Fifty 8-month-old infants participated in a study of the interrelations among cognition, temperament, and electrophysiology. Better performance on a working memory task (assessed using a looking version of the A-not-B task) was associated with increases in frontal–parietal EEG coherence from baseline to task, as well as elevated levels of frontal–occipital coherence during both baseline and task. Enhanced performance was also associated with decreased heart period (increased heart rate) from baseline to task. Infants with better working memory performance had parents who rated them high on activity level and distress to limitations. When considered collectively, EEG coherence and heart period contributed unique variance in the prediction of high and low performance groups. Implications for the study of infant cognition are discussed.

There are dramatic improvements in cognitive control abilities (i.e., working memory, inhibitory control, sustained attention) across infancy. Recent neuroscience evidence allows for empirical support, as well as much speculation, regarding the development of brain systems associated with these critical changes in early cognitive behavior (Casey, Tottenham, Listen, & Durston, 2005; Diamond, 2002). Yet, all infants do not improve in their cognitive control abilities at the same rate (Diamond, Prevor, Callender, & Druin, 1997). Even among a group of normally developing infants, there may be great variability in cognitive performance and in brain electrical activity measures of maturation and task performance (Bell, 2001; Bell & Fox, 1992). Other factors, such as infant temperament or parenting may affect developmental trajectories in cognitive development because they may alter either brain structure or functioning (Colombo & Saxon, 2002; Diamond & Amso, 2008). The purpose of this study was to investigate the interrelations among three factors that have been theoretically and empirically linked with infant cognitive control, specifically working memory. These factors are brain electrical activity (the electroencephalogram [EEG]), cardiac activity (heart period), and temperament. Thus, this work took a psychobiological perspective on infant working memory.

Infant working memory is typically measured using looking A-not-B or delayed response tasks that focus on infants’ abilities to remember the spatial location of hidden objects (Diamond, 1990). During these tasks, infants constantly form and update temporary representations of objects and their locations (Reznick, 2007). The value of these tasks is that performance relies on the propensity of infants to search, by looking, for an intriguing hidden object without the need for explicit task instructions (Schwartz & Reznick, 1999). Successful performance on the tasks also requires infants to inhibit looking toward a previously rewarded hiding location and instead look at the current correct location (i.e., success requires inhibitory control). In addition, successful search likely requires effortful or sustained attention throughout task performance (Bell & Adams, 1999; Diamond et al., 1997).

These characteristics may make the infant working memory task qualitatively different from child and adult versions of the task, which tend to rely on verbal instructions and require unambiguous working memory skills (e.g., backwards digit span tasks, n-back tasks). However, several recent cross-sectional and longitudinal studies provide evidence of quantitative developments in working memory performance between 5 and 12 months of age.
These quantitative changes are evidenced by increasing percentages of correct search with age and increasing amount of delay tolerated between hiding and search with age (Cuevas & Bell, 2010a; Hofstadter & Reznick, 1996; Matthews, Ellis, & Nelson, 1996; Pelphrey et al., 2004). These task characteristics and the cognitive skills required for successful task performance make infant working memory tasks an important resource for the examination of information processing during the 1st year (Diamond, 2002; Noland, Reznick, Stone, Walden, & Sheridan, 2010).

EEG Coherence

Infant EEG recorded during working memory tasks exhibits an increase in 6–9 Hz power values, relative to baseline, at both anterior and posterior scalp locations (Bell, 2001, 2002; Bell & Wolfe, 2007; Orekhova, Stroganova, & Posikera, 2001). EEG coherence values can provide additional information regarding frontal scalp electrical activity during cognitive processing. Coherence is the frequency-dependent squared cross-correlation of electrical signals between two scalp electrode sites (Nunez, 1981; Thatcher, Krause, & Hrybyk, 1986). Coherence values range from 0 to 1, and Thatcher (1994) has proposed that coherence is a designation of the strength and number of synaptic connections and, thus, is reflective of the level of connectivity between two scalp electrode sites (and, perhaps, two cortical areas). Higher coherence values indicate that cortical regions are intricately linked and working together. Unlike EEG power values, EEG coherence is not affected by arousal, opening or closing of eyes, or changes in state (Thatcher, 1994). Thus, coherence values may be reflective of brain organization (Thatcher, 1994) and may be useful in describing developmental changes in this organization (Thatcher et al., 1986). Thatcher et al. (1986) have reported that the frontal region is strongly coupled to the posterior regions via long-distance axonal connections and that the frontal areas appear to be the driving force in coherence development (Thatcher, 1994).

Task-related changes in EEG coherence relative to baseline have been reported for infants. Globally, coherence values decrease from baseline to task across the entire scalp during an infant working memory task (Bell & Wolfe, 2007). That is, during cognition the separate cortical areas are more likely to work independently, as opposed to in conjunction with each other. An exception is the frontal–parietal electrode pairs. Among 8-month-old infants, there is greater frontal–parietal coherence during task performance than at baseline, meaning that these areas of the cortex are working together during the task (Bell, 2001). This infant finding replicates recent functional magnetic resonance imaging work with children (Nelson et al., 2000) and adults (Ungerleider, Courtney, & Haxby, 1998) implicating frontal and parietal interactions during spatial working memory tasks.

Heart Period

Cardiac measures frequently are used to assess physiological changes associated with cognitive processing in infants (Fox, Schmidt, Henderson, & Marshall, 2007). Heart period and its inverse measure of heart rate are the most frequently used measures of attentional state (e.g., Richards & Casey, 1992) and sustained attention may be similar to working memory during infancy (Diamond et al., 1997). Two attention-related heart rate patterns are found in the developmental literature. The first pattern, evident in early infancy, involves an orienting response to a stimulus that is marked by an abrupt decrease in heart rate. The resulting engagement of attention is associated with sustained lower heart rate (i.e., higher heart period) and then acceleration back to baseline levels with attention termination (Richards & Casey, 1992). A second pattern of attentional response occurs during a stressor, such as a challenging mental task, and is associated with an increase in heart rate or a decrease in heart period (Manuck, Kasprowicz, & Muldoon, 1990). This second pattern is more likely to emerge near the end of the 1st year of life in association with the development of anterior attention system (Ruff & Rothbart, 1996), similar in conceptualization to Posner’s executive attention system (Posner & Rothbart, 2000).

Temperament

Early infancy is marked by reactivity to distressful and frustrating internal and environmental events. With the emergence of attentional and inhibitory processes late in the 1st year associated with developmental of the frontal lobes, infants begin to exhibit primitive voluntary regulation of distress (Posner & Rothbart, 2000; Rothbart & Bates, 2006; Rothbart, Derryberry, & Posner, 1994). Individual differences in emotion reactivity and emotion regulation are based on some combination of constitutional and socialized factors (Rothbart, Posner, & Rosiky, 1994). These individual differences
have been the focus of temperament research examining social development (Rothbart & Bates, 2006).

The emergence of these early regulatory processes may have implications for cognitive development as well (Rothbart, Derryberry, et al., 1994). Late in the 1st year, infants begin to exhibit inhibitory control on working memory tasks (Diamond, 1990; Diamond, Cruttenden, & Neiderman, 1994; Diamond et al., 1997). Differences among same-age infants in task performance are considered to reflect differences in maturation of brain regions associated with various aspects of task performance, including frontal cortex (Bell, 2001; Bell & Fox, 1992, 1997). It may be, however, that the inhibitory processes associated with cognitive behaviors are similar to those associated with temperament. Indeed, there is much speculation in the infant literature that some relation exists between temperament and cognitive processing (e.g., Fox, 1994; Posner & Rothbart, 2007; Rothbart, Posner, & Boylan, 1990; Ruff & Rothbart, 1996), although few studies have explored the development of these associations during infancy. There are reports of infant temperament being correlated with performance on recognition memory and novelty preference tasks (e.g., Miceli, Whitman, Borkowski, Braungart-Rieker, & Mitchell, 1998; Ohr, Fleckenstein, Fagen, Klein, & Pioli, 1990; Wachs, Morrow, & Slabach, 1990). Only one study has reported associations between infant temperament and working memory; however, the work was done with extremely low birth weight infants when they were 18–22 months of age (Lowe, MacLean, Shaffer, & Watterberg, 2009). Keenan (2002) reported that negative affect resulted in lower levels of performance on the A-not-B task, but this was measured as negative emotion (on a scale from 1 to 5) during participation in A-not-B testing, not as a temperamental trait.

Research Questions and Hypotheses

These previous findings from the developmental neuroscience and psychobiology literatures led to the following research questions and hypotheses associated with this study:

1. **Which EEG coherence pairs are the best indicators of infant working memory performance?** Based on previous electrophysiological and functional magnetic resonance imaging work, it was hypothesized that frontal–parietal EEG coherence would discriminate high and low performance on the task. Specifically, better performance would be associated with an increase in coherence between frontal and parietal scalp locations relative to baseline coherence values.

2. **Do heart period values distinguish better from poorer infant working memory performance?** It was hypothesized that better performance would be associated with a decrease in heart period (i.e., an increase in heart rate) from baseline to task and that worse performance will not be associated with a heart period change between baseline and task.

3. **Which temperament measures are most closely linked with infant working memory performance?** It was hypothesized that attentional and regulatory aspects of temperament would be associated with working memory performance.

4. **How do EEG, heart period, and temperament together predict high and low working memory performance during infancy?** It was proposed that EEG coherence, heart period, and temperament would collectively discriminate high and low performance, with each contributing unique variance.

Method

Participants

Fifty healthy 8-month-old infants (28 male, 22 female; 46 Caucasian, 1 African American, 1 Asian American, 1 Hispanic, 1 Native American) were recruited from birth announcements placed in the local newspaper in a small college town in the mid-Atlantic area. Infants were born to parents with at least a high school diploma. Seventy-nine percent of the mothers had college degrees, as did 82% of the fathers. Mothers were approximately 29 years old (range = 18–39) and fathers were approximately 30.5 years old (range = 20–47). All infants were full term and were healthy at the time of testing. Infants were seen when they were between 8.0 and 8.5 months of age, so that only 2 weeks separated the oldest and youngest infants in the study. Parents were paid for their infants’ participation in the study. Eight-month-olds were the focus of this work because of the variability in working memory performance at this age (e.g., Bell & Adams, 1999; Diamond et al., 1997).

Procedure

Upon arrival at the research lab, parents were shown the electrophysiological equipment and all research procedures were explained. After obtaining
written parental consent, EEG, and ECG electrodes were applied and 1 min of baseline physiology was recorded. Electrodes remained on the scalp and chest during the working memory task.

**EEG recording.** EEG recordings were accomplished during baseline and during a working memory task. Recordings were made from 16 left and right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), central (C3, C4), anterior temporal (T3, T4), posterior temporal (T7, T8), parietal (P3, P4), and occipital (O1, O2). All electrode sites were referenced to Cz during recording.

Baseline EEG was recorded for 1 min while the infant sat on mother’s lap. During the baseline recording, a research assistant manipulated a toy containing brightly colored balls on top of the testing table, 1.1 m in front of the infant. This procedure quieted the infant and yielded minimal eye movements and gross motor movements, thus allowing the infant to tolerate the EEG cap for the recording. Mothers were instructed not to talk to infants during the EEG recording. Immediately after baseline, the working memory task was administered.

EEG was recorded using a stretch cap (ElectroCap, Inc., Eaton, OH) with electrodes in the 10/20 system pattern. After the cap was placed on the head, recommended procedures regarding EEG data collection with infants and young children were followed (Pivik et al., 1993). Specifically, a small amount of abrasive was placed into each recording site, and the scalp was gently rubbed. Following this, conductive gel was placed in each site. Electrode impedances were measured and accepted if they were below 5000 ohms. EOG, digitized along with the EEG channels and used for subsequent artifact editing, was recorded using disposable electrodes. Electrodes were placed on the external canthus and the supra orbit of the right eye.

The electrical activity from each lead was amplified using separate SA Instrumentation Bioamps and bandpassed from 0.1 to 100 Hz. Activity for each lead was displayed on the monitor of an acquisition computer. The EEG signal was digitized on-line at 512 samples per second for each channel so that the data were not affected by aliasing. The acquisition software was Snapshot-Snapstream (HEM Data Corp., Southfield, MI) and the raw data were stored for later analyses. Prior to the recording of each subject a 10 Hz, 50 μV peak-to-peak sine wave was input through each amplifier. This calibration signal was digitized for 30 s and stored for subsequent analysis.

Spectral analysis of the calibration signal and computation of power at the 9–11 Hz frequency band was accomplished. The power figures were used to calibrate the power derived from the subsequent spectral analysis of the EEG. EEG data were examined and analyzed using EEG Analysis System software developed by James Long Company (Caroga Lake, NY). First, the data were re-referenced via software to an average reference configuration (Lehmann, 1987). Average referencing, in effect, weighted all the electrode sites equally and eliminated the need for a noncephalic reference. Active (F3, F4, etc.) to reference (Cz) electrode distances vary across the scalp. Without the re-referencing, power values at each active site may reflect interelectrode distance as much as they reflect electrical potential. For example, using an infant EEG sample that was recalculated with three different reference montages, Stroganova and Orekhova (2007) showed that average reference and linked ears montages exhibit similar EEG rhythms at the same scalp locations, whereas the Cz reference montage yields a pattern of amplitude changes at very different scalp sites, especially for the electrode sites furthest away from Cz. The average reference configuration requires that a sufficient number of electrodes be sampled and that these electrodes be evenly distributed across the scalp. Luck (2005) has demonstrated with event-related potential recordings that voltage can be affected by average reference montage when only midline electrodes, as opposed to an entire scalp of electrodes, are used. Currently, there is no agreement concerning the appropriate number of electrodes (Davidson, Jackson, & Larson, 2000; Hagemann, Naumann, & Thayer, 2001; Luck, 2005), although the 10/20 configuration that we used does satisfy the requirement of even scalp distribution. Average referencing is considered the optimal configuration when computing coherence between spatially distinct electrodes (Fein, Raz, Brown, & Merrin, 1988).

The average reference EEG data were artifact scored for eye movements using a peak-to-peak criterion of 100 μV or greater. Transfer of eye movements is significant in the 0–6 Hz frequency band and transfer for eye blinks occurs as high as adult alpha band (8–13 Hz) frequencies (Gasser, Sroka, & Mocks, 1985). However, blink artifacts were readily identified via visual inspection of the EEG and artifact scored. An EOG correction algorithm was not used because algorithms remove power across the entire scalp across all frequency bands (Somsen & van Beek, 1998), thus filtering out some of the maturation change in frontal EEG power. Selecting
artifact-free data yielded a more accurate portrayal of the EEG developmental record (Somsen & van Beek, 1998).

Artifact associated with gross motor movements over 200 μV peak to peak was also scored. These artifact-scored epochs were eliminated from all subsequent analyses. The data then were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1 s width and 50% overlap. Power was computed for the 6–9 Hz frequency band. Infants 8 months of age have a dominant frequency between 6 and 9 Hz (Bell & Fox, 1992; Marshall, Bar-Haim, & Fox, 2002), and this particular frequency band discriminates baseline EEG from task EEG, as well as correct from incorrect responses, during an infant working memory task (Bell, 2001, 2002). The power was expressed as mean square microvolts and the data transformed using the natural log (ln) to normalize the distribution. Coherence between medial frontal and all other electrode sites within each hemisphere was computed for the 6–9 Hz band using an algorithm by Saltzberg, Burton, Burch, Flechter, and Michaels (1986).

Heart period recording. Cardiac activity also was measured during baseline and task from two neonatal disposable electrodes using modified lead II (right collarbone and lower left rib; Stern, Ray, & Quigley, 2001), grounded at the scalp near electrode site Fz. The cardiac electrical activity was amplified using a SA Instrumentation Bioamp and the QRS complex was displayed on the acquisition computer monitor along with the EEG data. The cardiac signal was digitized at 512 samples per second. The acquisition software was Snapshot-Snapp-stream (HEM Data Corp.) and the raw data were stored for later analyses.

Heart data were examined and analyzed using IBI Analysis System software developed by James Long Company. First, R waves were detected and movement artifact, designated by the absence of at least three consecutive R waves, was scored. These artifact-scored epochs were eliminated from all the calculation of interbeat intervals. Heart period, the time between R waves (interbeat interval, IBI), was calculated in milliseconds. Heart period variability was calculated as the standard deviation of the IBI.

Working memory task. The testing apparatus was a table measuring 90 cm (L) × 60 cm (W) × 75 cm (H) and the hiding sites were bright orange and blue plastic tubs that measured 17 cm in diameter and 11 cm deep. The infant sat on the parent’s lap 1.1 m from the edge of the testing table as the experimenter manipulated a mechanical toy and hid it under one of the two (17.5 cm on either side of midline) plastic tubs. The infant searched for a hidden toy by making an eye movement to one of two possible hiding locations. Much like the reaching version of the infant working memory task (the classic A-not-B task), the looking version required the infant to constantly update memory of where the toy was hidden through a series of displacements and to inhibit looking back toward a previously rewarded hiding place (Bell, 2001; Bell & Adams, 1999; Diamond, 1990; Diamond et al., 1997).

After the toy was hidden, the infant’s gaze to the hiding site was broken and brought to midline by the experimenter calling the infant’s name and asking, “Where’s the toy?” The direction of the infant’s first eye movement after being brought to midline was scored as either correct or incorrect. A video camera was placed behind and above the experimenter’s head and focused so as to maintain a close-up view of the infant’s face. Because the infants were not allowed to manipulate the toys, the visual experience they received from the moving, mechanical toy, and the smiles and praise they received (“Good job! You found it!”) from the experimenter after an eye movement to the correct tub had to provide the impetus to continue to search for the toy. For an eye movement to the incorrect tub, the infants received a sigh and sad vocalizations from the experimenter (“Oh, no. It’s not there.”).

The pattern of toy placement was determined by the infant’s performance, with initial side of hiding randomized among infants (Bell & Adams, 1999). Two consecutive successful eye movements toward the same side (e.g., toward the infant’s right) resulted in a reversal hiding, with the toy being hidden under the tub on the opposite side (toward the infant’s left; i.e., Right-Right-Left). All infants received reversal trials. Regardless of whether or not the infant was successful on the reversal trial, new “same-side” trials commenced at the reversal site and continued until two consecutive successful eye movements were executed, initiating another reversal (i.e., L-L-R). Thus, flawless performance by an infant would result in this pattern of trials: R-R-L-L-R-R-so forth. In reality, most infants were not flawless in performance and some needed multiple same-side trials in order to achieve two consecutive successful eye movements prior to reversal trials (e.g., L-L-L-L-L-R-R-R-L-etc.). Assessment ceased when the infant made an eye movement toward the incorrect side in two reversal trials. The average number of trials (combining
same-side and reversals) from which EEG data were collected was 18 per infant \((SE = 0.82)\).

An event marker was used in conjunction with the EEG and ECG recordings during testing so that it was possible to mark which portions of the electrophysiological record were associated with the most cognitively demanding sections of the looking task. This meant that the task-related EEG and ECG started with the covering of the hiding site and nonhiding site with the orange and blue tubs, continued through the breaking of the infant’s gaze and the infant’s first eye movement toward one of the hiding sites, and stopped when the experimenter lifted a tub prior to giving the infant appropriate verbal feedback. Thus, electrophysiological data not included in the analyses were that recorded when the experimenter was manipulating the toy prior to hiding it and that recorded when the experimenter was giving appropriate feedback to the infant after the infant’s eye movement to one of the hiding sites. The artifact-free EEG and ECG data from all trials (correct and incorrect) were used in these analyses.

**Temperament measure.** The Infant Behavioral Questionnaire (IBQ; Rothbart, 1981) was used to examine parental perceptions of infant temperament. The questionnaire was mailed to the parents 1 week prior to the laboratory appointment and collected upon arrival for the lab visit. This temperament scale assesses parent ratings of infant behaviors that factor into the following scales: activity level, distress to limitations, latency to approach, duration of orienting, smiling and laughter, and soothability. Internal reliabilities of the scales at 9 months range from .73 to .84 (Rothbart, 1981).

**Complete data for analyses.** Forty-three infants had complete data and were included in all analyses. Of the 50 infants recruited for the study, 7 were missing data for various reasons. Two of the infants cried during the working memory task and 1 infant was omitted due to experimenter error during the working memory task. Three infants did not wear the EEG cap and 1 infant who did wear the cap had no usable baseline EEG data due to excessive movement artifact.

**Results**

The 43 infants with complete data were divided into two groups based on performance on the working memory task. K-means cluster analysis was used to group the infants based on their percentage of correct responses on the same-side trials and their percentage of correct responses on the reversal trials (Diamond, 1990; Diamond et al., 1994, Diamond et al., 1997). Thus, same-side and reversal trials were both entered into the K-means analysis, as opposed to combining both types of trials and creating above-the-mean and below-the-mean groups. The resulting high working memory performance group \((n = 13)\) had 59% correct performance on same-side trials \((range = 24\%–91\%)\) and 64% on reversal trials \((range = 33\%–100\%)\). The two high working memory performance group infants with 24% correct performance on same-side trials had 50% and 100% correct performance on the reversal trials. The low working memory performance group \((n = 30)\) had 38% correct performance on same-side trials \((range = 0\%–67\%)\) and 7% on reversals \((range = 0\%–33\%)\). The one low performance group infant with 67% correct performance on the same-side trials had 0% correct performance on the reversal trials. Thus, there was some overlap in performance between the high and low groups on the same-side trials, but none on the reversal trials (i.e., those most likely to require working memory skills; Diamond et al., 1997).

**Working Memory and EEG**

To insure that the two working memory groups had equal amounts of artifact-free EEG to analyze (Pivik et al., 1993), a multivariate analysis of variance (MANOVA) analysis was performed on the amount of EEG data during baseline and task. The software program (James Long Company) for the Fourier analyses of the EEG uses a window width of 1 s. The mean number of EEG data windows for the high performance group during baseline was 80.00 \((SE = 8.52, range = 22–117)\) and during working memory task was 114.46 \((SE = 15.60, range = 27–232)\). The mean number of EEG data windows for the low performance group during baseline was 67.07 \((SE = 6.63, range = 4–136)\) and during the working memory task was 112.70 \((SE = 14.09, range = 20–343)\).

Thus, in the initial MANOVA analysis, number of data windows was the dependent variable, the within-subjects factor was condition (baseline, task) and the between-subjects factor was working memory performance group (low, high). There was no main effect for group and no group by condition interaction. There was, however, a main effect for condition, $F(1, 41) = 16.08, p < .001$. As would be expected, there were more DFT windows (i.e., more EEG data) for the task than for the 1-min baseline.
To assess working memory group differences in EEG coherence during baseline and task, a repeated measures MANOVA was performed on the coherence values. Coherence analyses focused on electrode pairs that included left and right medial frontal. The within-subjects factors were condition (baseline, task), pair (medial frontal paired with frontal pole, lateral frontal, parietal, and occipital), and hemisphere (left, right). The between-subjects grouping factor was working memory performance group (high, low). Of major interest were the main effects and interactions involving the group and condition variables.

There was a main effect for coherence pair \((p < .001)\), but this was superceded by a two-way interaction between condition and pair, Hotelling \(T^2 = 0.29, F(3, 39) = 3.72, p = .02, \eta_p^2 = .22\). There also was a two-way interaction between group and condition, Hotelling \(T^2 = 0.17, F(1, 41) = 6.80, p = .01, \eta_p^2 = .14\), and a trend toward a three-way interaction among group, condition, and pair, Hotelling \(T^2 = 0.18, F(3, 39) = 2.36, p = .087, \eta_p^2 = .15\).

To examine the various interactions among group, condition, and pair (and because there was an initial main effect for pair), separate multivariate analyses of variance (MANOVAs) were performed on the EEG coherence values for each electrode pair. In each MANOVA, working memory performance group (high, low) was the between-subjects factor and condition (baseline, task) and hemisphere (left, right) were the within-subjects factors.

**Frontal pole–medial frontal (Fp1–F3 and Fp2–F4).** There was a main effect for condition \((p = .04)\) that was superceded by a Group × Condition interaction, Hotelling \(T^2 = 0.13, F(1, 41) = 5.32, p = .03, \eta_p^2 = .12\). The high performance group showed comparable coherence from baseline to task. The low performance group showed a decrease in coherence from baseline to task (see Figure 1).

**Medial frontal–lateral frontal (F3–F7 and F4–F8).** There was a main effect for condition, Hotelling \(T^2 = 0.16, F(1, 41) = 6.73, p = .01, \eta_p^2 = .14\). Coherence values were higher at baseline relative to task (see Figure 1).

**Medial frontal–parietal (F3–P3 and F4–P4).** There was a Group × Condition interaction, Hotelling \(T^2 = 0.30, F(1, 41) = 12.35, p = .001, \eta_p^2 = .23\). The high performance group increased frontal–parietal coherence from baseline to task, whereas the low performance group decreased coherence (see Figure 1).

**Medial frontal–occipital (F3–O1 and F4–O2).** There was a main effect for group, \(F(1, 41) = 5.45, p = .02, \eta_p^2 = .12\), with the high performance group having greater coherence values than the low performance group. There was also a main effect for hemisphere, Hotelling \(T^2 = 0.23, F(1, 41) = 9.35, p = .004, \eta_p^2 = .19\), with coherence values lower in the right hemisphere relative to left hemisphere (see Figure 1).

EEG was also examined during the feedback portion of the task. Because the infants in the high performance group were more likely to receive positive feedback and the infants in the low performance group were more likely to receive the negative feedback, there was the potential for the EEG coherence values to reflect these feedback differences and then to carry over into the EEG analyzed during the task. Thus, separate MANOVAs were performed on the EEG coherence values for each electrode pair comparing coherence values during baseline and feedback. In each MANOVA, working memory performance group (high, low) was the between-subjects factor and condition (baseline, feedback portion of task) and hemisphere (left, right) were the within-subjects factors. There was a main effect of condition for the frontal pole—medial frontal pairs, Hotelling \(T^2 = 0.11, F(1, 41) = 4.39, p = .04, \eta_p^2 = .10\). EEG coherence during the feedback portion of the task was lower than EEG coherence during baseline. There were no other effects or interactions involving condition and there were no effects or interactions involving group.

**Summary.** The high working memory performance group showed an increase in coherence from baseline to task at the medial frontal–parietal electrode pair and stability in coherence from baseline to task at the frontal pole–medial frontal pair. The low working memory performance group showed a decrease in coherence from baseline to task at the medial frontal–parietal pair and a decrease from baseline to task at frontal pole–medial frontal. In addition, the high working memory performance group exhibited greater overall coherence at medial frontal–occipital relative to the low performance group. None of these group effects were hemisphere specific.

**Working Memory and Heart Period**

To assess performance group differences in heart period during baseline and task, a repeated measures MANOVA was done using heart period and heart period variability. Working memory performance group (high, low) was the between-subjects factor and condition (baseline, task) was the within-subjects factor. There was a main effect of cardiac measure \((\eta_p^2 = 99)\), as heart period values are larger than heart period variability values, and there was a Cardiac Measure × Condition interaction.
(\(\eta^2_p = .12\)), but these were superceded by a three-way interaction among group, condition, and cardiac measure, Hotelling \(T^2 = 0.11, F(1, 41,) = 4.29, p = .05, \eta^2_p = .10\).

To examine the interaction among group, condition, and cardiac measure, separate MANOVAs were performed on heart period and heart period variability measures. In each MANOVA, working memory performance group (high, low) was the between-subjects factor and condition (baseline, task) was the within-subjects factor. There was a trend toward a Group \(\times\) Condition interaction, \(F(1, 41) = 3.79, p = .058, \eta^2_p = .09\). The high working memory group exhibited a decrease in heart period (i.e., an increase in heart rate) from baseline to task. The low group displayed the opposite pattern (see Figure 2).

Similar analyses were completed on the heart period variability values. There was a main effect of condition, \(F(1, 41) = 10.70, p = .002, \eta^2_p = .21\). The variability in heart period was greater during the task \((M = .03, SD = .02)\) than during baseline \((M = .02 SD = .01)\). There was no group effect \((p = .47)\) and no Group \(\times\) Condition interaction \((p = .35)\).

**Working Memory and Temperament**

MANOVA was performed on the IBQ scales with working memory performance group (high, low) as the between-subjects factor. There was a main effect for group, Hotelling \(T^2 = 0.41, F(6, 36) = 2.48, p = .04, \eta^2_p = .29\). Follow-up analyses of variance (ANOVAs) on the individual scales showed the working memory groups differed on Activity
Level and Distress to Limitations, with the high performance group scoring higher on each scale (see Table 1).

**Predicting Working Memory Performance Group Membership**

In the analyses reported above, several electro-physiological and temperament variables were associated with working memory performance group. The EEG analysis involving medial frontal–parietal coherence during baseline and task yielded the largest effect size with respect to analyses involving other coherence pairs. The cardiac variables analyses demonstrated a trend in heart period \( (p = .058) \), but not heart period variability, between the groups. And the temperament analyses demonstrated that the Activity Level and Distress to Limitations scales showed working memory performance group differences. These were all separate analyses, however, and as such there is no indication how the variables individually contribute to the classification results.

Thus, these variables were used as predictors in a binary logistic regression analysis with working memory performance group as the outcome variable. To maintain an acceptable number of degrees of freedom for the analysis, change scores for the baseline and task electrophysiology variables were calculated so that information from both baseline and task could be used in the analysis. For example, the variable “F3P3 EEG change” was calculated as the task EEG coherence at F3P3 minus the baseline EEG coherence at F3P3. Thus, a positive change score indicated increased EEG coherence from baseline to task, whereas a negative change score indicated decreased EEG coherence from baseline to task. Table 2 shows regression coefficients, Wald statistics, betas, standard errors of betas, and 95% confidence intervals for each predictor.

A test of this model against a constant only model was significant, \( \chi^2(8) = 29.92, p < .001 \) (Cox & Snell \( R^2 = .49 \)), indicating that the set of predictors distinguished between the high and low working memory performance groups. As shown in Table 2, significant predictors in the regression equation were the change in F4P4 and the change in heart period from baseline to task. Distress to Limitations temperament variable approached significance \( (p = .066) \). The overall percentage of correct group classification with this set of predictors was 93%, with 77% correct for the high performance group and 100% correct for the low performance group.

**Discussion**

The data in this study allowed examination of inter-relations among working memory, EEG coherence, heart period, and temperament at 8 months of age. Potential correlates of high versus low working memory task performance were examined separately. Then variables that discriminated high and low task performance groups were analyzed collectively to determine which variables contributed unique variance in the determination of performance group membership.
Which EEG Coherence Pairs Are the Best Indicators of Infant Working Memory Performance?

After dividing the infants into high and low performance groups, it was possible to determine group differences in EEG coherence values that were specific to the brain electrical activity recorded during the spatial working memory task. Both the frontal pole–medial frontal and the medial frontal–parietal electrode pairs yielded performance group by condition interactions, but the interactions were manifested in very different ways.

For the frontal pole–medial frontal pairs, the high performance group showed stable coherence from baseline to task, whereas, the low performance group exhibited a decrease in coherence from baseline to task. For the medial frontal–parietal pairs, the high performance group showed an increase in coherence from baseline to task, whereas the low group again exhibited a decrease in coherence.

Other reports of EEG coherence in the cognitive neuroscience literature focus on the interaction of the frontal and parietal regions during spatial working memory tasks in infancy (Bell, 2001) and adulthood (e.g., Ross & Segalowitz, 2000; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005; Sauseng et al., 2004). The EEG coherence measure used in this study appears to be tapping into that frontal–parietal interaction. The increase in coherence demonstrated by the high performance group is indicative of increased connectivity between frontal and parietal areas (and by assumption, increased communication) during the infant working memory task (Thatcher, 1994; Thatcher et al., 1986). It appears that this increase is essential for successful task performance. Indeed, in a study of adults with mild traumatic brain injury, EEG coherence between frontal and parietal scalp locations was similar to control adults during baseline recordings. However, during the performance of spatial working memory tasks, the brain injury group exhibited lower frontal–parietal coherence than the control group. This was interpreted as problems with neuronal communication (Kumar, Rao, Chandramouli, & Pillai, 2009). The low performance group of infants in this study do not have brain trauma, but perhaps they do have less developed patterns of neuronal connections between frontal and parietal areas, leading to lower coherence values during task performance. Just as in the adult brain injury study, the infants in the two working memory performance groups did not differ in baseline EEG coherence at frontal–parietal locations. Only when the task at hand required frontal–parietal involvement did the coherence values differ.

For the frontal pole–occipital pairs there was a main effect of performance group, with the high group having greater coherence values during baseline and task. Studies employing EEG power values during infancy indicate that the occipital area is different between high and low performers on both the classic Piagetian A-not-B task and the spatial

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Wald (df)</th>
<th>B</th>
<th>SE</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3P3 EEG change</td>
<td>2.32 (1)</td>
<td>-13.59</td>
<td>8.91</td>
<td>.13</td>
</tr>
<tr>
<td>F4P4 EEG change</td>
<td>5.69 (1)</td>
<td>-23.05</td>
<td>9.66</td>
<td>.02</td>
</tr>
<tr>
<td>Heart period change</td>
<td>6.07 (1)</td>
<td>117.41</td>
<td>47.67</td>
<td>.01</td>
</tr>
<tr>
<td>Activity level</td>
<td>-0.73 (1)</td>
<td>0.74</td>
<td>0.85</td>
<td>.39</td>
</tr>
<tr>
<td>Distress to limitations</td>
<td>3.37 (1)</td>
<td>-2.27</td>
<td>1.24</td>
<td>.07</td>
</tr>
</tbody>
</table>

Note. “F3P3 EEG change” refers to the difference between baseline and task F3P3 EEG coherence measures. “Heart period change” refers to the difference between baseline and task heart period measures.

Table 1
Working Memory Performance Group Differences on IBQ Temperament Scale Means (Standard Errors)

<table>
<thead>
<tr>
<th></th>
<th>High WM group</th>
<th>Low WM group</th>
<th>F</th>
<th>p</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 13)</td>
<td>(n = 30)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity level</td>
<td>5.10 (.16)</td>
<td>4.50 (.14)</td>
<td>6.15</td>
<td>.017</td>
<td>.13</td>
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<tr>
<td>Distress to limitations</td>
<td>3.81 (.18)</td>
<td>3.28 (.12)</td>
<td>5.90</td>
<td>.020</td>
<td>.13</td>
</tr>
<tr>
<td>Latency to approach</td>
<td>3.11 (.21)</td>
<td>2.90 (.12)</td>
<td>0.83</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Duration of orienting</td>
<td>3.77 (.27)</td>
<td>3.30 (.16)</td>
<td>2.51</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Smiling and laughter</td>
<td>5.20 (.25)</td>
<td>4.86 (.10)</td>
<td>2.18</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Soothability</td>
<td>5.11 (.24)</td>
<td>4.77 (.15)</td>
<td>1.43</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

Note. For each analysis of variance, the degrees of freedom were (1,41). IBQ = Infant Behavioral Questionnaire; WM = working memory.

Table 2
Binary Logistic Regression Analysis Predicting Working Memory Performance Group Membership

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Wald (df)</th>
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<th>SE</th>
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</tr>
</tbody>
</table>

Note. “F3P3 EEG change” refers to the difference between baseline and task F3P3 EEG coherence measures. “Heart period change” refers to the difference between baseline and task heart period measures.
working memory task (Bell, 2001; Bell & Fox, 1992, 1997). In those studies as well, greater occipital EEG power values were associated with better task performance. Wilson, O-Scalaidhe, and Goldman-Rakic (1993) have highlighted the interconnections of the frontal and occipital lobes in non human primates. Both the frontal and occipital regions of the cortex have areas used in object identity and object location. Perhaps these areas are more involved in working memory performance during infancy, compared to childhood to adulthood. Electrophysiological research demonstrates that infants may have more widespread cortical involvement during cognitive processing than do preschool children (Bell & Wolfe, 2007). This lack of cortical specialization during infant working memory task performance may be indicative of qualitative changes in cortical functioning from infancy to early childhood. It should be noted, however, that Richards has demonstrated changes in cortical efficiency and organization during attention and recognition memory tasks between 4.5 and 7.5 months of age using high-density EEG recordings and source localization techniques (Reynolds & Richards, 2005; Richards, Reynolds, & Courage, 2010). However, our work has not shown a similar pattern of increasing cortical specialization during infant working memory task performance (Cuevas & Bell, 2010b).

**Do Heart Period Values Distinguish Better From Poorer Infant Working Memory Performance?**

A decrease in heart period (increase in heart rate) from baseline to task was specific to the high performance group. The low performance group exhibited an increase in heart period (decrease in heart rate) from baseline to task. This finding, in conjunction with the changes in EEG coherence from baseline to task, indicates that this infant working memory task was associated with cognitive processing in the high performance infants. The increased heart period values are also indicative of the cognitive stress this task placed on the high performance infants (Manuck et al., 1990). Indeed, the cognitive stress may be in the form of endogenous or sustained attention (Colombo, 2002; Diamond et al., 1997).

Perhaps it should not be surprising that the heart period variability measure increased from baseline to task but did not distinguish between the two performance groups. This variability measure has been used extensively to assess individual differences in temperamental reactivity and regulation (e.g., Calkins, 1997). Perhaps variability in cardiac functioning is not as prominent with higher order cognitive processing.

**Which Temperament Measures Are Most Closely Linked With Infant Working Memory Performance?**

Maternal report measures linked augmented cognitive performance with increased distress and activity levels. This counterintuitive finding linking these particular temperament traits with enhanced cognitive performance on the working memory task may mean that these infants require more parental support in the development of their attentional skills, a result that may lead to enhanced cognitive skills as the infants get older if that support from the parent is appropriate and sensitive. Indeed, sensitive maternal behaviors are related to regulatory behaviors in infants (Calkins & Johnson, 1998; Calkins, Smith, Gill, & Johnson, 1998; Diener, Mangesdorf, McHale, & Frosch, 2002) and to cognitive behaviors in young children (Stams, Juffer, & van IJzendoorn, 2002), especially on tasks associated with frontal functioning (Bernier, Carlson, & Whipple, 2010). The view that maternal sensitivity is vital for healthy psychosocial growth is incorporated into classic psychological theories (Thompson, 2006). Although the environment, and specifically the caregiving environment, has been given such an essential role in an infant’s social development and later outcome (Stright, Gallagher, & Kelley, 2008), not much attention has been given to the role of that same caregiving environment to the development of complex cognition. It may be, however, that by supporting infants in the development of attentional skill, in part to relieve infant distress (Ruff & Rothbart, 1996), caregivers are contributing to the attentional skills associated with later complex cognitive processing. Thus, parental behavior may also be essential for cognition (Colombo & Saxon, 2002). This speculation deserves further attention. The addition of sustained attention tasks, temperament reactivity tasks, maternal sensitivity measures, as well as multiple data collection points, would allow more systematic examination of these speculations.

**How Do EEG, Heart Period, and Temperament Together Predict High and Low Working Memory Performance During Infancy?**

The brain/behavior system that has the capacity to tie together these cognitive, electrophysiological, and temperament processes is Posner’s construct of the “executive attention system” (Posner &
Rothbart, 2000), which begins to show some developmental changes in the second 6 months of life (Rothbart, Derryberry, et al., 1994; Ruff & Rothbart, 1996). The executive attention system is involved in cognitive processing when there is a resolution of conflict between two forms of stored information. The choice of hiding locations in the infant working memory task may represent this type of conflict (Posner & Rothbart, 1998). Furthermore, this system focuses on the emotion (i.e., temperament)-attention and cognitive-attention functions of the anterior cingulate gyrus, which has many projections to different areas of the frontal cortex. In the developmental literature, EEG from frontal scalp locations has been associated with performance on infant working memory tasks (e.g., Bell, 2001; Bell & Fox, 1992, 1997), as well as individual differences in temperament reactivity and regulation (e.g., Fox, Bell, & Jones, 1992; Fox, Calkins, & Bell, 1994; Fox, Henderson, Rubin, Calkins, & Schmidt, 2001).

When considered collectively, the variables contributing unique variance to the prediction of high and low infant working memory performance were the changes in right hemisphere frontal–parietal coherence and heart period between baseline and task, with a trend for maternal ratings of distress. In addition to their potential common links via the executive attention system, these three variables also have in common their association with the right frontal cortex. Right hemisphere frontal and parietal areas have long been connected with spatial cognition in adults, with both EEG (e.g., Davidson, Chapman, Chapman, & Henriques, 1990) and fMRI studies (e.g., Maclin, Gratton, & Fabiana, 2001) demonstrating the association. Right frontal areas are linked with regulation of heart rate (Ahern et al., 2001), although the effect may be more lateralized in older adults than younger adults (Thayer et al., 2009). Finally, from both positive–negative and approach–withdrawal conceptual frameworks, temperamental distress is linked to right frontal functioning (Fox, 1994). Why might various aspects of right frontal functioning figure so prominently in determining high and low performance in this study?

It should be noted that the beta weights for the logistic regression analyses were more descriptive of the low performance group than of the high performance group. For example, the negative weight associated with the change in frontal–parietal EEG coherence from baseline to task (calculated as task coherence minus baseline coherence) indicates that coherence values decreased from baseline to task. MANOVA analyses showed that this was associated with the low performance group. Similarly, the positive beta weight for change in heart period from baseline to task indicates that heart period increased (i.e., heart rate decreased), also associated with the low performance group. The negative beta weight associated with the trend in temperamental distress is also associated with the low performance group, as the ANOVA showed that the high performance group had higher maternal ratings of distress. Having the beta weights associated with the low performance group is further demonstrated by the fact that the logistic regression model predicted membership in the low group with 100% efficiency, with membership in the high group predicted with 77% accuracy. Thus, it would be informative to see if more evenly balanced membership in high and low performance groups would yield a model that likewise has unique variance associated with right hemisphere functioning. Given what we know from adult spatial working memory and spatial conflict research, I would predict that this would indeed be the case, but perhaps with different beta weight signs (i.e., positive, negative) associated with performance group membership.

In sum, high versus low performance on an infant working memory task was associated with specific patterns of EEG coherence and heart period from baseline to task, as well as with specific trait behavior patterns as indicated in parent report of temperament. These data give further support to the infant working memory task as a valid indicator of early frontal lobe cognitive processing. They also lay the foundation for future studies exploring various psychobiological influences on individual difference in task performance.

References


Cuevas, K., & Bell, M. A. (2010b). EEG and ECG from 5 to 10 months of age: Developmental changes in baseline activation and cognitive processing during a spatial working memory task. Manuscript submitted for publication.


