateo, Kozak, Foster & Beilock, 2011). While it may be difficult to accurately assess young children's perceptions and feelings during laboratory assessments, future research should examine how the link between EF skills and RSA response trajectory may vary as a function of children's subjective experience. Further, we must examine whether young children's physiological arousal can be manipulated by different emotion and behavioral regulation strategies.

Limitations

The study has several limitations that need to be addressed by further research. First, we were limited by a small sample in testing all four EF variables in the same model and the effects of covariates on the slopes. We were also unable to examine other EF components (e.g. inhibitory control), other covariates, or the interplay between different types of EF skills. Future studies should continue examining the specificity of reported associations between EF skills and RSA responsivity using more sophisticated latent variable methods that can separate unique EF components from a general EF factor. Second, future studies of RSA response trajectory should measure initial levels earlier, starting just before rather than during the introduction to the task, to better capture pre-challenge arousal. Third, our findings need to be replicated using consistent posture during and after the challenge task. Fourth, our study was unable to investigate whether physiological response trajectories that were associated with greater EF skills were also associated with more adaptive behavior or identify other mechanisms that may explain the link between EF skills and RSA responses. Fifth, assessor-rated EF skills were observed during the socio-cognitive task and EF assessment among other procedures, leading to non-independence of these measures. Finally, the correlational nature of our study limits any conclusion about directionality of the association between EF skills and RSA arousal.

Conclusion

In sum, our study highlights the need to employ more dynamic approaches in examining how physiological responsivity contributes to and reflects children's adaptation and resilience (Del Giudice *et al*., 2011). Representing children's physiological response as a simple point estimate may obscure important individual differences. Our findings support the notion that physiological reactivity is not a unitary construct that implies vulnerability, but rather a complex process that depends on physiological recovery and relates to children's self-regulation skills (Obradović, 2012, 2016). Future research should extend this inquiry to examine how EF skills relate to the interplay of parasympathetic and sympathetic responses. Ultimately, we need to better understand the dynamic covariation between behavioral and physiological response trajectories, both in the moment and longitudinally, to identify important targets for intervention that will promote adaptive behaviors and learning across various challenging settings.

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