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The Association between Heart Rate Reactivity and Fluid Intelligence in Children

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Abstract

This study aimed to examine (a) whether findings of increased cardiovascular reactivity in relation to cognitive ability seen in infants, young adults and the elderly can be extended to middle childhood, and (b) which specific aspect(s) of intelligence is related to cardiovascular reactivity. We examined cardiovascular activity in 340 8- and 9-year-old children during a number judgment task and measured fluid and crystallized IQ using the WISC-IV (Wechsler, 2003). Regression analyses revealed that heart rate (HR) reactivity was positively associated with fluid intelligence and perceptual reasoning in particular, after controlling for the effects of sex, age, task performance, social adversity, and resting HR. Intelligence scores were not associated with respiratory sinus arrhythmia (RSA) reactivity. Findings are consistent with prior literature in infants and older populations and for the first time suggest that the association between HR reactivity and cognitive ability is specific for fluid reasoning.

Keywords

heart rate; respiratory sinus arrhythmia; fluid intelligence; child

The association between cardiovascular reactivity and cognitive ability has received scant attention (see review by Ginty, Phillips, Der, Deary, & Carroll, 2011a, b). Furthermore, the literature is conducted mostly with adults and infants, and few studies focus on typically developing elementary school-aged children. For example, Backs and Seljos (1994) administered to 24 participants (12 female, 12 male, mean age= 22 years) a continuous memory task varying in memory load (one or three items) and temporal demand (inter-

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stimulus interval of 2, 3, or 4s), and found that as memory load and temporal demand increased, good performers, those whose error rate was below the median of the sample, had a smaller decrease in heart period, while poor performers, those whose error rate exceeded the median of the sample, had a larger decrease in heart period. In another study, Wright, Kunz-Ebrecht, Iliffe, Foese, and Steptoe (2005) administered two standardized verbal paired-associates recall tasks and a matrix reasoning task to 139 participants (ages 65–80 years), and measured heart rate (HR) before, during, and after each task. They found that greater memory in the verbal paired-associates task was related to more effective post-task recovery of HR.

Recently, Ginty, Phillips, Der, Deary, and Carroll (2011a) in a sample of 1,647 participants, ages 24, 44, and 63, measured HR before, during, and after the paced auditory serial addition test (PASAT). In the PASAT, participants heard a series of single-digit numbers and were instructed to add sequential number pairs while keeping the second number of the pair in memory to add to the next number. HR reactivity was calculated as the difference between baseline HR and HR during the PASAT. They found that higher HR reactivity was correlated with a higher IQ score assessed five and 12 years later and less of a decline between follow-up assessments. In another report, Ginty et al. (2011b) linked general intelligence, simple reaction time, and subsequent cardiovascular reactivity in 409 55-year-olds with HR reactions to an acute mental arithmetic task 7 years later. They found that low HR reactivity was characteristic of those with relatively low cognitive ability. Taken together, the researchers concluded that the low HR reactivity – low cognitive ability association is bidirectional, and robust, because associations withheld following adjustment for a wide range of potentially confounding variables including baseline cardiovascular activity, socio-demographics, body mass index, medication status, and stress task performance (Ginty, Phillips, Roseboom, Carroll, & Derooij, 2012). Given that certain brain regions, including the striatum and ventromedial prefrontal cortex, are critically involved in cognitive functioning (Busato, Prins, Elshout, & Hamaker, 2000; Dweck, 1986) and HR reactivity (Carroll, Lovallo, & Phillips, 2009; Carroll, Phillips, & Lovallo, 2011; Lovallo, 2011), it was argued that central motivational dysregulation, as supported by both regions, may contribute to both cognitive ability and HR reactivity (Ginty et al., 2011a, b). However, one limitation of the prior literature was that it was based on either adults (Bucks & Seljos, 1994; Ginty et al., 2011a, 2011b, 2012) or infants (DeGangi, DiPietro, Greenspan, & Porges, 1991); none of the studies tested school-age children using a comprehensive battery of cognitive tests. The first goal of the present study was to build on and extend prior literature through the assessment of cardiovascular activity in relation to cognitive functioning and intelligence in typically developing school-age children from diverse ethnic backgrounds. We aimed to determine whether the same patterns of findings observed in infants and adults may also be present in children. It was predicted that large HR reactivity to a stress task would be associated with better cognitive functioning and higher IQ scores.

The second goal was to gain a better understanding of the specificity of these relationships by examining the different categories of intelligence. Intelligence is a multifaceted construct, and it reflects a variety of measurable skills. For example, fluid and crystallized intelligence have been considered by many intelligence theories as two major categories of cognitive abilities, subserved by different parts of the brain (e.g., Colom et al., 2009; see review by

Blair, 2006). Fluid intelligence refers to inductive and deductive reasons, skills to solve new problems on the spot and the ability to learn new things (Cattell, 1971), and it is thought to be largely influenced by neurological and biological factors; crystallized intelligence refers to knowledge and skills that one accumulated by applying one's fluid ability in different areas (Cattell, 1971), and it is primarily influenced by environmental and sociocultural factors (e.g., Rindermann et al., 2010).

Findings from both imaging research and clinical neuropsychological research have linked the prefrontal cortex (PFC) with fluid intelligence. In addition, neural circuitry including the superior parietal temporal and occipital cortex, and subcortical regions such as the striatum are also involved (Crone et al., 2009; Duncan et al., 2000; Gray et al., 2003; Jung & Haier, 2007; Lee et al., 2006; Olesen et al., 2004). In contrast, crystallized intelligence has been found to be much less affected by the damage to PFC (Waltz et al., 1999). Meanwhile, research has shown that complex and interconnected cortical and subcortical regions including the medial PFC, insular, anterior cingulate, amygdala, striatum, and the cerebellum, are involved in HR reactivity (Carroll, et al. 2009; 2011; Critchley et al., 2000, 2003, 2005; Gianaros et al., 2004; Lovullo, 2011; Wong, Masse, Kimmerly, Menon, & Shoemaker, 2006). Taken together, it was expected that increased HR reactivity would be strongly associated with fluid but not crystallized intelligence.

Another cardiovascular measure that has been correlated with cognitive functioning is respiratory sinus arrhythmia (RSA). In contrast to HR, which is influenced by both sympathetic and parasympathetic nervous systems, RSA is a measure of parasympathetic nervous system-linked cardiac activity, and reflects the variability of HR across the respiration cycle due to the influence of vagus nerve on the sinoatrial node (SA) (Beauchaine, 2001; Grossman, van Beek, & Wientjes, 1990). RSA typically decreases (e.g., RSA suppression) during stressors and engagements that require increases in attention, and this process reflects the ability to maintain the internal homeostatic balance in responses to stressors and to sustain attention to the changes in the environment (Porges, 1991). Typically, change in RSA from baseline to task is described as RSA reactivity, with low reactivity indicating smaller than average decreases (or even augmentation) in RSA from baseline, and large reactivity indicating greater than average decreases (withdrawal) in RSA. Low RSA reactivity is proposed to reflect inactive engagement and ineffectively coping with stressors (Beauchaine, 2001; Porges, 2007), whereas large RSA reactivity is postulated to be associated with better cognitive performance and higher intelligence. Since HR is greatly influenced by both sympathetic and parasympathetic nervous systems (Beauchaine, 2001) whereas RSA is an index of parasympathetic functioning, examining RSA in relation to intelligence will help us determine the predominant driving factor for the intelligence – HR reactivity association.

Findings from empirical studies on the relationship between RSA and cognitive performance are mixed. DeGangi et al. (1991) measured RSA of 35 infants during sensory and cognitive challenges, and found that greater decreases of RSA during mental testing were related to higher functional levels. Duschek, Muckenthaler, Werner, and Reyes del Paso (2009) reported a trend towards better attention capacity in individuals with stronger decreases in RSA in 60 college students. In contrast, Staton, El-Sheikh, and Buckhalt (2009) failed to

find a significant relationship between RSA reactivity and cognitive performance on a set of standardized tests examining fluid intelligence (e.g., working memory and cognitive efficiency) in a group of elementary school-age children.

In the current study, three hundred and forty 8- to 9-year old boys and girls from the community were administered a number judgment task while HR and RSA were assessed at rest and during the task. In this task, children determined if the number on the screen was higher or lower in value than the previous one, and it was expected that the task performance would be associated with fluid intelligence score. Children's intelligence was assessed using four subtests of the Wechsler Intelligence Scale for Children (WISC), the most widely used intelligence and neuropsychological assessment in children. Based on prior literature, it was hypothesized that large HR reactivity would be associated with better cognitive performance and higher IQ scores, and these associations would be specific to fluid intelligence. Due to mixed findings, we did not form any specific hypothesis on the relationship between RSA reactivity and IQ scores.

Method

Participants

Data were collected as part of the Healthy Childhood Study, an ongoing longitudinal study examining the development of behavioral problems in middle childhood. The sample consisted of 8- and 9-year old boys and girls (Mean age = 9.06, $SD = 0.60$) living in Brooklyn, New York. Within the study area, fliers soliciting enrollment were placed in recreation centers, libraries, churches, and other community centers. Targeted mailings were also sent to parents of 8- to 9- year-old children living in the geographic catchment area. Children with a diagnosed psychiatric disorder, intellectual disability, or a pervasive developmental disorder were excluded. The initial sample consisted of 340 subjects, 164 of whom were male (48.2%), with ethnic breakdown as follows: 11% Hispanic, 21% Caucasian, 52% Black, 2% Asian, and the remaining 14% of mixed/other. Compared to the ethnic distribution in the Kings County or New York population (<http://quickfacts.census.gov/qfd/states/36000.html>), our sample consisted of more African Americans and people with more than one race.

Caregiver participants were primarily biological mothers of the children (86.4%), although other relatives were also interviewed, including biological fathers (10.8%), or other relatives (2.8%). Fifty-nine percent of the children were living with both biological parents and 29% were living alone with their biological mother. Among the remaining families in which the biological parents were not living together (because of separation, divorce, or death of the parent), the majority of these (9%) were remarried to a partner at the time of testing. Thus, the majority of the children lived in two-parent households, although 2% of the children did live in a single-parent household with no other adult in the home. The remainder of the children (1%) resided with a single parent as well as one or more other adults (mostly grandparents).

Median family income was \$43,200, which is slightly lower than the median income in Kings County (average median = \$45,215) of the state of New York between 2008 and 2012

(<http://quickfacts.census.gov/qfd/states/36/36047.html>). Maternal and paternal education levels, measured as years of schooling, were significantly correlated ($r = .70, p < .05$), and significantly higher mean levels of education were reported for mothers ($M = 14.37, SD = 4.11$) than for fathers ($M = 13.19, SD = 4.15, t = 5.65, p < .001$).

Procedures

Data from the first wave of assessment are included in the current study. Participants and their main caregivers were invited to the university for a laboratory assessment. During a 2-hr visit, psychophysiological recording, behavioral interviews, neurocognitive testing, and social risk factor assessments were conducted. Caregivers were also interviewed about their child's behavior, as well as their own behavior and relationship to their child. A \$60 incentive plus transportation reimbursement was provided to the participating families at the end of the assessment. All of the study procedures were approved by the City University of New York Institutional Review Board, and both parental consent and child assent were obtained. All interviews were conducted in English.

Cardiovascular measures were recorded during a psychophysiological testing session, which lasted approximately 40 minutes and included several tasks. Before administering the tasks, baseline recordings were obtained for 2 minutes during which time the child was instructed to sit quietly and relax. The number judgment task (see details below) was administered right after the rest period. After the psychophysiological testing session, participants were administered an IQ test and behavioral assessment by trained research assistants.

Measures

Intelligence—Four subtests of the WISC, the fourth edition (WISC-IV), were administered (Wechsler, 2003). It consists of 15 core subtests and five supplementary subtests and recognizes four factor indexes, including the Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI), in addition to full scale IQ. We assessed the VCI using the Vocabulary task, in which participants are asked to define increasingly difficult words presented orally. For example, an early (easier) trial asks participants to define “UMBRELLA,” whereas a later (harder) trial asks participants to define “DILATORY.” The task continues until participants answer five consecutive trials incorrectly or until completing the last trial. The WMI was assessed using the Digit Span task, in which participants are read digit sequences of increasing length and asked to reproduce them orally. There are two trials per string length, and participants are asked to reproduce strings in forward order and backwards order. The task continues until both trials of a given string length are answered incorrectly or until reaching the last item. The PRI was assessed using the Matrix Reasoning task, in which participants are presented with a matrix containing a sequence of pictures with one blank cell. Below the matrix are presented five pictures, and participants are asked to select the picture that correctly completes the sequence. The task continues until the participant answers four consecutive trials incorrectly, four trials incorrectly out of five consecutive trials, or until completing the last trial. Finally, the PSI was assessed using a Coding task, in which participants are presented with a piece of paper with a “key” linking the digits one through nine with simple symbols. Participants are instructed to draw the appropriate

symbol below each number for multiple rows of numbers. The task is timed to two minutes. In addition to full scale IQ, scores on the WMI, PRI, and PSI were summated to yield a measure of fluid IQ, while the VCI assesses crystallized intelligence (Keith, Fine, Taub, Reynolds, & Kranzler, 2006).

The Number Judgment Task—Participants performed a computerized task in which single-digit numbers were presented on a computer screen in random order. Participants were required to press one button if the number presented was higher in value than the preceding number, and press another button if it was lower. The next trial was presented when the correct button was pressed. Participants received 10¢ for each correct answer, and the amount of money earned was displayed in the upper left corner of the screen. The game was timed to 120s. By the end of the task, the number of correct trials completed within 120s was recorded, and higher numbers indicate better performance.

Social adversity—A social adversity index was created based on 10 variables along the lines of prior literature (Fung, Raine, & Gao, 2009; Gao, Raine, Chan, Venables, & Mednick, 2010; Raine, Yaralian, Reynolds, Venables, & Mednick, 2002). A total adversity score was created by adding 1 point for each of the following ten variables: Divorced Parents (single parent family, remarriage, or living with guardians other than parents), Foster Home, Public Housing, Welfare Food Stamps, Parent Ever Arrested (either parent has been arrested at least once), Parents Physically Ill, Parents Mentally Ill, Crowded Home (five or more family members per house room), Teenager Mother (aged 19 years or younger when child was born), and Large Family (sibling order fifth or higher by age 3 years). All items were scored either 0 (*no*) or 1 (*yes*), with a high total score indicating higher social adversity.

Psychophysiological Data Acquisition and Reduction—All electrocardiogram (ECG) and respiration (RSP) data were collected continually at 1000 Hz using a Biopac system (MP150-BIOPAC Systems Inc., Goleta, CA) during the 2-min rest period and the 2-min number judgment task. ECG signal was recorded using ECG100C with two pre-jelled Ag-AgCl disposable vinyl electrodes placed at a modified Lead II configuration. RSP was assessed by putting a respiration belt around the abdomen of the subject at the point of complete exhalation.

All physiological data were analyzed with AcqKnowledge 4.2 software (BIOPAC Inc.) offline. RSA was derived from the ECG100C amplifier with a band pass filter of 35 Hz and 1.0 Hz and a RSP100C respiration amplifier with a band pass filter of 1.0 Hz and 0.05 HZ. Saved ECG signal was visually inspected for artifacts, and then converted to R-R intervals using the AcqKnowledge automated modified Pan-Tompkins QRS detector. The AcqKnowledge automated function for RSA analysis was utilized. We followed the well-validated peak-valley method (Grossman et al., 1990), in which RSA was computed in milliseconds as the difference between the minimum and the maximum R-R intervals during respiration. Higher values reflect greater while lower values indicate lower parasympathetic nervous system activity.

HR was measured in beats per minute (bpm) based on the average of inter-beat intervals (R-R intervals) during the rest period and the task. HR reactivity was computed by subtracting baseline HR from task HR. Following previous research (Calkins, 1997), RSA reactivity was computed by subtracting task RSA from baseline RSA, with positive values indicating greater RSA suppression.

Statistical Analyses

Sex differences in all study variables were examined using independent samples *t*-tests. Repeated-measures ANOVAs, using baseline and task HR/RSA as repeated measures, were undertaken to confirm that the number judgment task perturbed HR/RSA activity. The relationships between IQ scores, task performance, cardiovascular measures, and demographic variables were investigated by Pearson's correlation. A series of two-step hierarchical linear regressions were then undertaken to determine if cardiovascular reactivity was significantly associated with IQ scores after potential confounding variables were controlled. In all analyses, the outcome variables were children's HR or RSA reactivity. In each regression analysis, potential confounding variables were entered in step 1 to control for their effects. Resting HR/RSA was also entered in the first step to control for its effect in accord with the law of initial values. Then full scale IQ (step 2a), fluid IQ (step 2b), or crystallized IQ (step 2c) was entered in step 2. Furthermore, to determine which subtest score(s) of the fluid IQ was significantly associated with HR/RSA measures, the PRI, PSI, and WMI scores were entered simultaneously in step 2 (step 2d).

Results

Descriptive Statistics

Prior to conducting analyses, outliers (± 3 SDs from the mean) were examined. Ten outliers were found for cardiovascular measures, and were removed from all subsequent analyses. Descriptive statistics for primary study variables among the overall sample and for boys and girls separately are presented in Table 1. Average performance on the WISC-IV total score is slightly higher than the standardized average scores ($M = 100$), and SDs reflect a wide range of performance in our sample. Compared to girls, boys were slightly older ($t = 2.57, p = .04$) and had higher crystallized IQ ($t = 3.01, p = .03$) and lower PSI scores ($t = -3.05, p = .03$). There was a trend that boys had lower resting HR ($t = -1.73, p = .08$), and better task performance ($t = 1.79, p = .07$). Repeated-measures ANOVAs, using baseline and task HR/RSA as repeated measures, showed that the number judgment task significantly increased HR [$F = 25.67, p < .001$, partial $\eta^2 = .09$] and decreased RSA [$F = 23.98, p < .001$, partial $\eta^2 = .11$].

The correlations between main study variables are presented in Table 2. HR reactivity was significantly associated with fluid IQ ($r = .13, p = .04$) and PRI ($r = .21, p = .007$). Resting RSA was marginally associated with full scale IQ ($r = -.12, p = .07$) and PRI ($r = -.10, p = .09$). RSA reactivity was also marginally associated with WMI ($r = -.12, p = .07$). No other significant associations between IQ scores and cardiovascular measures were found. Task performance was associated with WMI ($r = -.17, p = .006$). Social adversity was significantly associated with resting HR ($r = -.13, p = .04$), task HR ($r = -.20, p = .002$), and

marginally associated with task RSA ($r = .12, p = .07$). Finally, age was significantly associated with resting HR ($r = -.19, p = .004$), task HR ($r = -.20, p = .003$), and task performance ($r = .19, p = .005$).

Hierarchical Regression

A series of two-step hierarchical linear regression models were conducted to determine whether HR/RSA reactivity was associated with IQ scores, after potential confounding variables, including sex, age, social adversity, task performance, and baseline cardiovascular measures were controlled for. In the following analyses, these variables were entered in the first step and IQ measures were entered in the second step. Hierarchical regression analyses results are presented in Table 3.

After sex, age, social adversity, task performance, and baseline HR were controlled for, full scale IQ was not significantly associated with HR reactivity, $\beta = .08, p = .56, R^2 = .01$ (Step 2a). However, HR reactivity was associated with Fluid IQ, $\beta = .13, p = .03, R^2 = .02$ (Step 2b), but not crystallized IQ, $\beta = -.03, p = .78, R^2 = .01$ (Step 2c). Finally, when PRI, PSI, and WMI scores were entered simultaneously in the second step (step 2d), only PRI scores were significantly associated with HR reactivity after all those effects were partialled out, $\beta = .20, p = .009; R^2 = .04, p = .04$.

To visually display the relationship between HR reactivity and PRI score, three groups were formed based on their HR reactivity. The high reactivity group was defined as those who fell into the top 1/3 of reactivity (> 4 bpm, mean HR reactivity = 7.97, $SD = 4.26$), the low reactivity group included those who fell into the bottom 1/3 of reactivity values (< 0 bpm, mean HR reactivity = $-3.77, SD = 4.20$), and others were in the moderate reactivity group (mean HR = 2.00, $SD = 1.13$). ANOVA revealed that the group effect was marginally significant, $F = 2.88, p = .058$. Post Hoc comparisons with Bonferroni corrections indicated a trend that the high reactivity group (mean = 32.33, $SD = 8.76$) had higher PSI scores than the low reactivity group (mean = 29.52, $SD = 7.42, p = .059$); the moderate group (mean = 30.42, $SD = 7.55$) did not differ from either the high or low reactivity group ($p > .33$, Figure 1).

When predicting RSA reactivity, task performance ($\beta = .14, p = .02$) and resting RSA ($\beta = .43, p < .001$) were significant predictors ($R^2 = .21, p < .001$, step 1). After the effects of sex, age, social adversity, task performance, and baseline RSA were controlled for, none of the IQ measures were significantly associated with RSA reactivity, although there was a trend that RSA reactivity was positively associated with PRI ($\beta = .12, p = .09$) and negatively associated with WMI ($\beta = -.13, p = .09, R^2 = .02$) (see Table 3).

Discussion

To our knowledge, this is the first study to investigate HR reactivity in relation to intelligence and cognitive functioning in typically developing schoolchildren using a comprehensive battery of cognitive tests, and also the first to examine the specificity of these relationships by examining the different categories of intelligence. In this sample of 8- to 9-year-old children, higher HR reactivity was significantly associated with higher fluid IQ

after adjusting for potential confounding variables (age, sex, social adversity, task performance, and baseline HR). In contrast, hierarchical regression analyses did not reveal significant associations between RSA reactivity and intelligence scores. Findings are consistent with prior research suggesting that central motivational dysregulation, as supported by the striatum and ventromedial prefrontal cortex, may contribute to both cognitive ability and HR reactivity (Ginty et al., 2011a, b). This study extends the findings from adults and infants to typically developing schoolchildren from diverse ethnic backgrounds, and for the first time suggests that the association is specific for fluid reasoning.

We found that higher HR reactivity was associated with higher fluid but not crystallized IQ scores, although no significant relationship between HR reactivity and full scale IQ was detected. After sex, age, social adversity, task performance, and baseline HR were controlled for, HR reactivity accounted for 2–4% of unique variance in children's fluid intelligence and its three subscales. Furthermore, HR reactivity was specifically associated with the PRI score as measured by the Matrix Reasoning subtest. The Matrix Reasoning test is based on Raven's Colored Progressive Matrices that primarily taps nonverbal fluid reasoning. In this test, the participant is asked to identify the missing element that completes a pattern, and the ability to think logically and make sense of complexity, i.e., deductive ability, is assessed (Raven, Raven, & Court, 1998). This association suggests that HR reactivity is related more to performing tasks that require making sense of complexity and logical thinking than those involving retrieval of previously learned information. At the neuroanatomical level, evidence has shown that overlapping brain circuitry subserves both HR responses and fluid reasoning ability. For example, orbitofrontal gray matter volume was found to be associated with Raven's Progressive Matrices performance (Schilling et al., 2013), while lesions to the same region were also linked to abnormal HR responses during emotional tasks (Angrilli, Palomba, Cantagallo, Maietti, & Stegagno, 1999). Overall, evidence suggests that the same brain regions are involved in both HR reactivity to stressors and fluid reasoning ability, which focuses on logical reasoning and problem solving.

Unlike findings from three earlier studies that found lower cardiovascular reactivity to be associated with poor performance on a mental stress task (DeGangi et al., 1991; Ginty et al., 2011a, b), no relationship was detected between HR reactivity and task performance. This finding is not unexpected, since three other studies failed to find an association between HR reactivity and cognitive ability as revealed by performance on a stress task (Backs & Seljos, 1994; Staton et al., 2009; Wright et al., 2005). In addition, we did not observe resting RSA to be related to cognitive functioning, as reported in the study by Staton et al. (2009), who found that in 41 6–13-year old children, those with higher levels of basal RSA performed better on tasks related to overall intellectual ability, processing speed, working memory, cognitive efficiency, and reaction time. In fact, we found that *lower* resting RSA was marginally associated with higher full IQ scores. However, after adjusting for potential confounding variables, resting RSA was not significantly related to either fluid or crystallized IQ.

RSA reactivity was not significantly associated with any of the IQ measures, although it was marginally associated with PRI and WMI scores (Table 3). The trend that RSA reactivity

was positively associated with PRI is supportive of the proposition that larger RSA reactivity (e.g., greater vagal withdrawal) reflects better cognitive function (Beauchaine, 2001; Duschek et al., 2009; Porges, 2007). However, there was also a trend that RSA reactivity was negatively associated with WMI as measured by the Digit Span task that includes both forward and backward trials. The verbal forward digit span is better described as a simple verbal short-term or immediate memory task and verbal backward digit span as a true working memory task that requires the maintenance of information while additional new information is presented for processing. In addition, although similar brain regions are involved, different levels of activation underline backward and forward digit span (Hoshi et al., 2000). It is interesting for future studies to specifically target the RSA- digit span association attributable to working memory.

As mentioned above, HR is regulated by both sympathetic and parasympathetic branches of the autonomic nervous system (Beauchaine, 2001). Thus, low HR reactivity could reflect reduced sympathetic influence or weaker parasympathetic functioning during the stress task. The null finding between cognitive functioning and RSA reactivity suggests that the low HR reactivity in relation to low fluid intelligence may be predominantly driven by an underaroused sympathetic nervous system. This is consistent with the proposition that enhanced sympathetic influences may partly contribute to both larger HR responses and an adaptive state associated with improved cognitive-attentional functioning (Duschek et al., 2009).

This study has a few limitations. First, our study is cross-sectional and all children were 8- to 9- years old. Given that reasoning ability changes rapidly during childhood (Ferrer, O'Hare, & Bunge, 2009), longitudinal studies are needed to examine whether the HR reactivity – fluid intelligence association changes developmentally. Nonetheless, we found that the significant association between HR and intelligence withheld after controlling for age. Taken together with prior literature showing that HR reactivity is positively associated with cognitive ability in infants (DeGangi et al., 1991) and adults (Bucks & Seljos, 1994; Ginty et al., 2011a, 2011b; Wright et al., 2005), it is conceivable that this association may have an early neurodevelopmental basis. Second, only four out of 15 subtests of WISC-IV were administered due to the time limit, and only HR and RSA were assessed.

Administering the whole intelligence battery and incorporating a more comprehensive assessment of hemodynamics (i.e., sympathetic nervous system-linked cardiac activity such as pre-ejection period) may help us achieve a more in-depth understanding of the above associations. Third, we did not assess the level of engagement or stressfulness of the task; therefore it is yet to determine if the same pattern is present when more demanding tasks are used. Cardiovascular responses have been found to be sensitive to level of difficulty on a number of cognitive tasks, including mental arithmetic and Raven's matrices (Carroll, Turner, & Prasad, 1986). Specifically, more difficult tasks elicited more HR increases than the easy tasks. In the current study, the HR reactivity was small (2 bpm), suggesting that our task may not be very difficult or stressful, which in turn may contribute to the small effect sizes and lack of significant associations between RSA reactivity and intelligence. Future research using a more demanding task is expected to produce stronger associations.

In conclusion, our findings are the first to demonstrate that larger HR reactivity is associated with better fluid reasoning ability in typically developed elementary schoolchildren, and this association may be more strongly driven by the influence from the sympathetic than from the parasympathetic nervous system. These findings are also consistent with neuroimaging evidence suggesting that overlapping brain circuitry is involved in both HR responses to stressors and fluid intelligence. Future studies using longitudinal designs could further explore how the relationships between fluid intelligence and cardiovascular activity change with age.

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Highlights

1. Cardiovascular activity and intelligence were assessed in a community sample of 8-to 9-year-olds.
2. Higher heart rate reactivity was associated with higher fluid intelligence score.
3. Respiratory sinus arrhythmia reactivity was not associated with intelligence scores.
4. Findings extend the relationships to typically developing school-age children, and for the first time suggest that the association between HR reactivity and cognitive ability is specific for fluid reasoning.

Figure 1.

Children with high HR reactivity (HR reactivity > 4 bpm) demonstrated higher PSI scores than those with low HR reactivity (HR reactivity < 0 bpm, $p = .059$). The moderate group (0 < HR reactivity < 4) did not differ significantly from the other two groups ($p > .33$).

Table 1

Descriptive Statistics for Main Study Variables and Group Differences

	Overall Sample				Boys		Girls		<i>t</i>
	Mean	S.D.	Minimum	Maximum	Mean	S.D.	Mean	S.D.	
Resting HR	86.93	10.80	61.80	121.24	85.85	10.81	88.00	10.72	-1.73 ^a
Task HR	88.89	11.42	59.83	123.77	87.89	11.53	89.84	11.28	-1.39
HR Reactivity	2.11	5.97	-30.70	25.45	2.12	6.39	2.11	5.55	0.02
Resting RSA	125.66	59.91	22.82	310.81	122.13	60.99	129.16	58.84	-0.96
Task RSA	111.80	59.02	17.40	295.82	113.86	61.79	109.87	56.49	0.51
RSA Reactivity	16.23	46.94	-202.40	227.22	11.26	52.88	21.06	39.98	1.54
Task Performance	78.07	25.11	23.00	155.00	80.77	25.44	75.53	24.61	1.79 ^a
Full IQ	104.76	18.01	70.00	155.00	105.67	17.95	103.89	18.09	0.87
Fluid IQ	24.02	4.28	13.67	36.67	23.80	4.39	24.22	4.17	-0.86
Crystallized IQ	32.71	8.95	12.00	57.00	34.26	8.80	31.22	8.86	3.01 ^{**}
PRI	30.53	7.95	9.00	54.00	30.66	7.83	30.40	8.08	0.29
PSI	19.05	5.68	10.00	38.00	18.05	5.81	20.00	5.41	-3.05 ^{**}
WMI	22.48	5.43	10.00	38.00	22.71	5.57	22.27	5.31	0.71
Age	9.07	0.61	7.51	10.75	9.16	0.56	8.98	0.64	2.57 [*]
Social Adversity	2.98	2.06	0.00	10.00	3.10	2.10	2.86	2.02	1.03

Note.

^a $p < .10$,^{*} $p < .05$,^{**} $p < .01$.

PRI = Perceptual Reasoning Index; PSI = Processing Speed Index; WMI = Working Memory Index.

Table 2

Correlations between Main Study Variables

	Resting HR	Task HR	HR Reactivity	Resting RSA	Task RSA	RSA Reactivity	Task Performance	Total IQ	Fluid IQ	Crystallized IQ	PRI	PSI	WMI	Social Adversity
Resting HR	1													
Task HR	.86***	1												
HR Reactivity	-.10	.43***	1											
Resting RSA	-.52***	-.52***	-.02	1										
Task RSA	-.50***	-.60**	-.29***	.70***	1									
RSA Reactivity	.11	-.09	-.39***	.42***	-.36***	1								
Task Performance	-.07	-.05	.03	-.07	-.10	.07	1							
Total IQ	.04	.11 ^a	.08	-.12 ^a	-.09	.04	-.03	1						
Fluid IQ	.06	.16*	.13*	-.10	-.09	.01	-.07	.89***	1					
Crystallized IQ	-.02	-.01	-.02	-.10	-.04	-.09	.03	.74***	.35***	1				
PRI	.05	.19***	.21**	-.10 ^a	-.17*	.10	-.02	.71***	.79***	.30***	1			
PSI	.08	.05	-.05	-.04	-.01	-.02	.04	.45***	.58***	.09	.15**	1		
WMI	-.02	.05	.07	-.04	.05	-.12 ^a	-.17**	.58***	.61***	.29***	.24***	.09	1	
Social Adversity	-.13*	-.10	-.09	.08	.15*	-.07	.07	-.09	-.11 ^a	-.02	-.08	-.10 ^a	1	
Age	-.19**	-.20**	-.07	.08	.12 ^a	-.09	.19**	-.08	-.11 ^a	-.01	-.10 ^a	-.01	-.10 ^a	.02

Note.

^a p < .10,

*

p < .05,

**

p < .01,

p < .001.

PRI = Perceptual Reasoning Index; PSI = Processing Speed Index; WMI = Working Memory Index.

Table 3

Hierarchical Regression Analyses Predicting HR and RSA Reactivity

HR Reactivity				RSA Reactivity			
	SE	β	R ²		SE	β	R ²
<i>Step 1</i>			.03	<i>Step 1</i>			.21***
Sex	.78	-.01		Sex	6.00	.09	
Age	.19	-.08		Age	5.19	-.13 ^a	
Social Adversity	.65	-.10		Social Adversity	1.46	-.12 ^a	
Task Performance	.02	.06		Task Performance	.12	.14*	
Resting HR	.04	-.12 ^a		Resting RSA	.05	.43***	
<i>Step 2a</i>			.01	<i>Step 2a</i>			.01
Full IQ	.02	.08		Full IQ	.17	-.02	
<i>Step 2b</i>			.02*	<i>Step 2b</i>			.01
Fluid IQ	.09	.13*		Fluid IQ	.70	-.02	
<i>Step 2c</i>			.01	<i>Step 2c</i>			.01
Crystallized IQ	.04	-.03		Crystallized IQ	.33	-.04	
<i>Step 2d</i>			.04*	<i>Step 2d</i>			.02
PRI	.05	.20**		PRI	.39	.12 ^a	
PSI	.07	-.08		PSI	.54	-.02	
WMI	.07	.03		WMI	.59	-.13 ^a	

Note.

^a $p < .10$,* $p < .05$,** $p < .01$,*** $p < .001$.

PRI = Perceptual Reasoning Index; PSI = Processing Speed Index; WMI = Working Memory Index.