Hearts and minds: Coordination of neurocognitive and cardiovascular regulation in children and adolescents

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A B S T R A C T

Emotional reactions involve changes in both cognitive and bodily processes. Therefore, effective emotion regulation may also involve modulation of responses in both of these systems. The present study investigated the relationship between regulation of cognition and regulation of the heart in children and adolescents, using a go/nogo task in combination with the induction of negative emotions. Behavioral, temperamental and event-related brain potential (ERP) indicators of inhibitory cognitive control were collected, as was a measure of parasympathetic control of the heart (respiratory sinus arrhythmia, RSA). Independently of age, RSA was correlated with nogo N2 magnitudes during the emotion-induction procedure. RSA during the task was also correlated with N2 latencies and with behavioral accuracy before, during and after the emotion induction. Resting RSA was correlated with individual differences in the capacity for effortful cognitive control, as measured by questionnaire. These results suggest that emotional responses in seemingly distinct neurophysiological systems may be regulated in an integrated fashion throughout the developmental span tested.

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1. Introduction

The experience of emotion involves changes in multiple processes, including cognition (Phelps, 2006), physiology (Ekman et al., 1983; Kreibig et al., 2007), motivation (Tice et al., 2001) and behavior (Frijda, 1988). Given this fact, it is likely that emotion regulation – the ability to modulate emotional responses to facilitate adaptive functioning – also involves regulation of responses in each of these systems. Indeed, certain aspects of the bodily (Beauchaine, 2001) and cognitive (Ochsner and Gross, 2005) regulatory systems have been quite well studied, contributing to a growing understanding of both adaptive and maladaptive emotion regulation. However, less is known about how regulatory responses in different systems might interact. Intuition suggests that regulation of responses in different systems should be coordinated. For example, it might not be very helpful to implement a cognitive regulatory strategy if bodily responses such as a pounding heart and trembling hands cannot be also controlled. On the other hand, more recently evolved cognitive regulatory responses could be deployed independently of primitive mechanisms governing homeostasis. Consistent with this idea, different regulatory processes have been linked to at least partially distinct neural substrates (Craig, 2003; Ochsner and Gross, 2005).

Given that the relationship between regulatory responses in different systems remains largely unexplored, our aim was to investigate the degree of interaction among these systems in children and adolescents ages 8–17 years. Specifically, we selected one aspect of cognitive control that is important in emotion regulation – inhibitory control – and examined whether it is associated with an important aspect of physiological regulation – parasympathetic cardiovascular control. If individuals who are more effective cognitive regulators are also more effective cardiac regulators, it would suggest that regulation of emotional responses is coordinated across these different neurophysiological systems. In what follows, we discuss the selected measures in more detail, and consider what effective regulation might look like in these two modalities.

We selected inhibitory control as our index of cognitive regulation since inhibition is thought to be important in emotion regulation, allowing routine or automatic emotional responses to be overridden. To tap inhibitory processes, we used a go/nogo task in which participants must inhibit a prepotent tendency to respond to all stimuli. We also examined a neural correlate of response inhibition, the inhibitory or nogo N2 event-related potential (ERP; Falkenstein et al., 1999; Jodo and Kayama, 1992). Behaviorally, we assumed that higher accuracy on nogo trials indicates better regulation. For the ERP measures, past research suggests that in healthy populations, smaller-magnitude N2s are related to efficient...
neurocognitive regulation. For example, children and adolescents with better executive function (as measured by Stroop and Iowa Gambling Task performance) have smaller-magnitude N2s (Lamm et al., 2006). These decreases in N2 magnitude may reflect more efficient or focal activation of brain areas that are important in executive control (Casey et al., 1997; Durston et al., 2002; Falkenstein et al., 1999). Similarly, shorter ERP latencies are often taken as an indicator of faster processing (Folstein and Van Petten, 2008; Verleger, 1997). Thus, in a go/nogo task effective inhibitory control should manifest as higher behavioral accuracy as well as smaller N2 magnitudes and shorter N2 latencies.

On the bodily side, we examined parasympathetic (inhibitory) control of heart rate. Analogous to inhibitory control of emotional response options, inhibitory cardiovascular control is thought to be an important aspect of physiological emotion regulation (Beauchaine et al., 2007; Porges, 1995). Parasympathetic control can be assessed via respiratory sinus arrhythmia (RSA), a phenomenon that consists of rhythmic fluctuations in heart period at the frequency of respiration (Bernston et al., 1997). The magnitude of these fluctuations largely reflects the level of activity in the vagus nerve, the source of parasympathetic innervation to the heart (Bernston et al., 1997). We therefore measured RSA as our index of bodily regulation.

In considering what might constitute effective regulation of RSA, it is important to distinguish between RSA measured at baseline (“resting” RSA) and in response to a challenge (“reactive” RSA). Differences in resting RSA are thought to reflect relatively stable, trait-like differences in regulatory style, while within-person changes in reactive RSA are believed to reflect more dynamic processes such as the engagement of regulatory processes or changes in emotional state (Beauchaine, 2001). Since we were primarily interested in regulation during a challenging go/nogo task, our main focus was on reactive RSA. Under challenging circumstances, the adaptive cardiovascular response is thought to be a decrease in RSA (i.e., decreased parasympathetic control), which mobilizes resources to deal with the situation (Porges, 1995). For example, adults who showed larger RSA decreases during a visual attention test performed better on the task (Duschek et al., 2009); children who showed larger RSA decreases in response to a sad film clip demonstrated more effective emotion regulation (Gentzler et al., 2009). Conversely, children who showed smaller RSA decreases during a peer provocation task reported poorer emotion regulation skills (Calkins and Keane, 2004; see also Gottman and Katz, 2002; Hessler and Katz, 2007). Thus, effective cardiovascular regulation should manifest as larger reactive RSA decreases during a go/nogo task.

Returning to the hypothesis that individuals who are more effective cognitive regulators should also be more effective cardiac regulators, we can now make more explicit predictions about how our measures of regulation in these domains should be related. Specifically, individuals who are more accurate on the go/nogo task and have smaller magnitude/shorter latency N2s should also have larger reactive RSA decreases. This pattern of correlations would suggest that regulation of emotional responses occurs in a coordinated fashion across these distinct modalities.

To examine the relationship between our measures of regulation in the context of emotional arousal, we combined the go/nogo task with an affect-induction procedure designed to elicit negative emotions. Participants were told that they could earn points toward a desired prize by performing well on the go/nogo task. During the experiment, point allocation was manipulated in several stages. In the first block of the task, children accumulated points rapidly. In the second block, the points algorithm was modified such that children lost all of their points, leading to feelings of frustration and sadness (Lewis et al., 2006). In the third and final block, the algorithm was restored to its original parameters, such that children earned back their points and obtained the prize. This procedure allowed us to examine the association between cardiovascular and neurocognitive regulation both in a relatively neutral or positive emotional context (i.e., in the first and third blocks) and under the influence of negative emotions (i.e., in the second block).

We predicted that during the task, a correlation between our indicators of cardiovascular and neurocognitive regulation would emerge primarily when children were experiencing negative emotions, i.e., in the second block. We anticipated that these emotions would evoke the strongest regulatory efforts, as children attempted to maintain performance in spite of emotional distress. Thus, correlations between go/nogo accuracy, N2 parameters and reactive RSA should be strongest during the second block of the task.

In addition to analyzing on-task cognitive and cardiovascular control, we also examined measures that are thought to reflect more stable, trait-like differences in regulatory abilities. On the cognitive side, we examined individual differences in effortful cognitive control using a questionnaire measure of temperament. On the bodily side, we measured RSA during a quiet baseline period. In contrast to reactive RSA, where larger decreases are thought to be the adaptive pattern, higher levels of resting RSA may indicate appropriate engagement and emotional regulation (Beauchaine, 2001; Gyurak and Ayduk, 2008), while low resting RSA is correlated with a range of internalizing and externalizing disorders (Demaree and Everhart, 2004; Leboff et al., 1997; Watkins et al., 1999). Thus, high levels of resting RSA are thought to be associated with effective cardiovascular regulation. We therefore predicted that during the resting period, children with lower RSA would also score higher on a temperament measure of trait-like cognitive regulatory abilities. Given the hypothesized dissociation between dynamic and stable indicators of regulation (Beauchaine, 2001), we did not expect that resting RSA would predict neurocognitive variables during the go/nogo task, or that RSA during the task would predict temperature differences in regulatory abilities.

Although the age range of our sample encompasses many developmental changes in the ability to regulate both cognition and emotion, few studies have examined how the measures of neurocognitive and bodily regulation that we assessed change with age. Therefore, in addition to assessing the interaction between measures of regulation across different modalities, we also analyzed developmental trends within this data set. In keeping with past results, we predicted that N2 magnitudes and latencies would decline with age (Lewis et al., 2006). Regarding possible RSA changes, although resting RSA has been found to increase over infancy and early childhood (Porges et al., 1994; Stifter and Jain, 1996; Suess et al., 1994), it appears to stabilize by middle childhood at the latest (Bornstein and Suess, 2000). Extrapolating from this, we expected that baseline RSA would not change across the period of mid- to late-childhood and adolescence that we examined. Results for reactive RSA are more mixed, with some studies reporting no change in mean reactive RSA over early childhood (Bornstein and Suess, 2000), while others have found either an effect of age (smaller RSA changes with increasing age), or no effect, depending on the task (El-Sheikh, 2005). Given the scant and mixed evidence on reactive RSA changes with development, we had no strong hypothesis about how reactive RSA might change with development in our sample.

2. Methods

2.1. Participants

Ninety-nine normally developing children and adolescents (37 female) ages 8–17 years were recruited through advertisements placed in local newspapers. All children were free from uncorrected visual impairments and psychiatric illnesses (determined by parent report and subclinical scores on the child behavior
2.2. Individual difference measure of executive function

The early adolescent temperament questionnaire—revised (EATQ) parent report form (Ellis and Rothbart, 2001) was administered as a measure of more trait-like individual differences in effortful cognitive control. Parents completed the EATQ while their children performed the go/nogo task. The effortful control scale was of primary interest to the current study. EATQ effortful control consists of the following subscales: inhibitory control, which measures the capacity to plan and to suppress inappropriate responses (e.g., “my son/daughter has a hard time waiting his/her turn to speak when excited”); activation control, which measures the ability to perform an action when there is a tendency to avoid it (e.g., “my son/daughter has a hard time finishing things on time”); and attention, which measures the ability to focus and shift attention (e.g., “my son/daughter has a difficult time tuning out background noise and concentrating”; Ellis and Rothbart, 2001). The effortful control subscales have alpha values ranging from 0.66 to 0.86, indicating acceptable reliability (Ellis and Rothbart, 2001). Moreover, EATQ effortful control has been found to predict mental health outcomes such as internalizing and externalizing disorders (Oldeninkel et al., 2007).

Although not of primary interest, we also report the results of analyses conducted on the other EATQ scales for completeness. These scales measure dispositional fear, frustration, shyness, aggression, depressive mood, affiliation, and surgency.

2.3. Procedure

Children were accompanied to the laboratory by a parent. Following a brief orientation to the procedures, parental consent and child assent were obtained. For a subset of 36 children, measures of resting RSA were obtained before beginning the go/nogo experiment. The electrocardiography (ECG) electrodes were applied to the child, and the child and his/her parent engaged in a 20 min discussion task, part of a separate experiment that will be reported elsewhere. The discussion task consisted of 15 min of conversation about positive and negative topics, followed by 5 min of quiet, seated rest during which parents and children were instructed not to interact. The conversation period allowed children to become comfortable with the experimental setting, the experimenter and the ECG apparatus before resting RSA was collected. ECG data from the final 2 min of the rest period were used to compute resting RSA. To ensure that the rest period was not contaminated by excessive activity, the session was videotaped and footage of the rest period was visually inspected. If activity in the form of large movements or talking was noticed, we selected a different 2 min period where the behavior was calm for analysis. Children were generally quiet during this phase and no data had to be discarded due to overactivity.

The go/nogo experiment took place in a different facility. For children who completed the discussion task, approximately 1 h elapsed between the two experiments. In the go/nogo task, children were informed they would be playing a computer game in which they could earn points by responding correctly. They were told that if they performed well by accumulating many points, they would win a desirable toy or gift certificate; if they performed poorly, they would receive a smaller, less desirable toy. This contingency between performance and reward was important to enhance motivation, since children have difficulty attending to boring tasks for extended periods in the service of long-term rewards (e.g., participant payments). To enhance motivation, children were allowed to choose a toy they would like to earn before the start of the game. Children were seated in front of a computer monitor after which the ECG sensor net and ECG electrodes (for children who did not complete the discussion task) were applied. A chin rest was used to control head position, body posture and distance from the monitor. Responses were made by pressing a button on a response pad with the index finger of the dominant hand. Thirty practice trials were given, and more practice trials were provided if needed.

2.4. ERP task and emotion induction

In our go/nogo task, children were instructed to press the button as quickly as possible each time a letter was presented, but to withhold responding when the same letter was presented twice in a row. A nogo error rate of 50 ± 10% was maintained by dynamically adjusting stimulus durations: stimulus duration was increased following each error on a nogo trial and decreased following each correct response on a nogo trial that was preceded by a correct go trial. After the practice period, children were presented with three blocks of trials (A, B, and C). In Block A, children gained points rapidly. In Block B, the points algorithm was modified so that children lost all or most of their points, a manipulation that we have previously shown to induce negative emotions such as frustration, sadness and anger (Lewis et al., 2002). In Block C, the original parameters of the go/nogo task were restored, children earned their points back and all were able to win the desired prize. Blocks A and C each consisted of 200 trials including 66 nogo trials, presented in pseudorandom order. Block B consisted of only 150 trials with 40 nogo trials, to limit the duration of any emotional distress associated with the loss of points. In all blocks, the number of points earned was displayed on a feedback screen every 5–25 trials so as to highlight gains and losses. If the child had lost points since the previous feedback screen, an unpleasant buzzing sound was played and the number of points lost was displayed in red. If the child had gained points since the previous feedback screen, a pleasant tinkling sound was played and the points were displayed in green.

2.5. Analysis of behavioral data

In go/nogo paradigms, perseverative responding leads to high accuracy on go trials and low accuracy on nogo trials, while chronic non-responding leads to high accuracy on nogo trials and low accuracy on go trials. For statistical analysis, we therefore computed the average accuracy of go and nogo trials to provide an overall indication of accuracy on both trial types. Reaction time was computed from the onset of the stimulus to the beginning of a correct (go) or incorrect (nogo) button press.

2.6. Event-related potential acquisition and scoring

EEG was recorded using a 128-channel geodesic sensor net and sampled at 250 Hz, using EGI software (Electrical Geodesic Inc., Eugene, OR). Impedances for all channels were kept below 50 kΩ when the task began, which is acceptable for the ‘wet’ geodesic system. All channels were referenced to Cz during recording and later rereferenced against an average reference (Bertrand et al., 1985; Tucker et al., 2001; Falkenstein et al., 1999). ECG electrodes were applied with the index finger of the dominant hand. Thirty practice trials were given, with the distance from the monitor. Responses were made by pressing a button on a response box. A chin rest was used to control head position, body posture and sensor net and ECG electrodes (for children who did not complete the discussion task) were applied. A chin rest was used to control head position, body posture and RSA data were collected. ECG data from the final 2 min of the rest period were used to compute resting RSA. To ensure that the rest period was not contaminated by excessive activity, the session was videotaped and footage of the rest period was visually inspected. If activity in the form of large movements or talking was noticed, we selected a different 2 min period where the behavior was calm for analysis. Children were generally quiet during this phase and no data had to be discarded due to overactivity.

2.7. ECG acquisition and RSA analysis

ECG data were acquired at a sampling rate of 1000 Hz using a BIOPAC MP150 system (BIOPac Systems Inc., Goleta, CA), with electrodes positioned diagonally across the heart in a standard Lead II configuration. Data analysis was conducted using ANSLab software (Wilhelm et al., 1999). After automatic R-wave detection, each file was inspected for artifacts. Small artifacts were corrected when possible by adding or deleting R-wave markers. Files that contained large artifacts or smaller artifacts that could not be corrected were excluded from further analysis. Eight files from the ERP session were discarded for this reason; no files from the resting period were discarded. The R–R interval series was then converted into a time series with a sample rate of 4 Hz. Data were linearly detrended using a 0.01 Hz lowpass filter, and power spectral densities were computed for each period of interest (block or resting period) using the Welch algorithm. RSA was calculated by summing the power spectral density values across the bands related to respiration (0.14–0.3 Hz). Finally, these values were normalized using the natural logarithm.

Studies that examine RSA in response to a challenge commonly calculate a difference score between resting and task conditions, as an indicator of RSA reactivity (e.g., Beauchaine, 2001; Butler et al., 2006; S.D. Calkins et al., 2007). In our experiment, the rest phase and go/nogo task occurred in quite distinct experimental settings (different facilities, different apparatus) and were separated by a significant amount of time (∼1 h). As such, we were concerned that RSA difference scores would be confounded by motor processing for the go trials, and an oddball effect for the infrequent nogo trials (see for example Bekker et al., 2005; Donkers and van Bostel, 2004; Falkenstein et al., 1999; Nieuwenhuis et al., 2003).

Grand-averaged ERPs revealed maximal activation for the N2 at electrodes Fz and FCz. Based on these findings, an average of Fz and FCz was used to analyze RSA activation.
would be contaminated by excessive noise due to these factors. Indeed, in preliminary analyses we found that aside from a single unpredicted correlation, there was no relationship between RSA difference scores and any of our neurocognitive variables. However, absolute RSA measured during the go/nogo task was significantly associated with a number of variables of interest (see Section 3). When we report reactive RSA we are therefore referring to absolute RSA as measured during the go/nogo task.

3. Results

3.1. Effects of age and block on RSA, behavior and ERPs

Age effects were examined by subdividing the age span into five periods (ages 8–9 years, n = 30; 10–11 years, n = 24; 12–13 years, n = 23; 14–15 years, n = 11; 16–17 years, n = 11). Although behavioral and ERP results from the go/nogo task are reported in more detail elsewhere (Lamm and Lewis, 2010), we present an overview of these data below to facilitate interpretation of relationships between RSA and the neurocognitive variables.

3.1.1. Behavioral analyses

A 5 (age group) × 3 (block) mixed-measures ANOVA revealed significant main effects of age (F(4,87) = 5.70, p < 0.001) and block (F(2,174) = 286, p < 0.001) on combined go/nogo accuracy. Older children were more accurate than younger children, and accuracy decreased for all age groups from Block A to Block B, but recovered fully at Block C (Table 1; quadratic pattern: F(1,87) = 573, p < 0.001). Thus, the emotion induction compromised performance at all ages, but older children were more accurate overall.

Reaction times were analyzed separately for go and nogo trials, yielding similar results for the two trial types. For both go and nogo trials, there was a main effect of age, with older children showing faster reaction times than younger children (go trials, F(4,88) = 10.2, p < 0.001; nogo trials, F(4,88) = 11.1, p < 0.001). As given in Table 1, go and nogo reaction times also showed a main effect of block (go trials, F(2,176) = 153, p < 0.001; nogo trials, F(2,176) = 63.0, p < 0.001), with reaction times decreasing from Block A to Block B, and recovering only slightly in Block C (quadratic pattern for go trials: F(1,88) = 92.8, p < 0.001; for nogo trials: F(1,88) = 91.2, p < 0.001). The combination of faster reaction times and decreased accuracy during Block B suggests greater impulsivity under conditions of emotional arousal, or an effort to regain points through quicker responding. Incomplete recovery of reaction times in Block C could reflect several factors. One possibility is that the effects of the emotion manipulation might persist even as points were regained, resulting in decreased reaction times. Alternatively, given that children were accurate as well as fast during Block C, decreased reaction times in this block could indicate a practice effect.

3.1.2. EATQ analyses

Age was not correlated with EATQ effortful control scores (p > 0.4), or with any other EATQ scale (all p-values > 0.1). Although regulatory control presumably does improve with age, as suggested by improved speed and accuracy on the go/nogo task, the EATQ appears to tap more stable aspects of temperamental regulatory ability.

3.1.3. ERP analyses

We found a main effect of age on N2 magnitudes (F(4,60) = 3.90, p < 0.05), with older children showing smaller magnitudes. The effect of block was not significant (F < 1). Similarly, there was an effect of age on N2 latencies (F(4,60) = 5.23, p < 0.001); older children had shorter latencies. There was no significant effect of block on latencies (F < 1). Fig. 1 shows a grand-averaged ERP waveform collapsed across blocks and age groups.

3.1.4. RSA analyses

The mean resting RSA value was 8.05 ms² (SD = 1.29). A one-way ANOVA on resting RSA showed no significant effect of age (F < 1). To examine RSA during the go/nogo task, a 5 (age group) × 3 (block) mixed-measures ANOVA was conducted. We found no main effect of age (F < 1) and no age × block interaction (F < 1). However, there was a significant main effect of block (F(2,140) = 6.43, p < 0.01). RSA decreased from Blocks A to C in a linear fashion (Table 1; linear pattern: F(1,70) = 10.63, p < 0.01). No significant quadratic pattern was evident (F(1,70) = 1.79, p > 0.1). The RSA decrease from Blocks A to B could reflect the negative emotions induced by losing points. Indeed, negative emotional states have previously been found to be associated with RSA decreases (Calkins, 1997; Calkins and Keane, 2004; Forbes et al., 2006; Thayer et al., 1996). However, on this account it is somewhat surprising that RSA did not rebound in Block C, when points were regained. One possibility is that negative emotions from Block B may have carried over into Block C, as suggested by the lack of reaction time increase during Block C (although as discussed above, this could also be due to a practice effect). Alternatively, the desire to regain points in Block B could have evoked a state of challenge or general emotional arousal that continued into Block C. Behavioral challenge and arousal (independent of valence) are also associated with decreases in RSA (Brenner et al., 2005; Duschek et al., 2009; Frazier et al., 2004; Movius and Allen, 2005).

Fig. 1. Grand-averaged ERP waveform at electrode FCz, collapsing across blocks and age groups. Activation is shown as negative down.
3.2 Relationships between indicators of cardiovascular and neurocognitive regulation

3.2.1. During the resting period

RSA during the rest period was significantly correlated with the EATQ Effortful Control scale (r = 0.370, p < 0.05). As shown in Fig. 2, children with higher resting RSA had higher effortful control scores, suggesting a better ability to control emotional responses in spite of more maladaptive tendencies. This was consistent with our overall prediction concerning the regulatory advantage of high resting RSA. Resting RSA was also negatively correlated with scores on the EATQ Aggression scale (r = −0.34, p < 0.05); children with lower resting RSA showed more aggressive behaviors. No other EATQ scales showed significant correlations with resting RSA (all p’s > 0.1). RSA during the go/nogo task was not correlated with any other EATQ scale (all p’s > 0.15).

3.2.2. During the go/nogo task

To assess the relationship between cardiovascular and neurocognitive measures during the task, we conducted Pearson correlations between RSA and go/nogo accuracy, reaction times and N2 magnitudes and latencies. The correlation analyses required usable data in each pair of modalities examined, resulting in decreased sample sizes for these tests (range 51–73 participants). As predicted, we found that lower RSA during Block B was significantly correlated with smaller N2 magnitudes only during Block B (Table 2, Fig. 3A; r = −0.36, p < 0.01). In contrast to this specificity, N2 latencies were correlated with RSA in a number of cells of the matrix, including off-diagonals (Table 3). For illustration, Fig. 3B and C shows the correlation between N2 latencies and RSA during Blocks B and C, respectively; off-diagonal correlations were of similar appearance. The less focused pattern of correlations between N2 latencies and RSA suggests that the emotion manipulation had little effect on the relationship between these measures.

We also found a relationship between RSA and go/nogo accuracy. As shown in Table 4, lower RSA was correlated significantly or at trend level with accuracy during all three blocks, again including off-diagonals. Similar to the N2 latencies, this suggests that the emotion manipulation had little effect on the relationship between RSA and behavioral accuracy; rather, these relationships extended across blocks. RSA was not significantly associated with reaction times during any block.

Because of the significant effects of age on N2 amplitudes and accuracy, we ran partial correlations between RSA and the neurocognitive variables while controlling for age. Controlling for age did not change the pattern of significant correlations with RSA for N2 magnitudes, N2 latencies or go/nogo accuracy.

In a final series of analyses, we tested whether resting RSA was associated with any on-task neurocognitive variables. Resting RSA was not associated with N2 latencies, magnitudes, or go/nogo accuracy (all p’s > 0.1).

4. Discussion

This study examined the relationship between indicators of cardiovascular and neurocognitive regulation in children and adolescents. We found associations between our measures both during a resting baseline and when children were faced with a behavioral challenge, namely the need to maintain go/nogo performance during and after an emotion-induction procedure. During the baseline period, we found a relationship between RSA and an individual difference measure of effortful cognitive control. During the go/nogo task, a relationship between RSA and N2 magnitudes was observed only during Block B, when children were actively losing points. By contrast, RSA was correlated with N2 latencies and with behavioral accuracy during most blocks, suggesting that these relationships hold even under less arousing conditions.

Taken together, these results are consistent with the hypothesis that children who are better bodily regulators are also better cognitive regulators. At rest, higher RSA is thought to reflect an adaptive regulatory style, indicating physiological flexibility and allowing for appropriate emotional reactivity (Beauchaine, 2001; Porges, 1995).

Table 2: Relationship between N2 magnitudes and RSA during the go/nogo task.

<table>
<thead>
<tr>
<th></th>
<th>Block A RSA</th>
<th>Block B RSA</th>
<th>Block C RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A N2 magnitude</td>
<td>r = −0.017</td>
<td>r = −0.23</td>
<td>r = −0.169</td>
</tr>
<tr>
<td></td>
<td>p = 0.906</td>
<td>p = 0.098</td>
<td>p = 0.237</td>
</tr>
<tr>
<td>Block B N2 magnitude</td>
<td>r = −0.166</td>
<td>r = −0.36</td>
<td>r = −0.263</td>
</tr>
<tr>
<td></td>
<td>p = 0.245</td>
<td>p = 0.009**</td>
<td>p = 0.062</td>
</tr>
<tr>
<td>Block C N2 magnitude</td>
<td>r = −0.007</td>
<td>r = −0.0179</td>
<td>r = −0.139</td>
</tr>
<tr>
<td></td>
<td>p = 0.959</td>
<td>p = 0.209</td>
<td>p = 0.332</td>
</tr>
</tbody>
</table>

** p < 0.01.

Table 3: Relationship between N2 latencies and RSA during the go/nogo task.

<table>
<thead>
<tr>
<th></th>
<th>Block A RSA</th>
<th>Block B RSA</th>
<th>Block C RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A N2 latency</td>
<td>r = 0.12</td>
<td>r = 0.13</td>
<td>r = 0.17</td>
</tr>
<tr>
<td></td>
<td>p = 0.374</td>
<td>p = 0.332</td>
<td>p = 0.203</td>
</tr>
<tr>
<td>Block B N2 latency</td>
<td>r = 0.26</td>
<td>r = 0.322</td>
<td>r = −0.21</td>
</tr>
<tr>
<td></td>
<td>p = 0.071</td>
<td>p = 0.021**</td>
<td>p = 0.074</td>
</tr>
<tr>
<td>Block C N2 latency</td>
<td>r = 0.321</td>
<td>r = 0.253</td>
<td>r = 0.345</td>
</tr>
<tr>
<td></td>
<td>p = 0.017</td>
<td>p = 0.063</td>
<td>p = 0.01**</td>
</tr>
</tbody>
</table>

* p < 0.05.

** p < 0.01.

Table 4: Relationship between behavioral accuracy and RSA during the go/nogo task.

<table>
<thead>
<tr>
<th></th>
<th>Block A RSA</th>
<th>Block B RSA</th>
<th>Block C RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A accuracy</td>
<td>r = −0.20</td>
<td>r = −0.23</td>
<td>r = −0.27</td>
</tr>
<tr>
<td></td>
<td>p = 0.091</td>
<td>p = 0.051</td>
<td>p = 0.022</td>
</tr>
<tr>
<td>Block B accuracy</td>
<td>r = −0.17</td>
<td>r = −0.183</td>
<td>r = −0.21</td>
</tr>
<tr>
<td></td>
<td>p = 0.142</td>
<td>p = 0.121</td>
<td>p = 0.074</td>
</tr>
<tr>
<td>Block C accuracy</td>
<td>r = −0.34</td>
<td>r = −0.37</td>
<td>r = −0.38</td>
</tr>
<tr>
<td></td>
<td>p = 0.004**</td>
<td>p = 0.001**</td>
<td>p = 0.001**</td>
</tr>
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</table>

* p < 0.05.

** p < 0.01.
while low resting RSA is associated with a variety of psychopathologies (Demaree and Everhart, 2004; Lehofer et al., 1997; Watkins et al., 1999). The positive association that we found between resting RSA and EATQ effortful control scores suggests that a stable temperamental trait indexing effective cognitive regulation is also correlated with high resting RSA. Moreover, the negative relationship found between resting RSA and EATQ aggression scores further supports the notion that high RSA during a resting state indicates better control over one’s emotions, particularly activating ones such as aggression. In contrast to resting RSA, lower RSA during a behavioral challenge, or “reactive” RSA, is thought to be correlated with high resting RSA. Moreover, the negative relationship between RSA and N2 latencies suggests that a stable association between RSA and N2 latencies may reflect individual differences in emotional regulation that mimics cortical maturation, requiring fewer resources to maintain performance.

The emotion-induction procedure had mixed effects on the relationship between reactive RSA and neurocognitive variables. We originally hypothesized that correlations would primarily emerge during Block B, when the need for self-control in the face of negative emotions is strongest. That was indeed the case for reactive RSA and N2 magnitudes, which were only correlated during Block B. However, N2 latencies and behavioral accuracy were correlated with reactive RSA during a number of blocks, including off the diagonal (e.g., N2 latencies in Block C were correlated with RSA during all three blocks). This suggests that while the association between RSA and N2 magnitudes may reflect individual differences in emotional regulatory abilities, the association between RSA and N2 latencies/accuracy may reflect more a general capacity for on-task self-control. The lack of specificity for behavioral accuracy is consistent with other work showing an association between RSA and attentional performance in the absence of emotional arousal (DeGangi et al., 1993; Duschek et al., 2009). Alternatively, it may be that general emotional arousal, independent of positive or negative valence, underlies the relationship between RSA and N2 latencies/behavioral accuracy (Brenner et al., 2005; Frazier et al., 2004).

An outstanding issue is whether the associations we observed between cognitive and bodily regulation will hold for other control processes. Cognitive control is often conceptualized as a suite of executive functions, of which inhibitory control is just one. Similarly, we examined only one aspect of bodily control: parasympathetic regulation of the heart. One possibility is that other aspects of cognitive and bodily control may not be as well-integrated as the ones we examined. Indeed, some cognitive control strategies, such as suppressing the external signs of emotion, have counterproductive effects on bodily arousal (Gross and Levenson, 1993). On the other hand, it is possible that a brain area such as the ACC serves as an integration region, whose function may be to coordinate cognitive states with bodily arousal in the service of adaptive behavior (Critchley, 2005).

To our knowledge, this is the first research to demonstrate an association between regulation of neurocognitive and cardiovascular systems. Given the exploratory nature of our work, we did not perform a statistical correction for multiple comparisons, and replication will be needed to confirm the observed associations. An additional limitation is that we were not able to compute a difference score between resting RSA and RSA during the go/nogo task, as is commonly performed. This was unavoidable, since our facilities for the resting and ERP tasks were located in different buildings.
While we have shown a relationship between absolute RSA during the go/no-go task and neurocognitive variables, future work should examine whether RSA change is similarly associated with these variables. It is also unclear why no block effect was found for the N2 magnitudes. However, in spite of the null effect of block at the group level, we still observed an association between individual differences in N2 magnitudes and RSA during the go/no-go task, suggesting that the relationship between cognitive and bodily indicators of regulation is important.

Lastly, our experimental design did not include a neutral control condition. Blocks A and C were associated with reward, as children gained points, while Block B was punishing due to the loss of points. This was a calculated trade-off: unlike adults, children have great difficulty in attending to boring tasks for long periods. We have argued elsewhere that such age differences in motivation could contribute to discrepancies among studies that have investigated the neurodevelopmental correlates of executive functioning (Lewis et al., 2006). The design of our task therefore highlighted the need to examine effects of valence and arousal independently.

In conclusion, the results of this study indicate a relationship between parasympathetic control of the heart and several aspects of cognitive regulation, including behavioral and ERP correlates of inhibitory control and more stable differences in effortful control of cognitive regulation, including behavioral and ERP correlates of the N2 component of the ERP: a review. Psychophysiology 45 (1), 152–170.


