Published in final edited form as:

Dev Psychobiol. 2018 July ; 60(5): 595–607. doi:10.1002/dev.21636.

Cardiac Vagal Regulation in Infancy Predicts Executive Function and Social Competence in Preschool: Indirect Effects through Language

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Abstract

Parasympathetic nervous system functioning in infancy may serve a foundational role in the development of cognitive and socioemotional skills (Calkins, 2007). In this study ($N = 297$), we investigated the potential indirect effects of cardiac vagal regulation in infancy on children's executive functioning and social competence in preschool via expressive and receptive language in toddlerhood. Vagal regulation was assessed at 10 months during two attention conditions (social, non-social) via task-related changes in respiratory sinus arrhythmia (RSA). A path analysis revealed that decreased RSA from baseline in the non-social condition, and increased RSA in the social condition, were related to larger vocabularies in toddlerhood. Additionally, children's vocabulary sizes were positively related to their executive function and social competence in preschool. Indirect effects from vagal regulation in both contexts to both 4-year outcomes were significant, suggesting that early advances in language may represent a mechanism through which biological functioning in infancy impacts social and cognitive functioning in childhood.

Keywords

RSA; vagal regulation; language; executive function; social competence; infancy

Early childhood is a developmental period characterized by increasing control over self and awareness of others (Kopp, 1982). The development of cognitive control and social interaction skills are both particularly important for children's well-being. Executive function (EF) refers to a set of neurocognitive skills associated with the prefrontal cortex involved in the conscious control of thought and action (Zelazo, 2015). Social competence (SC) is similarly understood as a set of skills involved in the formation and maintenance of positive peer relationships (Rose-Krasnor & Denham, 2009). EF and SC both support children's readiness for school, where they are expected to behave in accordance with

classroom rules and get along with teachers and peers (Denham, 2006; Müller, Lieberman, Frye, & Zelazo, 2008). Further, these skills have been linked to children's physical health (Groppe & Elsner, 2014; Jackson & Cunningham, 2015), academic achievement (Blair & Razza, 2007; Wentzel & Caldwell, 1997), and psychological adjustment (Bornstein, Hahn, & Haynes, 2010; Utendale & Hastings, 2011). Thus, identifying factors that may shape their developments is crucial.

A self-regulation framework highlights the central role of biological processes in the development of a broad range of adaptive skills (Calkins & Fox, 2002). Specifically, this view considers children's emerging competencies as operating at multiple levels that are hierarchically organized, such that biological processes may constrain or facilitate subsequent psychological or behavioral functioning (Calkins, 2007). The parasympathetic nervous system (PNS), which is involved in the control of physiological arousal, may therefore serve a foundational role in the development of children's cognitive or socioemotional skills (Porges, 1995). Cardiac vagal regulation, an index of PNS functioning, has been directly linked to EF and SC in children (Graziano, Keane, & Calkins, 2007; Kahle, Utendale, Widaman, & Hastings, 2017; Marcovitch, Leigh, Calkins, Leerkes, O'Brien, & Blankson, 2010). However, the findings have been mixed, and thus difficult to interpret.

The development of language across the toddler years may represent an indirect mechanism through which PNS functioning in infancy influences EF and SC in childhood. In infancy, PNS functioning has been linked to attentional control and socioemotional engagement (Porges, 1992; 2003), processes that EF and SC may build upon (Garon, Bryson, & Smith, 2008; Mundy & Acra, 2006). Specifically, these early processes may facilitate learning words, which may contribute towards the developments of EF and SC by allowing children to effectively communicate with themselves and others (Gallagher, 1993; Zelazo, 2015). Thus, although direct links may help explain their associations with PNS functioning, it is important to also consider indirect effects that could have unfolded over time. Thus, the primary goal of the current study was to assess whether children's PNS functioning in infancy influenced their EF and SC in preschool *indirectly* through its role in vocabulary acquisition.

PNS functioning, executive function, and social competence

Children's ability to behave in accordance with rules, or to respond appropriately in social contexts, may be limited or facilitated by how their internal resources are allocated within the body (Porges, 1995). The autonomic nervous system (ANS), for example, is responsible for conveying information from the brain to visceral organs in the body, allowing for adaptive physiological responses to external demands and challenges. The vagus (or 10th cranial) nerve is part of the parasympathetic branch of the ANS, and represents a bidirectional feedback system between the heart and brainstem (Porges, 1995). At rest, the vagus conserves metabolic resources by inhibiting the cardiac pacemaker, keeping heart rate low, while promoting restorative processes (e.g., digestion) in the body. However, when individuals need to actively cope or engage with the environment, PNS influence on the heart may be adjusted (i.e., vagal regulation) to accommodate situational demands. That is,

the vagus may exert more or less inhibition on the heart depending on the context. PNS influence on the heart via the vagus nerve can be noninvasively estimated by quantifying the amplitude of respiratory sinus arrhythmia (RSA), the variation in heart rate due to breathing (Porges, 1995). Measures of resting RSA have been used extensively in previous research, and may provide an index of temperamental reactivity, or a child's characteristic awareness of and responsiveness to environmental events; event-related changes in RSA (i.e., task - baseline) provide an index of vagal regulation (Calkins, 1997).

Higher-order cognitive processes such as EF require controlled attentional engagement, and cardiac vagal regulation has been linked to attentional control. Specifically, Porges (1992) distinguished between passive-involuntary and active-voluntary forms of attention. Unlike passive forms of attention, which may rely largely on long-term memory (e.g., orienting to novelty), active attention processes place demands on *working* memory, and are thus metabolically costly (Porges, 1992). To actively maintain attention, infants may need to reduce PNS influence on the heart so that neural resources can be reallocated from servicing homeostatic functions in the body to the prefrontal cortex. Vagal withdrawal has been observed in infants and young children during periods of sustained attention (Richards & Casey, 1991; Suess, Porges, & Plude, 1994), and has related positively to their attention spans (Calkins, Dedmon, Gill, Lomax, & Johnson, 2002; Huffman, Bryan, Carmen, Pedersen, Doussard-Roosevelt, & Porges, 1998). Although EF is more complex and likely involves additional processes, the ability to strategically reduce PNS influence on the heart to control attention in infancy may represent a biological basis for its development.

In contrast, theoretical and empirical work has indicated that *increased* PNS influence (i.e., vagal augmentation) may be related to greater social functioning. In addition to its impact on cardiac function (i.e., 'visceromotor' component), the vagus nerve is also innervated with the striated muscles of the face, head, and neck (i.e., 'somatomotor' component), which are involved in communication and emotional expression. Increased vagal influence is thought to foster positive engagement states characterized by 'facial expressivity and vocal intonation' (Porges, 2003). Importantly, because the somatomotor and visceromotor components are functionally integrated, social engagement may be compromised when vagal inhibition of the heart is reduced (i.e., vagal withdrawal). Consistent with this model, vagal augmentation has been observed in infants during responsive social interactions, whereas withdrawal has been observed during social challenges (e.g., adult is unresponsive; Bazhenova, Plonskaia, & Porges, 2001; Moore & Calkins, 2004). Thus, the ability to strategically increase PNS influence on the heart to engage with other people in infancy may represent a biological foundation for SC.

In combination, this work suggests that children's EF and SC may be differentially related to early PNS functioning, such that different amounts of vagal influence on the heart across social and non-social contexts may foster their developments. However, few studies have reported on the longitudinal associations between vagal regulation in infancy and EF or SC in childhood. Interestingly, the concurrent relations between vagal regulation and EF have been mixed. In school-aged children, greater vagal withdrawal during a computerized Stroop task was related to greater performance (Becker, Carrère, Siler, Jones, Bowie, & Cooke, 2012), suggesting that decreased PNS influence on the heart facilitated their ability to hold

information in working memory and inhibit inappropriate responses. However, during a verbal Stroop task with 3.5-year-olds, this relation was curvilinear, such that moderate amounts of withdrawal were related to greater EF (Marcovitch et al., 2010). Using the same task with 4-year-olds, Kahle and her colleagues (2017) recently found that greater vagal *augmentation* was related to better EF.

In children, the direct relations between vagal regulation and SC have varied depending on the context (social vs. non-social) of measurement. For instance, Graziano, Calkins, and Keane (2007) reported a significant positive association between 5.5-year-olds' vagal withdrawal during an independent puzzle task and their peers liking of them in kindergarten. However, in toddlers, greater vagal withdrawal during a socioemotional vignette designed to elicit empathy was related to less expressed concern for the characters, suggesting it may have interfered with their ability to relate to others (Gill & Calkins, 2003). In a similar study with older children, greater feelings of empathy were associated with a dynamic response pattern, characterized by initial vagal withdrawal in response to the sad content, followed by augmentation (Miller, Nuselovici, & Hastings, 2016). It is particularly important to identify factors that may help explain these discrepant findings.

Infants' PNS functioning in both social and non-social contexts may contribute to the developments of both EF and SC, and language acquisition may play a key role in these processes. Specifically, children may need to use language to engage with and relate positively to peers (Gallagher, 1993), and they may rely on inner speech to direct and guide their behaviors in accordance with rules (Zelazo, 2015). Attentional control and social engagement skills, both supported by varying degrees of vagal influence, have both been linked to vocabulary growth across the second year (e.g., Dixon, Salley, & Clements, 2006; Mundy & Gomes, 1998). Thus, one way that PNS functioning may shape the developments of EF and SC is *indirectly*, through its role in acquiring language.

Vagal regulation and language development

Language develops rapidly across the toddler years through infants' interactions with objects and people (Bakeman & Adamson, 1984). Thus, infants' PNS functioning in both social and non-social contexts may be relevant to this process. Although, varying degrees of PNS influence on the heart across these contexts may be optimal for learning words. First, because infants learn words from other people, their capacity for social engagement is crucial to the development of both receptive (i.e., comprehension of words) and expressive (i.e., production of words) language (Baldwin, 1995; Brooks & Meltzoff, 2008; Mundy & Gomes, 1998). Increased PNS influence on the heart in social contexts is thought to foster states of positive social engagement (Porges, 2003), and may therefore foster advances in both components of language.

Second, although infants necessarily hear words from other people, their capacity for independently sustained attention may also contribute towards learning words. Indeed, engagement with objects and dynamic visual events in infancy are thought to play important roles in language development (Barr, 2008; Bornstein, 1989). Infants with greater control over their visual attention may be more capable of actively exploring objects and their

properties; consequentially, they may have greater access to information in memory that is important for understanding what words mean (Kannass & Oakes, 2008; Salley, Panneton, & Colombo, 2013). Thus, in addition to their capacity for social engagement, infants' capacity to withdraw vagal tone to attend to the non-social environment may also play a role in acquiring language.

Language, social competence, and executive function

Varying degrees of PNS influence on the heart across social and non-social contexts in infancy may facilitate the development of language. In turn, language development may play an active role in the developments of EF and SC. One potential reason for this is that the development of language itself marks an important transition in self-regulatory development whereby children are first expected to be able to follow rules and engage competently with peers. Toddlers who can understand and produce more words may have more opportunities to comply with adults' instructions and engage with their peers, experiences that may serve to promote the developments of EF and SC. Additionally, advances in language may fundamentally change how children think, which may contribute towards the increasing sophistication of these skills.

Expressive language is itself a core element of SC, as it is the process by which children initiate contact, participate in interactions, and communicate their needs to others (Gallagher, 1993). Indeed, children with larger expressive vocabularies have been viewed more positively by peers (Naerland, 2011; Troesch, Keller, & Grob, 2016). However, in addition to producing words, to be socially competent, children may need to consider others' perspectives when interacting (Fink, Begeer, Hunt, & de Rosnay, 2014; Mundy & Acra, 2006). Advances in receptive language could facilitate acquiring these skills. A child that knows the meanings of the words 'sad,' or 'mad,' for instance, can mentally represent those feeling states in others. Even words that are not emotional (e.g., train, shoe) could serve to orient children's attention to others' experiences (i.e., *people* ride trains and wear shoes). Although direct support for this claim is limited, preschoolers who produced *and* understood more words as toddlers were more likely to consider the unique perspective of an actor in explaining his/her actions (Watson, Painter, & Bornstein, 2001). Thus, in addition to their expressive language skills, advances in receptive language may play an important role in the development of SC.

Similarly, the development of EF may be facilitated by advances in both components of language. First, toddlers who can understand more words may have greater opportunities to comply with simple requests, a foundation from which EF may develop. Children with larger receptive vocabularies have displayed greater EF in preschool (Müller, Liebermann-Finestone, Carpendale, Hammond, & Bibok, 2012). However, to follow complex rules (e.g., that require inhibition of prepotent responses), children may ultimately need to use language internally (Zelazo, 2015); advances in *expressive* language may foster this ability. Specifically, children's early expressions of language may become internalized as a 'mental tool' that can be used to direct their own behaviors (Vygotsky, 1962). In support of this, Kuhn and her colleagues (2014) found that toddlers' expressive vocabularies mediated the relation between their display of gestures at 15 months and their EF at age 4. That is,

children who were more socially engaged as infants tended to say more words as toddlers, and consequentially, were better able to follow complex rules in preschool. Collectively, this research suggests that early advances in both expressive and receptive language may play essential roles in the developments of EF and SC.

The current study

A large body of empirical research suggests that PNS functioning in infancy, across both social and non-social contexts, may serve a foundational role in the developments of EF and SC. However, few studies have investigated these associations longitudinally, or considered the unique influences of PNS functioning in both contexts. Additionally, few studies have explored the associations between PNS functioning and language development, a potentially important yet relatively unexplored factor in this process. Specifically, the influence of vagal regulation on infants' attention and socioemotional engagement in both social and non-social contexts may contribute towards learning words. In turn, early advances in language may foster children's ability to control their own thoughts and actions and relate positively to peers. Thus, the purpose of this study was to examine language development as a potential indirect mechanism through which PNS functioning in infancy relates to EF and SC in preschool.

The first specific aim was to assess the direct relations between children's vagal regulation in infancy and their language competence in early childhood. Prior research has indicated that attention to both objects and people may contribute towards learning words (Bakeman & Adamson, 1984). However, these processes were proposed to involve different amounts of vagal influence on the heart (Porges, 1992; 2003). Thus, we expected that greater vagal augmentation during a social attention condition, and greater withdrawal during a non-social attention condition at 10 months, would both be associated with larger receptive and expressive vocabularies at ages 2 and 3.

The second aim was to assess the direct relations between children's early language competence and their EF and SC in preschool. Based on theory and previous research, we expected to find significant positive associations from expressive language at age 2 and receptive language at age 3 to both EF and SC at age 4. The final aim was to investigate the indirect relations between infants' vagal regulation (in both social and non-social contexts) and their EF and SC in preschool via their expressive and receptive vocabularies. Because language is thought to play important roles in both EF and SC (Gallagher, 1993; Zelazo, 2015), and because infants' social and independent learning experiences may both contribute towards learning words, we expected to find significant indirect effects from vagal regulation in both contexts at 10 months to both 4-year outcomes through both components of language.

Method

Participants

The current study used data from an ongoing longitudinal project investigating psychobiological processes in cognitive and emotional development. The full sample ($N =$

410) was recruited from two research sites (Blacksburg, VA; Greensboro, NC) via commercial mailing lists, flyers, and word of mouth. Participants included in the current study were typically developing, had available RSA data, and had at least 1 (of 4) dependent variables in the model. Twenty-two were excluded due to low birth weight, premature birth, or atypical developmental status; 66 were missing RSA data at 10 months (40 did not come into the lab; 1 rejected the electrocardiogram (ECG) electrodes; data for 6 was lost due to equipment failure; 2 did not complete either of the laboratory tasks; 17 lacked enough consecutive ECG data to calculate RSA); 25 were further excluded due to not having one or more dependent variables in the model, mostly due to attrition.

The reduced sample ($N = 297$) had a similar demographic profile as the full sample: 51% were male; 76% were of White/non-Hispanic background; 73% had at least one parent with a 4-year college degree (51% had both). Participants excluded from the sample were more likely to be non-White or Hispanic, $t(183) = 2.23$, $p = .03$, $d = 0.25$, and to have less educated parents, $t(400) = -2.66$, $p = .01$, $d = 0.21$, than those included. However, the groups did not differ significantly in terms of sex or temperament. All 297 participated in the 10-month visit and were 10.27 ($SD = 0.32$) months old on average; 286 participated at age 2 ($M = 24.85$, $SD = 0.87$); 268 participated at age 3 ($M = 37.03$, $SD = 1.03$); 253 participated at age 4 ($M = 48.88$, $SD = 0.96$).

Procedures

Data were collected at both sites using identical protocols that were approved by their respective university institutional review boards. Research assistants from both locations were trained together by the project's Principal Investigator on protocol administration and psychophysiological editing. To ensure data were collected and analyzed identically across sites, the Blacksburg site periodically viewed DVDs and psychophysiology files collected by the Greensboro site.

Upon each arrival to the research laboratory, participants were greeted by a research assistant who explained the procedures and obtained signed consent from the mother. After a brief warm-up period, heart rate electrodes were applied and children participated in a variety of laboratory tasks assessing cognitive and emotional functioning. The sessions were digitally recorded for later coding. Families were compensated \$50 for each laboratory visit.

Measures

Vagal regulation—To assess the degree of PNS influence on the heart during a neutral baseline period, ECG was recorded for 1 min. as infants sat on their mothers' laps and watched a research assistant manipulate a toy containing brightly colored balls on a testing table 1.1m in front of them; mothers were instructed not to talk or interact with their infants. This procedure quieted the infants and yielded minimal gross motor movements. To assess infants' vagal regulation during a non-social attention condition, following baseline, ECG was recorded as infants watched a brief ($M = 44$ s), dynamic video clip from *Sesame Street* (*Cecile, Up Down, In Out, Over Under*). To assess infants' vagal regulation during a social attention condition, following the video, ECG was collected as infants played a game of 'peek-a-boo' ($M = 104$ s) with their mothers.

ECG was recorded from two neonatal disposable electrodes using modified lead II alignment (right collarbone and lower left rib; Stern, Ray, & Quigley, 2001). The cardiac electrical activity was amplified using a SA Instrumentation Bioamp (San Diego, CA, USA) and band-passed from 0.1 to 100 Hz. The QRS complex was displayed on a computer monitor using Snapshot-Snapstream software (HEM Corporation, Southfield, MI, USA) and was digitized at 512 samples per second. The raw data were stored for later R-wave detection and analyses.

Following data collection, ECG data were examined and analyzed using IBI Analysis System software developed by James Long Company (Caroga Lake, NY, USA). First, R-waves were detected offline with a four-pass peak detection algorithm, resulting in a data file with onset times for each detected R-wave. To edit artifact, the ECG signal was viewed alongside tick marks representing the times of software-detected R-waves. If an R-wave was not detected by the software, a tick mark was inserted into the graphical ECG record. If the undetected R-wave was visible in the ECG, it was marked manually. If the R-wave was not visible, the tick mark was placed based on the specific editing rules of Byrne and Porges (1993). Movement artifact was designated by the absence of at least three consecutive R-waves; these artifact-scored epochs were eliminated from all calculations. The edited R-wave was converted to heart period (i.e., time between beats).

Because vagal influence is measured by RSA (Porges, 1995), spectral analysis was used to calculate high-frequency variability in the heart period data using a discrete Fourier transform with a 16 s Hanning window and 50% overlap. The frequency band for quantification of RSA was 0.24–1.04 Hz, which is appropriate for infants and young children (Bar-Haim, Marshall, & Fox, 2000). The RSA data were transformed using the natural log to normalize the distribution. Vagal regulation was operationalized as the change in RSA from baseline to task (i.e., task – baseline). Thus, negative values indicated decreased PNS influence on the heart (i.e., vagal withdrawal) and positive values indicated an increase in its influence (i.e., augmentation).

Expressive vocabulary—At the 2-year visit, mothers completed the ‘Words and Sentences’ form from the MacArthur-Bates Communicative Development Inventory (MCDI; Fenson et al., 1992), a checklist of common words and phrases designed for use with 16- to 30-month-olds. Mothers indicated their toddlers’ production of each item on the inventory (e.g., *yum-yum*, *tiger*, *need to*) and reported on their grammatical ability. The total vocabulary production score was used in the current analyses; higher scores indicated a larger vocabulary size. MCDI data for 18 (6%) participants were missing: 11 did not participate in the 2-year visit; 7 left the lab without completing the questionnaire.

Receptive vocabulary—At the 3-year visit, children were administered the Peabody Picture Vocabulary Test-III (PPVT; Dunn & Dunn, 1997), a standardized assessment of receptive language. Children were asked to select one of four pictures displayed on an easel that best depicted a word (e.g., spoon, jumping) read aloud by an experimenter. Test items were grouped into 12-item sets that increased in difficulty; testing stopped when children answered incorrectly 8 or more times within a set. Following manual guidelines, the raw score was calculated by subtracting the number of errors from the ceiling item; higher scores

indicated a larger vocabulary. A standardized score was then calculated based on children's exact age in months. PPVT data for 54 (18%) participants were missing: 27 did not participate in the 3-year visit; 17 completed questionnaires only; 7 were not administered the task because it was not yet in the protocol; 3 were voided due to errors in administration.

Language develops rapidly across the second and third years of life. However, standardized measures of language (e.g., PPVT) are not well-suited for children younger than 3, many of whom still lack the comprehension to partake in a verbally-mediated assessment (e.g., Luinge, Post, Wit, & Goorhuis-Brouwer, 2006). Parents can provide a reliable index of their children's word production well before they can partake in a standardized test. Thus, assessing children's expressive and receptive vocabularies at 2 and 3 years allowed for a more complete picture of children's early language competence.

Executive function—At the 4-year visit, children were administered the Dimensional Change Card Sort (DCCS; Zelazo, 2006), a standardized measure of EF. Children were asked to sort 12 bivalent test cards (six blue cars, six red flowers) into one of two bins marked by bivalent target cards that matched the test cards on a single dimension (i.e., blue flowers and red cars). On pre-switch trials, children were instructed to sort six cards by one dimension (color). Then, the sorting rules changed (post-switch), and children were instructed to sort the remaining six cards by the other dimension (shape). The order of sorting dimension was counter-balanced across participants. Trained research assistants later coded the task using the DVD recording of the laboratory session. The proportion of correctly sorted post-switch trials was calculated and used in the analyses; higher scores indicated greater EF. Three children were not administered post-switch trials due to failing pre-switch and were awarded scores of zero. Reliability coding for this task was accomplished on 15% of the sample and the ICC was found to be within acceptable range (.98). DCCS data were missing for 70 (24%) participants: 44 did not participate in the 4-year visit; 24 completed questionnaires only; two were unable to be scored due to recording errors.

Social competence—At the 4-year visit, children's mothers completed the Social Interaction Survey (SIS), a norm-referenced instrument developed from the Vineland Adaptive Behavior Scales (Sparrow, Cicchetti, & Balla, 2005) for assessing socioemotional functioning across the lifespan. The SIS contains 99 phrases that describe various behaviors children may display at home, school, or other settings. The survey is broken up into three sections (Interpersonal Relations, Play-Leisure Time, Coping Skills) that assess the child's social orientation and awareness (e.g., *Acts when another person needs a helping hand*), ability to play and cooperate with others (e.g., *Shares toys or possessions*), and ability to regulate emotions and behaviors in social settings (e.g., *Controls anger or hurt feelings when he or she does not get his or her way*). The behaviors in each section range from those considered appropriate for infants (e.g., *Shows affection to familiar persons*), children (e.g., *Shows desire to please others*), and adolescents (e.g., *Cooperates with others to plan or be part of an activity*). Mothers indicated the extent to which their child displayed each behavior using a 3-point scale (0 = never, 1 = sometimes, 2 = usually), and stopped responding after they provided four consecutive zeros within a section (higher-numbered

items described more advanced behaviors than lower-numbered items). Scale scores were calculated by summing within each section; a composite score was then obtained by summing across the three scale scores (Cronbach's $\alpha = .81$). Higher scores indicated greater SC. SIS data for 111 (37%) participants were missing: 44 did not participate in the 4-year visit; 57 were not administered this survey due to differences in protocol across cohorts; 10 left the lab without completing the survey.

Results

Descriptive statistics and bivariate correlations for all study variables are presented in Table 1. Baseline RSA was negatively correlated with both RSA change scores, indicating that infants with greater RSA at rest tended to show less positive change (i.e., increases) in RSA across both tasks. The RSA change scores were significantly positively correlated, indicating that the direction of change in RSA from baseline tended to be similar for both tasks. In other words, larger decreases in PNS influence during the video task were related to lesser increases in PNS influence during the peek-a-boo task. Infants missing RSA for either task because of excessive artifact ($N = 22$) did not significantly differ from infants with usable RSA for both tasks in terms of baseline RSA, $t(295) = 1.08, p = .28$. Additionally, the number of DFT windows (i.e., consecutive 16 s of artifact-free ECG) for any task was not significantly associated with RSA values for any task. The significant positive correlation between children's MCDI and PPVT scores indicates that children who said more words at age 2 tended to understand more words at age 3. Similarly, the DCCS and SIS scores were significantly positively correlated, indicating that children with better EF tended to have greater SC at age 4.

A path analysis was conducted to examine the longitudinal associations between cardiac vagal regulation at 10 months, expressive and receptive vocabulary at 2 and 3 years, and EF and SC at 4 years. The complete path model including standardized estimates can be seen in Figure 1. Mplus (v.7; Muthén & Muthén, 2012) was used to conduct the analyses and Full Information Maximum Likelihood was used to handle missing data. To control for differences in language exposure, maternal education level was entered in the model as a control variable. As can be seen in Table 1, children of more educated mothers tended to have larger receptive vocabularies and greater DCCS task performance. Evaluation of model fit was assessed by examining the comparative fit index (CFI; Marsh & Hau, 2007) and the root mean square error of approximation (RMSEA; Cole & Maxwell, 2003). Values greater than .95 are desirable for the CFI, while RMSEA values should be less than or equal to .05 for good model fit (Hu & Bentler, 1999). Based on these criteria, the hypothesized model fit well, $\chi^2(4, N = 297) = 5.69, p = .22, CFI = .99, RMSEA = .04 [CI = .00, .10]$. Because the majority (65%) of children missing data for the SC measure were from an earlier cohort that was not administered the survey (because it was not yet in the protocol), the path analysis was run with and without these children in the model. Because model fit and structural path estimates from these models were similar, results from the model containing the full sample are reported.

The first aim of the study was to examine the associations between infants' cardiac vagal regulation (in social and non-social contexts) and their expressive and receptive vocabularies

in early childhood. To assess these relations, the RSA change scores from the peek-a-boo and video tasks at 10 months were modeled as predictors of the 2-year MCDI and 3-year PPVT scores.

Results indicated that infants' vagal regulation during both tasks was significantly associated with their receptive vocabularies, but that only vagal regulation during the social condition was related to their expressive vocabularies. Specifically, RSA-change from baseline during the peek-a-boo task *positively* associated with children's MCDI and PPVT scores. RSA-change from baseline during the video task was *negatively* related to children's PPVT scores, but was not significantly related to their MCDI scores (see Figure 1 for standardized estimates). Thus, *increases* in PNS influence on the heart during a social attention condition at 10 months was related to greater expressive and receptive vocabularies in early childhood, whereas *decreases* in PNS influence during a non-social attention condition was related to greater receptive, but not expressive, vocabulary.

The second aim of the study was to examine the associations between children's expressive and receptive vocabularies and their EF and SC in preschool. To assess these relations, the 2-year MCDI and 3-year PPVT scores were modeled as predictors of the 4-year DCCS and SIS scores. Results indicated that children's expressive and receptive vocabularies were both significantly and positively associated with both 4-year outcomes. Specifically, children's MCDI scores were positively associated with their DCCS and SIS scores at age 4. Children's PPVT scores were also positively associated with their DCCS and SIS scores (see Figure 1 for standardized estimates). Thus, children's expressive and receptive vocabularies were both positively associated with their EF and SC in preschool.

The final aim of the study was to examine whether infants' vagal regulation (in both social and non-social contexts) at 10 months was significantly related to their EF and SC in preschool, indirectly, through its influence on their early language skills. Indirect effects from both RSA change scores to both 4-year outcomes were tested using a bias-corrected (BC) bootstrapping procedure (10,000 draws); this has been shown to generate the most accurate confidence intervals for indirect effects, reducing Type 1 error rates and increasing power over other similar tests (MacKinnon, Lockwood, & Williams, 2004). A total of six indirect paths were estimated (effects mediated through expressive language were not examined for the video task as this path was not significant in the model).

Results indicated that all six indirect effects were significant. First, the indirect effects from RSA-change during the peek-a-boo task to observed EF at age 4 through expressive (unstandardized estimate = .02, 95% BC Bootstrap CI [.01, .05]) and receptive language (unstandardized estimate = .03, 95% BC Bootstrap CI [.01, .05]) were significant. Second, the indirect effects from RSA change during the peek-a-boo task to maternal report of SC at age 4 through expressive (unstandardized estimate = .85, 95% BC Bootstrap CI [.18, 2.06]) and receptive language (unstandardized estimate = .79, 95% BC Bootstrap CI [.12, 1.85]) were significant. Third, the indirect effect from RSA change during the video task to observed EF at age 4 through receptive language was significant (unstandardized estimate = -.02, 95% BC Bootstrap CI [-.04, -.01]). Last, the indirect effect from RSA change during the video task to maternal report of SC at age 4 through receptive language was significant

(unstandardized estimate = $-.68$, 95% BC Bootstrap CI $[-1.81, -.05]$). Thus, greater *increases* in PNS influence on the heart during a social attention condition at 10 months were related to greater EF and SC in preschool indirectly through their influences on both receptive and expressive language. Additionally, greater *decreases* in PNS influence during a non-social attention condition were indirectly related to greater EF and SC through their influence on receptive language.

Discussion

Theoretical work has implicated the PNS in a variety of developmental processes (Beauchaine, 2001; Calkins, 2007; Porges, 1995). Our focus on PNS functioning in relation to EF and SC is consistent with theoretical perspectives (Porges, 1992; 2003) and empirical research directly linking these skills to cardiac vagal regulation in children (e.g., Marcovitch et al., 2010; Graziano et al., 2007). The findings from this work have been mixed, highlighting the need to investigate potential mediators. An important mechanism to consider is language, which may be supported by early PNS functioning, and contribute towards the emergence of children's cognitive control and social interaction skills (Porges, 2003; Vygotsky, 1962). Thus, the primary goal of the current study was to examine language development as a potential mechanism through which infants' PNS functioning impacts their EF and SC in early childhood.

Although the associations between PNS functioning and attention in early development have been thoroughly investigated (e.g., Richards & Casey, 1991), the role of PNS functioning in language development is practically unexplored. To address this important gap in the literature, we examined the associations between infants' cardiac vagal regulation and their expressive and receptive vocabularies in early childhood. Because infants' attention to both social and non-social sources of information may contribute towards learning words, and because different amounts of vagal influence on the heart across social and non-social contexts have been proposed to facilitate learning and engagement, we expected that different amounts of PNS influence under these conditions would relate positively to later language.

As hypothesized, greater *increases* in PNS influence (i.e., augmentation) on the heart during a 'peek-a-boo' game with mother at 10 months were related to larger expressive and receptive vocabularies at 2 and 3 years. Vagal augmentation is thought to foster positive engagement states, and has been associated with anticipatory attention and socioemotional engagement in infants (Bazhenova et al., 2001; Stroganova, Posikera, Pisarevskii, & Tsetlin, 2006). Infants who exhibited greater increases in PNS influence during this task may have been more responsive to social cues (e.g., gaze or gesture following) that facilitate learning words across the toddler years than infants who exhibited lesser increases or decreases. Further, because the vagus nerve is thought to innervate the muscles involved in emotional expression and vocalization (Porges, 2003), they may have also been more facially and vocally expressive during social interactions, which could have elicited greater language input from adults. Thus, this finding suggests that infants' vagal regulation in social contexts may be related to their ability to communicate with and learn words from other people. Future studies should examine these links more directly.

As expected, infants' PNS functioning in a non-social attention condition was also significantly related to language development. Specifically, greater *decreases* in PNS influence (i.e., withdrawal) on the heart during a dynamic video clip at 10 months was associated with larger receptive vocabularies at age 3. Theoretically, vagal withdrawal reflects a reallocation of internal resources to promote sustained attention to the environment, a metabolically costly process (Porges, 1992). Infants who exhibited greater decreases in PNS influence during this task may have exhibited more focused attention to objects and complex events across the toddler years, which prior research has found to be important for learning words (Kannass & Oakes, 2008). Thus, this finding suggests that infants' capacity to withdrawal vagal tone appropriately to attend to the non-social environment may also influence language development.

Importantly, infants' vagal regulation in the video task was not significantly related to their expressive vocabularies, underscoring the importance of considering the expressive and receptive components of language separately in research models. Although sustained attention to objects and complex events may facilitate learning what words mean, it may not necessarily facilitate producing them. Further, many of infants' first words are strictly communicative or relational in nature (e.g., hey, please, want), and thus do not have concrete referents that can be experienced independently. However, it is also possible that the ages at which expressive and receptive language were assessed contributed towards this finding. For instance, children may have had greater opportunities for independent exploration during the third versus second year of life. Consequentially, their PNS functioning in a non-social context may have been more strongly related to their vocabulary at age 3 than age 2. Replications of this work should assess both components of language at both time points to clarify these possibilities.

Generally, these findings are consistent with the view that attention to both objects and people across the toddler years is important for acquiring language (Bakeman & Adamson, 1984). Further, they suggest that vagal regulation in both social and non-social contexts may play important roles, and that different amounts of PNS influence on the heart across these contexts may facilitate learning. Thus, one possible interpretation of this research is that a flexible style of vagal regulation, characterized by greater PNS influence in social contexts and lesser PNS influence in non-social contexts, is optimal for learning words in those contexts. Although RSA values in the social task were larger than in the non-social task for most infants, 70% displayed the same direction of change in RSA from baseline across both tasks. Thus, it is not clear from this study how flexible individual infants were in their responding. Future studies should adopt a person-centered approach to examine how infants' PNS functioning in social and non-social contexts are related, and how they may interact to influence language development.

The second aim of the study was to examine the relations between children's expressive and receptive vocabularies and their EF and SC in preschool. Although many studies have examined these relations, few have considered the unique influences of expressive and receptive language. Thus, our study adds to the existing literature by providing information regarding their unique associations with children's cognitive and socioemotional skills.

As expected, children's expressive vocabularies were significantly related to their EF and SC in preschool. First, 4-year-olds who produced more words as toddlers were rated by their mothers as better able to recognize and respond to social cues, play and cooperate with others, and regulate their behaviors and emotions in social settings. These children likely created—for themselves—more opportunities for social interaction that resulted in constructive feedback regarding how best to get along with others. Additionally, toddlers who produced more words were better able to flexibly shift between using different rules on a card sorting task at age 4. Although speculative, this finding is in line with Vygotsky (1962), who suggested that children's early expressions of language become internalized as a mental tool for self-directing thoughts and actions. Thus, children's expressive vocabularies were positively related to both their EF and SC in preschool. Although, the mechanism is likely more complex than what was captured by our measure of expressive vocabulary: the MCDI assesses how many words from an inventory a child can produce; it does not assess how frequently they produce them. How children's everyday use of language may be contributing to differences in EF is a methodologically-challenging but important area of research.

Children's receptive language was also significantly related to their EF and SC in preschool. Specifically, children who understood more words at age 3 tended to have more flexible cognition and competent social functioning at age 4. Although speculative, these effects could be mediated through children's awareness of others' perspectives and comprehension of rules. Perspective-taking is thought to play an important role in SC (Mundy & Acra, 2006), and the words children can understand may provide them with mechanisms for perceiving and thinking about others. Similarly, as children learn the meanings of more and more words, they may begin to identify categorical relations between them (e.g., dog and cat are *kinds* of animal) that may lead them to reorganize how they think about different concepts. How comprehension of words may be influencing children's perspective-taking and analytical thinking skills are important areas for future research. Thus, although differentially related to earlier PNS functioning, children's expressive and receptive vocabularies were both positively associated with their EF and SC in preschool.

The final aim of the study was to investigate whether PNS functioning in infancy was indirectly related to EF and SC in preschool through its influence on language. In children, these direct associations have been mixed, such that greater vagal withdrawal *and* augmentation have been associated with greater EF (Becker et al., 2012; Kahle et al., 2017). Similarly, studies have found that dynamic increases and decreases in RSA during social challenges is related to more competent social functioning (Miller et al., 2016). Because EF and SC may build on the same existing capacities that involve different amounts of vagal influence on the heart (Porges, 1992; 2003), we expected that infants' vagal regulation in both social and non-social contexts may contribute to their developments. We further expected that these effects would be mediated through children's early language skills.

First, greater decreases in PNS influence on the heart in a non-social attention condition at 10 months were related to greater EF in preschool, indirectly, through children's receptive vocabulary at age 3. That is, infants who exhibited greater decreases in PNS influence during a dynamic video clip tended to have more flexible cognition in preschool, possibly

because they understood more words as toddlers. In infants, vagal withdrawal is thought to support controlled attention (Porges, 1992), which has been implicated in the later emerging ability to control thoughts and actions (Garon et al., 2008). This finding supports that view, and further suggests that conceptual development may partially explain that relation.

Additionally, through language, children's EF was indirectly related to their PNS functioning in a social interactive context in infancy. Specifically, infants who exhibited greater increases in PNS influence while interacting face-to-face with their mothers tended to have more flexible cognition in preschool; these effects were mediated through both components of language. Vagal augmentation in social contexts may foster states of positive social engagement (Porges, 2003), and social interactive experiences in the second year are crucial to learning and producing words. Because it may partially draw on their language skills (Zelazo, 2015), in addition to building upon their existing capacity to control attention, children's EF may also build on their existing capacity for social engagement.

Children's SC was also indirectly related to their PNS functioning in infancy. First, infants who exhibited greater increases in PNS influence during the social attention condition tended to have more competent social functioning in preschool, possibly because they understood and produced more words as toddlers. Social engagement experiences in infancy are thought to serve a foundational role in the development of SC (Mundy & Acra, 2006), and this finding suggests that learning language may be part of that developmental process. Additionally, infants who exhibited greater decreases in PNS influence during the video task tended to have greater SC in preschool, and this effect was mediated through receptive language. Thus, in addition to their capacity for social engagement, infants' capacity for independently sustained attention may also contribute to their emerging SC. Although, how it may be uniquely contributing is not clear from this study.

Although traditionally studied separately, recent empirical work suggests that EF and SC may involve similar developmental mechanisms (Miller & Marcovitch, 2015; Razza & Blair, 2009). Adding to that literature, findings from this study suggest they may both partially build on children's PNS responses to social and non-social demands in infancy. They further suggest that advances in both expressive and receptive language may partially explain those indirect links. Thus, when investigating sources of variation in children's emerging competencies, it may be important to maintain both a psychobiological and developmental perspective.

Strengths, limitations, and future directions

The current study adds meaningfully to the existing literature in several respects. First, few studies have examined children's PNS functioning across different contexts in relation to developmental outcomes. Additionally, although Porges' (2003) Polyvagal Theory explicitly implicated the PNS in infants' social and communication behaviors, only one study to our knowledge has examined early PNS functioning in relation to language competence and it was not longitudinal (Suess & Bornstein, 2000). Results from this study provide much-needed empirical support for the role of PNS functioning in the development of language, and further suggest that PNS functioning in social and non-social contexts may be differentially related to expressive and receptive language. Considering that discrepancies in

these components of language within children have been associated with neurodevelopmental disorders (e.g., ADHD, autism; Helland, Posserud, Helland, Heimann, & Lundervold, 2016; Hudry, Leadbitter, Temple, Slonims, McConachie, Aldred, ... & Charman, 2010), it is important to understand factors that may account for variation in early PNS functioning in both contexts.

Although this study adds in many ways to the existing literature, it has limitations that should be acknowledged. First, aside from mothers' education, extrinsic influences on children's vocabularies were not measured. Socio-cultural factors (e.g., exposure to books and reading, family size and structure) are essential to language development. The primary aim of our study was to investigate whether early biological functioning also contributes to this process. That infants' PNS functioning was significantly associated with their vocabularies as toddlers over and above the influence of maternal education suggests that it might. However, studies that examine the complex interactive influences of biological and social processes in the development of language are needed (Calkins, 2015).

A second limitation of the study is that the findings cannot speak to the mechanisms linking infants' PNS functioning to their later vocabularies. Our assumptions regarding what likely mediated those associations (attentional control, social engagement) were based on large bodies of existing research (e.g., Bazhenova et al., 2001; Kannass & Oakes, 2008; Mundy & Gomes, 1998; Richards & Casey, 1991). However, future studies should investigate those links more directly. Further, to understand *how* EF and SC develop, it is necessary to identify not only which factors are involved (e.g., language), but also the processes through which they exert their influences (Michel, 2001). Although our findings suggest that children's language skills contributed towards their development, additional research is needed to understand how.

Another limitation is that the infant tasks may have elicited dynamic responses in RSA that were not indexed by relatively static RSA change scores (see Brooker & Buss, 2009). Dynamic changes in RSA have been observed in infants across different phases of engagement in both social and non-social contexts (Bazhenova et al., 2001; Sullivan, 2016). Theoretically, infants initial (i.e., reactive) and sustained physiological responses to events could have independent effects on learning (Porges, 1992). Future studies should investigate whether greater or lesser PNS influence during different phases of social interaction or sustained attention are more strongly associated with language outcomes.

A final limitation is that extrinsic influences on infants' vagal regulation were not examined. Measures of autonomic functioning have been linked to body mass index in adults (Koenig, Jarczok, Warth, Ellis, Bach, Hillecke, & Thayer, 2014) and time of day in children (Massin, Maeyns, Withofs, Ravet, & Gérard, 2000), and could have impacted RSA values in this study. Prior exposure to screens in particular could have influenced infants' vagal regulation during the video task. Similarly, the quality of prior mother-infant interactions could have influenced vagal regulation during the social task. Moore and Calkins (2004), for example, found that 3-month-olds' vagal regulation during face-to-face play with their mothers was related to the degree of coordination between their behaviors. In a more recent study, 10-month-olds whose mothers were more sensitive at 5 months displayed greater vagal

withdrawal during an emotional challenge (Perry, Calkins, & Bell, 2016). Similar findings have been reported in older children (Calkins, Graziano, Berdan, Keane, & Degnan, 2008). Thus, maternal behaviors during the task, or infants' expectations for their responsiveness, could have influenced infants' PNS functioning in this study. Because maternal behaviors have been linked to advances in language (Tamis-LeMonda, Bornstein, & Baumwell, 2001), these possibilities should be explored in future work.

In conclusion, this study highlights the foundational role of biological processes in infancy in the development of early cognitive and socioemotional skills (Calkins, 2007). Although, more research is needed to understand how infants' PNS functioning in social and non-social contexts may be related, and how they may be influenced by environmental factors (e.g., caregiving).

Acknowledgments

This research was supported by grants HD049878 and HD043057 from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) awarded to Martha Ann Bell. The content of this manuscript is solely the responsibility of the authors and does not necessarily represent the official views of the NICHD or the National Institutes of Health. We are grateful to the families for their participation in our research. The assistance of our Blacksburg and Greensboro research assistants with data collection and coding is greatly appreciated. The authors have no conflicts of interest to disclose.

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Figure 1.

Path diagram containing standardized estimates for model predicting 2- and 3-year language and 4-year EF and SC from 10-month vagal regulation.

Note: * $p < .05$, ** $p < .01$, *** $p < .001$. RSA = respiratory sinus arrhythmia; attn = attention; dashed lines indicate non-significant paths. Maternal education was included as a covariate but not depicted for simplicity.

Table 1

Descriptive Statistics and Bivariate Correlations among Model Variables

	1	2	3	4	5	6	7	8	9	10
1. Maternal education	-									
2. Baseline RSA	-.07	-								
3. 'Video' RSA	-.06	** .63	-							
4. 'Peek-a-boo' RSA	-.09	** .51	** .53	-						
5. RSA (video - baseline)	.03	** -.46	** .40	.02	-					
6. RSA (peek-a-boo - baseline)	-.04	** -.56	* -.13	** .43	** .49	-				
7. MCDI score	.08	* -.12	* -.13	.01	.01	** .16	-			
8. PPVT score	** .37	-.06	-.12	.06	-.05	.13	** .31	-		
9. DCCS score	** .25	** -.23	** -.22	-.12	.04	* .16	** .34	** .37	-	
10. SIS score	.10	.01	.03	.08	.02	.06	** .25	** .25	** .21	-
Minimum	0.00	.99	1.29	2.00	-3.92	-3.14	5.00	67.00	.00	48.00
Maximum	4.00	8.87	8.53	9.26	3.48	3.78	683.00	147.00	1.00	190.00
Mean	2.61	4.67	4.70	4.91	0.04	0.27	313.74	111.00	.64	128.41
SD	1.13	1.15	1.11	1.01	0.98	1.04	167.91	14.29	.45	23.59
Skewness	-.51	0.38	0.31	0.64	-0.30	0.30	0.15	-0.17	-0.58	-0.38
Kurtosis	-.95	1.04	0.49	1.98	1.40	0.82	-0.80	0.09	-1.55	1.06
N	297	297	293	276	293	276	279	243	227	186

Note:

* $p < .05$,** $p < .01$;

RSA = respiratory sinus arrhythmia; = change; SD = standard deviation; MCDI = MacArthur Bates Communicative Development Inventory; PPVT = Peabody Picture Vocabulary Test; DCCS = Dimensional Change Card Sort; SIS = Social Interaction Survey