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Theoretical models of attention development have emphasized the role of neural networks in the emergence of attentional control towards the end of the first year of life. The current study aimed to assess the relation between neural network maturation and developing attention skills by examining changes in observed attention and EEG coherence across a short-term longitudinal study. Participants were 339 infants participating in a larger study; data was collected at 5 and 10 months of age. It was hypothesized that increases in frontal and fronto-parietal EEG coherence during this time would be positively associated with controlled attention behaviors at 10 months. Attention behaviors were coded using Video Coding System software developed by James Long Company. Results indicated that on average EEG coherence values were significantly greater at 10 months than at 5 months across multiple pairs. However, only for certain pairs were changes in EEG coherence significantly associated with changes in observed attention behaviors. Effect sizes were relatively small and do not provide strong support for the role or neural networks in developing attention skills. Results are discussed in terms of directions for future research.

LONGITUDINAL CHANGES IN VISUAL ATTENTION AND EEG COHERENCE: IMPLICATIONS FOR THE DEVELOPMENT OF ATTENTION NETWORKS

by

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CHAPTER I

INTRODUCTION

Attention refers to a set of processes that are involved in the selection and processing of stimuli in the external environment; these processes underlie our awareness of the world and are critical for the regulation of thoughts and feelings (Posner & Rothbart, 2007, p. 6). Researchers often characterize attention as either exogenous or endogenous. Exogenous attention processes are reflexive (i.e., bottom up) and controlled by factors that are external to the individual; in contrast, endogenous attention processes are internally directed (i.e., top down) and subject to conscious control (Colombo, 2001). Endogenous attention processes include concepts such as executive and sustained attention. For much of the first year, attentional processes are exclusively exogenous; the capacity to voluntarily control attention does not emerge until late in the first year and exhibits considerable growth across the toddler and early preschool years (Ruff & Rothbart, 1996; Colombo, 2001; Colombo & Cheatham, 2006; Courage, Reynolds, & Richards, 2006).

The development of attentional control is critical for adaptive functioning and development across multiple domains. Flexible control of attention facilitates active emotion regulation strategies in infancy (Rothbart & Bates, 2006; Rueda, Posner, & Rothbart, 2005; Morasch & Bell, 2010) and early childhood (Calkins, Dedmon, Gill, & Lomax, 2002; Graziano, Calkins, & Keane, 2011). Attentional control has also been demonstrated as a robust predictor of behavioral self-regulation in young children (Mischel & Ebbesen, 1970; Kopp, 1982, 1987; Barkley, 1997; Kochanska, Murray, & Harlan, 2000). Further, the majority of infant's cognitive and social learning occur during episodes of sustained attention, and it is during this time that active information processing occurs (Oakes & Tellinghuisen, 1994; Reynolds & Richards, 2008; Ruff & Rothbart, 1996). In this way, attentional control may be considered a foundation from which higher level cognitive and self-regulatory processes develop. Understanding the factors which influence its development is a critical task for developmental researchers.

Attentional control first begins to manifest around the end of the first year of life, and develops gradually across the toddler and preschool years. This developmental shift in attention coincides with a period of significant changes in brain organization (Huttenlocher, 1979; Thatcher, 1992). Current theoretical perspectives on attention consider neural networks as the basic mechanism of attention processes, and neural networks are frequently discussed in the literature in relation to attentional control (Posner & Petersen, 1990; Posner & Rothbart, 2007). However, there has been a surprising lack of investigation into the development of these networks as well as their functioning in infants and young children. Many studies have examined relations between cognitive processes involving attention and brain *activity* in infants and young children (e.g., Bell, 2001; 2012; Cuevas, Swingler, Bell, Marcovitch, & Calkins, 2012), but not whether this activity is part of a coordinated network. Studies that have examined coordinated brain activity in relation with attention have done so in older children and adults (e.g., Casey, Cohen, Jezzard, Turner, Noll, Trainor…& Rapoport, 1995; Casey, Trainor, Orendi, Schubert, Nystrom, Giedd … & Rapoport, 1997); there has been practically no investigation into the functioning of attention networks in young children and infants, even though it is during this time they are theorized to develop. Researchers who have utilized measures of brain organization in infancy (e.g., EEG coherence, fMRI) have tended to do so at a single point in time (e.g., Cuevas, Raj, & Bell, 2012). However, because attention networks are theorized to develop across the first few years of life, it is important to examine *changes* in brain organization over time. Although there are some longitudinal studies of brain organization (e.g., Thatcher, 1992; Gao, Zhu, Giovanello, Smith, Shen, Gilmore, & Lin, 2009), they do not attempt to relate their data with developing attention or cognitive abilities. Thus, there is practically no existing research which can speak directly to the functioning of attention networks in infants and young children or their development. To really understand the relations between neural networks and the development of attentional control, longitudinal analyses are needed. As a first step toward addressing this gap, the current study will examine changes in EEG coherence across the first year of life and their relations with attention behaviors.

Developmental Time Course of Attentional Control

The first few years of life are an important developmental period in the study of attention. Towards the end of the first year, there are observable changes in attention which indicate the emergence of more volitional attention processes. One such change is in the duration of time infants are able to visually attend towards stimuli and events in their environment. In the early months of life, attention is primarily reflexive and is characterized by obligatory attention to salient stimuli and motion and is highly susceptible to sticky fixation (Johnson, Posner, & Rothbart, 1991). Between 3 and 6 months of age, infants become more adept at disengaging and shifting attention allowing them to process information in their environment faster and more efficiently (Posner, Rothbart, & Thomas-Thrapp, 1997). During the latter half of the first year, infants begin to show improvement in their ability to sustain focus towards complex stimuli in their environment (Courage, Reynolds & Richards, 2006). John Colombo, John Richards and their colleagues (Colombo & Mitchell, 1990; Colombo, Harlan, & Mitchell, 1999; Colombo, 2001; Courage, Reynolds, & Richards, 2006) have documented these changes using visual habituation paradigms with infants and toddlers. In these studies, infants' and toddlers' aged 3 months to 2 years viewed a series of basic images (e.g., computer-generated black and white patterns) and a brief film clip of the movie *Sesame Street* and a series of during two 20-min sessions. For each age group the researchers calculated the average peak look duration for each type of stimuli. Their results indicated that mean look duration declined significantly between 3 and 6 months of age (for all stimuli types), which the researchers attributed to an increase in processing speed and maturation of posterior brain regions involved with disengaging and shifting attention (Posner & Raichle, 1994). Although look durations continued to decline for simple stimuli (e.g., static visual patterns), results also indicated that for complex visual stimuli (e.g., *Sesame Street*) mean look duration began to increase from about 8 months to 2 years of age. Because reduced processing speed is an inadequate explanation for this subsequent increase in look duration, the researchers concluded that infants are acquiring more endogenous control over their attention, allowing them to sustain attentional focus even after stimuli are processed (Courage, Reynolds, & Richards, 2006). This interpretation is supported by a similar body of research conducted by John Richards and his colleagues (Richards & Gibson 1997, 2001; Richards & Cronise, 2000) that has demonstrated that increased look duration during this time is accompanied by increases in heart rate defined periods of sustained attention (see Richards, 2010 for a review). This interpretation is also consistent with correlational research demonstrating that although in early infancy shorter look durations are associated more favorably with later cognitive functioning (e.g., Cuevas & Bell, 2014; see Colombo, 1993 for a review), beyond one year of age this association is typically negative, with longer looking periods associated with more favorable outcomes (Ruff & Capozzoli, 2003; Ruff & Lawson, 1990; Papageorgiou, Smith, Wu, Johnson, Kirkham, & Ronald, 2014). Studies from other laboratories have found that look durations continue to increase beyond the first year (Ruff & Rothbart, 1996; Ruff & Capozzoli, 2003) and that sustained attention shows considerable improvement across the toddler and preschool years (Breckenridge, Braddick, & Atkinson, 2013; Ruff & Lawson, 1990; Ruff, Lawson, Parrinello, & Weissberg, 1990; Reed, Pien, & Rothbart, 1984). Collectively, these data point towards a qualitative shift in attention towards the end of the first year whereby infants gain more voluntary control over their visual attention.

Another manifestation of attentional control that begins to emerge around the end of the first year is the capacity to detect and manage conflict. Conflict refers to situations that elicit incompatible response tendencies. The successful management of conflict involves suppressing processing or responding to the information that elicits an incorrect or inappropriate response; in this way, it is considered an endogenous rather than an exogenous attention processes. A common method for assessing infants' capacity to detect and manage conflict is the A-not-B paradigm. In the standard version of the A-not-B paradigm, first described by Piaget (1954), an infant watches as an object is hidden in one of two locations (A or B). The object is first hidden at location A and following a brief delay the infant is encouraged to search for the object. After several search trials at location A the object is hidden at location B. Because reaching towards location B has been rewarded previously, successful performance on the task involves overriding or inhibiting the tendency to respond this way again. Infants younger than 12 months of age often show a perseverative search response by continuing to reach towards location A (e.g., Diamond, 1990a; 1990b; 1991). With age, performance on this task increases along with the length of delay that infants can tolerate (Diamond, 1990a; 1990b; 1995; Diamond, Prevor, Callender, & Druin, 1997). However, some researchers have noted that infants will often *look* towards the correct location while reaching for the incorrect one (Diamond, 1985; Piaget, 1954). Studies employing both the standard and a modified looking version of the task have indeed found that infants achieve success on the looking version earlier than the standard version (Hofstadter & Reznick, 1996; Bell & Adams, 1999). For example, Bell and Fox (1997) found that most (two-thirds) of 8-month-olds were successful on the looking version of the task at a 0-second delay. However, infants' performance on both versions of the task are roughly equivalent by 9 or 10 months of age (Hofstadter & Reznick, 1996; Matthews, Ellis & Nelson, 1996; Cuevas & Bell, 2010; Bell & Adams, 1999), suggesting that attentional control skills precede and possibly underlie more complex (i.e., behavioral) manifestations of inhibitory control. These studies suggest that prior to the end of the first year, infants begin to use attention in a more conscious and controlled fashion.

The capacity to control visual attention shows considerable improvement across the second year of life (e.g., Sheese, Rothbart, Posner, White, & Fraundorf, 2008; Rothbart, Ellis, Rueda, & Posner, 2003; Clohessy, Posner, & Rothbart, 2001), supporting infants' capacity to explore the physical environment and participate in social interactions, experiences which are critical for the development of language and social-cognitive skills. Continued improvement in attention is observed across early childhood. By age four, there is noticeable improvement in children's capacity to flexibly shift between rules (Zelazo & Reznick, 1991) and to inhibit context-inappropriate behavior (see Carlson, 2005 for a review). The developmental timeline of these events, as well as empirical data (Papageorgiou et al., 2014) suggest that attentional control systems are becoming integrated with those of behavioral control. Thus, the control of visual attention—which appears to emerge in infancy—lays an important foundation for many important developmental competencies.

Attentional Control and Neural Networks

Current theoretical perspectives of attention maintain that attention processes (both exogenous and endogenous) are the result of coordinated activity between different brain regions, or neural networks. Two networks have been discussed in the literature in relation to attentional control: an executive (cingulo-frontal) network involved in the detection and management of conflict (Posner & Rothbart, 2007), and a fronto-parietal network involved in the control of visual orienting (Colombo & Cheatham, 2006). The maturation of these attention networks are theorized to underlie the developmental changes in attention across the first few years of life (Posner & Petersen, 1990; Colombo & Cheatham, 2006).

According to Posner and his colleagues (e.g., Posner & Petersen, 1990), the conscious and volitional control of attention is associated with a neural network involving the anterior cingulate cortex (ACC), basal ganglia, and the medial and lateral prefrontal cortices (Posner & Fan, 2008; Posner, Rothbart, Sheese, & Voelker, 2012). The ACC is a subcortical structure located in the medial frontal lobe and is believed to play a major role in the detection of conflict (Bush, Luu, & Posner, 2000), which (as previously discussed) is a core facet of attentional control. Neuroimaging studies with adults have found that the ACC is activated during situations that elicit conflict (Stroop; Casey et al., 1997; Carter, Braver, Barch, Botvinick, Noll, & Cohen, 1998; Bush et al., 2000; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003). Time-locked EEG activity (ERPs), believed to originate from the ACC, has also been observed when individuals make errors. For example, in choice reaction time (RT) tasks, a negative potential is observed at the scalp when subjects make errors. This potential, called the error-related negativity (ERN), begins to develop at around the time of the erroneous response, peaking about 100ms later, and is smaller or absent on trials where the subject makes the correct response (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1991; Falkenstein, Koshlykova, Kiroh, Hoorman, & Hohnsbein, 1995; Gehring, Goss, Coles, Meter, & Donchin, 1993; Gehring, Coles, Meyer, & Donchin, 1995; Miltner, Braun, & Coles, 1997; Tucker, Hartry-Speiser, McDougal, Lure, & deGrandpre, 1999; Santesso, Segalowitz, & Schmidt, 2005). Studies that have employed source localization techniques (e.g., equivalent dipole analysis, distributed source modeling) suggest that the ERN is generated in the ACC (Miltner, Lemke, Weiss, Holroyd, Scheffers, & Coles, 2003; Dehaene, Posner, & Tucker, 1994; Kiehl, Liddle, & Hopfinger, 2000; Gemba, Sasaki, & Brooks, 1986). The ERN has been primarily studied in adults and older children; only one study has investigated this component in infancy. Berger, Tzur, and Posner (2006) recorded EEG activity in 6- to 9-month-old infants during a modified error detection task (see Wynn, 1992). Results indicated that most infants looked significantly longer at the error condition than the correct condition, suggesting that they detected the error (and replicating the results from Wynn, 1992). For those infants who detected the error, the researchers created average ERN amplitudes by averaging the brain activity over medial frontal central (Fcz) electrode sites that occurred between 330-530 milliseconds following both trial types. Results indicated that infants—like adults—exhibit enhanced ERN amplitude for incorrect trials, suggesting that the neural underpinnings of attentional control are already beginning to develop before the end of the first year.

Age-related changes in conflict detection and management have been associated with the functioning of the lateral PFC (Bunge & Zelazo, 2006; Dempster, 1992; Diamond, 2002; Morton & Munakata, 2002). Tasks that elicit cognitive conflict (e.g., DCCS) are commonly associated with enhanced brain activity in the lateral PFC (Barber & Carter, 2005; Cole & Schneider, 2007). This has also been demonstrated in children (Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006). For example, in an fMRI study with 8-year-olds, performance on a set-switching task was associated with lateral PFC activity (Crone et al., 2006). There is evidence that these relations are also true for infants. For example, Diamond has demonstrated with nonhuman primate data that successful performance on the A-not-B task depends upon the intactness of the dorsolateral PFC (Diamond, 1990a, 1990b). Infant monkeys follow the same developmental progression on A-not-B as do human infants (Diamond & Goldman-Rakic, 1989), and infant monkeys receiving lesions in both hemispheres of the dorsolateral prefrontal cortex were unable to succeed on A-not-B with a delay between hiding and search (Diamond & Goldman-Rakic, 1986). Lateral PFC involvement in attentional control processes has also been demonstrated in human infants. Bell and Fox (1997) found that 8-month-old infants able to perform the A-not-B task successfully showed greater frontal EEG power values at baseline than infants who were unable to do so. EEG power values are thought to gradually increase across development (Marshall, Bar-Haim, & Fox, 2002), and have been used as an indicator of brain maturation in developmental studies (Bell & Fox, 1994). Increased baseline power values may indicate greater maturation of these regions. These data are consistent with the idea that the lateral PFC is involved in an attention control network; and given that conflict monitoring first emerges in infancy, it seems likely that such a network would begin to emerge during this time as well.

Another neural network that has been implicated in attentional control processes involves connections between the lateral PFC and parietal regions. Parietal regions have also been strongly implicated in both endogenous and exogenous attention processes, primarily in relation with shifting and disengaging attention (Posner & Dehaene, 1994; Chugani, Phelps, & Mazziotta, 1987; see Corbetta & Shulman, 2002 for a review). For example, damage to the parietal region in adults has been associated with deficits in disengaging attention (Posner, Walker, Friedrich, & Rafal, 1984; Corbetta, Miezin, Shulman, & Petersen, 1993). As proposed by Colombo and his colleagues (Colombo & Cheatham, 2006), the capacity to control visual attention may rely upon a neural network involving lateral frontal and parietal regions of the brain. Research with older children and adults using fMRI has also found that controlled attention shifting is associated with greater fronto-parietal connectivity (Morton, Bosma, & Ansari, 2009; Tamber-Rosenau, Esterman, Chiu & Yantis, 2011; Woldorff, Hazlett, Fichtenholtz, Weissman, Dale & Song, 2004; Fairhall, Indovina, Driver & Macaluso, 2009). Reduced fronto-parietal connectivity in children has been linked with ADHD (Silk, Vance, Rinehart, Braddhaw, & Cunnington, 2008), a disorder characterized by difficulty sustaining attention. EEG research with infants also suggests that top-down control over parietal regions is critical for sustained attention (Stroganova, Orekhova, & Posikera, 1997; Orekhova, Stroganova, & Posikera, 2001). Orekhova, Stroganova, and Posikera (2001) examined brain electrical activity in 7- to 12-month-old infants during both externally and internally controlled attention conditions. Their results indicated that infants exhibited greater alpha synchronization (i.e., power values) over posterior parietal sites during the internally versus externally controlled attention condition. Further analysis indicated that infants who demonstrated greater sustained attention during the internally controlled attention condition exhibited greater alpha synchronization across parietal electrode sites than infants who had shorter bouts. Synchronized EEG activity is indicative of cortical inhibition, likely originating from prefrontal regions (Klimesch, 1999). Because the parietal cortex has mostly been associated with shifting and disengaging attention (Posner et al., 1987), alpha synchronization over these regions may indicate top-down inhibition of reflexive attention processes, which would facilitate infants’ capacity to sustain attention. Thus, there is a great deal of research that suggests the control of visual attention is associated with a fronto-parietal attention network, and that such a network may already be in place in infancy.

Towards the end of the first year, infants experience a transition from a reactive or stimulus-driven form of attention towards a more volitional, internally controlled form of attention (Rothbart, Posner, & Boylan, 1990; Colombo & Cheatham, 2006; Courage, Reynolds, & Richards, 2006). This transition may facilitate infants’ capacity to participate in joint attention interactions, thus facilitating the acquisition of social-cognitive and language skills. Further, the control of visual attention may serve as the foundation for higher-level self-regulatory skills (Posner & Rothbart, 1998). Theoretical models of attention have maintained that this transition is associated with the maturation of neural attention networks. However, most of the empirical support for the existence of these networks and their involvement in attention processes comes from studies with older children and adults; there has been practically no investigation into their development or functioning in infancy or early childhood.

Brain Development in Infancy

Synaptic connections, the basic building blocks for neural networks, are rapidly forming in early post-natal development. Developmental changes in synaptic density across multiple brain regions have been studied extensively in non-human animals (Bourgeois, Goldman-Rakic, & Rakic, 1985; Goldman-Rakic, 1986; 1987; Bourgeois & Goldman-Rakic, 1986; Bourgeois & Rakic, 1993; Bourgeois, 1997). Across species, a common pattern is reported characterized by a synaptic overproduction (i.e., blooming) in early postnatal development followed by a prolonged period of synaptic elimination (i.e., pruning). For example, synaptic density in the cat visual cortex rapidly increases for the first month after birth, reaching its peak density around 2 months; then it exhibits a prolonged pruning phase until reaching adult levels (Cragg, 1975). Similar results have been found in both the visual and prefrontal cortices of monkeys (Lund, Boothe, & Lund, 1977; Zecevic & Rakic, 1991; Rakic, Eckendorf, Zecevic, & Goldman-Rakic, 1986; Rakic, Bourgeois, & Goldman-Rakic, 1994; Bourgeois et al., 1985). This pattern of synaptic "blooming and pruning" is considered adaptive in that it allows for maximum recovery in the event of injury (Huttenlocher, 1984) and promotes neural efficiency by retaining only those connections that were most active during the critical period (Greenough, Black, & Wallace, 1987).

Research indicates that a similar pattern occurs in humans, but on a slightly different time scale. For example, in the human visual cortex, rapid growth in dendritic arborization (most often accompanied by synaptic growth) is observed between the 2nd and 4th months of life, reaching maximum levels around the 5 months of age, and declining to adult levels by the end of the second year of life (Michel & Garey, 1984). Peter Huttenlocher and his colleagues (Huttenlocher, 1979; Huttenlocher, de Courten, Garey, & van der Loos, 1982; Huttenlocher & de Courten, 1987) have examined developmental changes in synaptic density in both the visual and prefrontal cortices in human infants using postmortem tissue. Data from his laboratory has demonstrated that, in the infant visual cortex, synaptic density was near adult levels shortly following birth, increased rapidly between 2 and 4 months of age, and reaching peak levels around 8 months of age that are sixty percent higher than those seen in adults (Huttenlocher et al., 1982; Huttenlocher & de Courten, 1987). Similar results were found for the frontal cortex: at birth, synaptic density was roughly equivalent to that observed in adults, increased rapidly throughout the first year, reaching peak density between 1 and 2 years of age (Huttenlocher, 1979), at which point it is roughly double that seen in adults. Between the ages of 2 and 16 years, densities declined to mature levels and remained constant throughout adulthood. These data suggest that synapses within the PFC are rapidly developing throughout the first 12 to 18 months of age, and that after 2 years of age, many of these synapses are eliminated. Importantly, the timing of these events is consistent with the developmental time course of attentional control previously reviewed in this paper.

Researchers have also proposed that periods of synaptic blooming and pruning are associated with the emergence and refinement of skills (Goldman-Rakic, 1987; Greenough, et al., 1987; Greenough & Black, 1992), and empirical data (from studies using both animals and humans) supports this perspective. For example, between 2 and 3 months of age, synaptic densities peak across multiple regions of the monkey cortex (Rakic et al., 1986). Coinciding with important developmental changes in somatosensory, visual, and motor skills (Carlson, 1984); this is also the period of time when they begin to exhibit successful performance on the A-not-B task (Diamond & Goldman-Rakic, 1983; 1986). In the human visual cortex, (Huttenlocher & de Courten, 1987) the greatest increases in synaptogenesis occur between the second and eighth months of life, with the most rapid increases between 2 and 4 months; this timing corresponds well with age-related changes in visual orienting (Posner & Raichle, 1994; Posner et al., 1987). Based on the Huttenlocher data (1979), in human infants, the PFC begins to dramatically increase its synaptic density towards the end of the first year, reaching peak levels between the ages of 1 and 2, and then gradually declines towards adult levels. This timing fits well with observed developmental changes in attentional control skills, which first emerge around the end of the first year, and exhibit noticeable improvement between ages 2 and 4.

Much of the existing research on infant brain development has focused on broad, localized regions of the brain (e.g., visual cortex, PFC). Attention network models are fairly specific as to the associated regions and involve long-range connections across spatially separated regions (e.g., fronto-parietal). Examining changes in synaptic connectivity between more specific regions (e.g., medial and lateral PFC) or those across regions (e.g., lateral PFC – parietal) may be necessary in order to trace the development of attention networks. Regions that share temporally correlated activity at rest are believed to constitute functional networks (e.g., Beckman, DeLuca, Devlin, & Smith, 2005; Damoiseaux, Rombouts, Barkhof, Scheltens, Stam, Smith & Beckmann, 2006; Fox, Synder, Vincent, Corbetta, Van Essen, & Raichle, 2005; Fox, Corbetta, Snyder, Vincent, & Raichle, 2006; Fox & Raichle, 2007). Functional MRI studies suggest these networks are already present in infancy (e.g., Fransson, Skiold, Horsch, Nordell, Blennow, Lagercrantz, & Aden, 2007). However, infants who partake in these studies often need to be sedated in order to obtain clean images, and the possible side-effects of these drugs on the results are rarely discussed. Less invasive methodologies that allow infants to remain in an attentive state may be necessary in order to assess the development of neural networks over time.

EEG Coherence as a Tool for Assessing Neural Networks

The electroencephalogram (EEG) is a noninvasive tool for assessing neural activity that can be used to assess longitudinal changes in brain development across infancy (e.g., Bell & Fox, 1992, 1994; Cuevas & Bell, 2011). The EEG signal recorded from the scalp is composed of multiple sine waves cycling at different frequencies. Fourier analysis decomposes the EEG into these different sine waves and estimates the spectral power at each frequency (Bell, 2012). EEG power is theorized to reflect the number of neurons that discharge synchronously from a particular neuronal population (Klimesch, 1999; Pizzagalli, 2007) and is considered an indicator of mental activity.

The EEG can also be used to identify network properties within the brain. EEG coherence is the frequency-dependent squared cross-correlation of the electrical signal at two scalp electrode sites (Thatcher, 2012), and is an indicator of the phase consistency between the activity at these regions. Coherence values range from zero to one: when the phase relationship remains constant (over a specified period of time) then coherence values approach one; if there is no relation in phase (i.e., moment-to-moment changes) then coherence values approach zero. Oscillatory activity at two spatially separated sites that is near constant in phase due to chance alone is statistically improbable, and is thus presumed due to their having shared neural connections (see Thatcher, 2012 for a detailed review). In this way, EEG coherence is often interpreted as a measure of “coupling” or the functional association between two brain regions (Nunez, 1981; 1995; Thatcher, 2012).

Thatcher (1994) has proposed that the coherence value between two EEG recording sites at rest reflects the number and/or strength of synaptic connections between those underlying regions. He and his colleagues have examined longitudinal changes in resting EEG coherence in a sample of over five hundred children from 3 months of age throughout early adulthood (Thatcher, 1992, 1998; Thatcher, Walker & Giudice, 1987; Thatcher, North, & Biver, 2008; Hanlon, Thatcher, & Cline, 2010). The primary focus of these papers was to identify general growth trends in EEG coherence across multiple scalp locations; results indicate that coherence values exhibit cyclical increases and decreases across development, which may reflect a mechanism by which synapses are grown and then selectively pruned. Increases in EEG coherence may be particularly likely during the first year when there is widespread myelination of axons and synaptogenesis (e.g., Huttenlocher, 1990) and when attention networks are theorized to begin developing (Posner & Petersen, 1990; Colombo & Cheatham, 2006).

Researchers have proposed that periods of rapid synaptic growth coincide with the emergence of cognitive functioning (Goldman-Rakic, 1987; Greenough et al., 1987; Thatcher et al., 1987). Changes in EEG coherence prior to and following the emergence of various skills have been reported in the empirical literature and support this view. For example, Bell and Fox (1996) examined EEG coherence in 8-month-old infants with varying amounts of crawling experience (none, 1-4 weeks, 5-8 weeks, 9^+ weeks). Their results indicated significant group differences in EEG coherence within the frontal region: infants who had not yet begun to crawl exhibited the lowest coherence values; those with less than 4 weeks experience crawling exhibited the highest coherence values; and infants with over 9 weeks of crawling experience exhibited low coherence values, not significantly different than infants without crawling experience. Because these data were cross-sectional they cannot directly demonstrate developmental change, however, they do support Greenough's general model. If the differences in coherence were in fact related to individual differences in motor skills, then there may also be differences in relation to developing attention skills towards the end of the first year.

The Current Study

The capacity to control attention plays an important role in early learning and is foundational for the development of higher-level cognitive and self-regulatory abilities. Attentional control emerges during the latter half of the first year, coinciding with significant changes in brain organization. Although researchers have theorized that the development of attentional control is supported by the maturation of neural networks, empirical support for such perspectives is surprisingly scant. EEG coherence is an indicator of the strength and/or number of synaptic connections between two brain regions, and can be analyzed longitudinally to assess the maturation of neural networks. Based on the documented changes in attention that have been reported around the end of the first year, it seems reasonable to suspect that there might be significant changes in coherence during this period, specifically between regions that have been associated with attention networks. Further, variation in the timing or magnitude of these changes may account for individual variation in the development of attentional control skills. To date no studies have assessed changes in EEG coherence within the alpha (6-9 Hz) frequency band longitudinally across infancy within a typically developing sample. The current study addresses this gap, and by examining these changes in relation to developing attention skills, it makes an important first step towards providing empirical support for the development of attention networks in infancy.

Research Questions and Hypotheses

1) Are there age-related changes in attention across the second half of the first year? Theoretical models of attention have suggested that an endogenous attention system emerges towards the end of the first year of life (Colombo, 2001), allowing infants to sustain attention towards complex stimuli in their environment and more flexibly shift attention. Thus, it is expected that towards the end of the first year, infants will exhibit (a) more controlled attention shifting and (b) greater sustained attention towards complex visual stimuli than towards the middle of the first year.

2) Are there age-related changes in EEG coherence across the second half of the first year? Theoretical models of attention networks have emphasized the role of two networks (cingulo-frontal, fronto-parietal) in the emergence of attentional control. EEG coherence is believed to reflect the strength and/or number of synaptic connections between two underlying brain regions; changes in EEG coherence over time may reflect changes in underlying brain organization. Thus, it is expected that towards the end of the first year, EEG coherence will be significantly greater than towards the middle of the first year; specifically, this is expected to be true for (a) medial frontal – lateral frontal and (b) lateral frontal – medial parietal regions.

3) Are there longitudinal relations between EEG coherence and attention during the second half of the first year? If changes in EEG coherence reflect changes in the strength and/or number of synaptic connections between two regions, and attention networks underlie developmental changes in attentional control skills, then changes in EEG coherence during the second half of the first year of life should be associated with changes in attention skills. Thus, it is expected that increases in EEG coherence across the second half of the first year will be positively associated with improvement in attentional control; this is specifically hypothesized to occur for (a) medial frontal – lateral frontal (F3F7, F4F8) and (b) lateral frontal – medial parietal (F7P3, F8P4) pairs.

CHAPTER II

METHODS

Recruitment and Attrition

Data for the current study came from an ongoing longitudinal study, the Cognition, Affect, and Psychophysiology (C.A.P.) Study. The C.A.P. Study is aimed towards identifying trajectories of cognitive and emotional development across infancy and early childhood within a psychobiological framework. Four-hundred six infants and their mothers were initially recruited for the study at two research locations (Blacksburg, Virginia, and Greensboro, North Carolina) via commercial mailing lists, newspaper birth announcements, and word of mouth. Dyads first came into the lab when infants were 5 months old, and were contacted for follow-up visits at 10 months, 2 years, 3 years, and 4 years of age. Mothers in the original sample were an average of 29.36 years old (SD = 5.61) at the time of their infant's birth. Fifty-one percent of the infants were female; 72.9% were White non-Hispanic; and 69.3% had at least one parent with a 4-year college degree.

Participants

The sample for the current study was drawn from the larger study and included only participants who had usable EEG and observed attention data for both the 5- and 10-month visits; this resulted in a sample size of 339 participants. At the 5-month visit, 91.7% of these infants were between 5 and 6 months old; at the 10-month visit, 90.6%

were between 10 and 11 months of age. One-hundred seventy-three (51%) were male; 258 (76.1%) were White/non-Hispanic; and 244 (72%) had at least 1 parent with a 4-year college degree at the time of the 10-month visit. Demographic information for the current sample can be seen in Table 1.

Table 1. Descriptive Information for Study Demographic Variables

	N	%
Infant Sex		
Male	173	51.0%
Infant Ethnicity		
Hispanic	18	5.3%
Infant Race		
European-American	275	81.1%
African-American	43	12.7%
Multi-racial	21	6.2%
Minority Status		
White/non-Hispanic	258	76.1%
Parent Education		
Neither parent has 4-year degree	95	28.0%
1 parent has 4-year degree	72	21.2%
Both parents have 4-year degree	172	50.7%

Measures

Observed visual attention. Visual attention behaviors were observed when infants were 5 and 10 months old during a structured laboratory task (Video 1). Infants were placed in a high-chair (mother seated close by) and watched a 1-minute video musical segment from *Sesame Street*. A video camera was placed on top of the TV monitor in order to capture infant looking behaviors. Data were coded by trained research assistants using the DVD recording of the laboratory session and the Video Coding System software developed by James Long Company (Caroga Lake, NY). Epoch files containing timestamps of all looks towards and away from the video were generated and used to calculate 4 variables: the total number of visual shifts, peak look duration towards the video, average look duration away from the video, and the proportion of time spent attending to the video. The items used to create these variables had internal reliability of .95 and .97 for 5 and 10 months respectively. Peak look duration towards the video has been used as an indicator of sustained attention in much of the existing attention development literature (see Courage, Reynolds, and Richards, 2006, p. 686). Because consecutive looks away from the video (i.e., off task shifts) were not event marked by coders, the total number of visual shifts may be underestimated for some infants. The average look away from the video thus reflects the average total duration of off-task looks; this variable was considered an indicator of whether off task glances were controlled and brief versus relatively long and wandering.

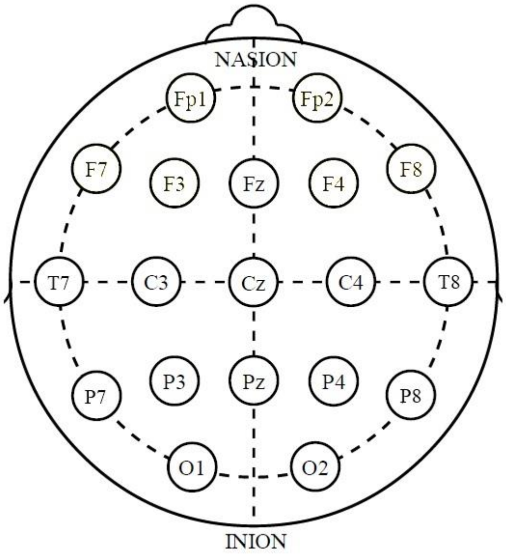
EEG Coherence. EEG was collected continuously throughout the 5- and 10-month laboratory visits; only data from the video attention task were used in analyses.

*EEG collection***.** Upon arriving to the lab, infants were fitted with a lycra stretch cap (Electro-Cap, Inc., Eaton, OH) with electrodes in the 10/20 system pattern (Jasper, 1958; Pizzagalli, 2007; see Figure 1). After the cap was placed on the head, recommended procedures regarding EEG data collection with infants and young children were followed (Pivik, Busby, & Brown, 1993). Specifically, a small amount of abrasive was placed into each recording site and the scalp gently rubbed. Following this, conductive gel was placed in each site. Electrode impedances were measured and accepted if they were below 5 kW. Recordings were made from 16 left and right scalp sites: frontal pole (F1/F2), medial frontal (F3/F4), lateral frontal (F7/F8), central (C3/C4), temporal (T7/T8), lateral parietal (P7/P8), medial parietal (P3/P4), and occipital (O1/O2). All electrode sites were referenced to Cz during recording. The electrical activity from each lead was amplified using separate SA Instrumentation (BioAmps, San Diego, CA) and band- passed from .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 Corporation, Southfield, MI), and the raw data were stored for later analyses. Prior to the recording of each subject, a 10 Hz, 50 mV peak-to-peak sine wave was input through each amplifier. This calibration signal was digitized for 30s and stored for subsequent analysis.

*EEG Coherence analysis***.** 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 non-cephalic reference. Active (e.g., F3, F4) to reference (Cz) electrode distances vary across the scalp. The average reference configuration requires that a sufficient number of electrodes be sampled and that these electrodes be evenly distributed across the scalp. 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; Nunez et al., 1999).

EEG data were artifact scored for eye movements using a peak-to-peak criterion of 50 mV or greater; artifact associated with gross motor movements over 200 mV 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. Coherence within frontal (F1/F2, F3/F4, F7/F8), and between frontal and all other electrode sites (C3/C4, T7/T8, P7/P8, P3/P4, O1/O2) within each hemisphere was computed for the 6-9 Hz frequency band using an algorithm by Saltzberg and colleagues (1986). Only intra-frontal, fronto-central, and fronto-parietal pairs were analyzed in the current study, which resulted in 18 coherence pairs per hemisphere (36).

Figure 1. 10/20 EEG Cap Placement Diagram



CHAPTER III

RESULTS

Missing Data

Participants were only included in the sample if they had some usable EEG *and* observed attention data at both 5 and 10 months. At each time point, less than four percent of participants were missing EEG data from the observed attention task; less than three were missing data for the video attention task. These data were imputed using SPSS multiple imputation. Baseline EEG coherence variables and observed attention data from a different task (not included in this study) were highly correlated with the target variables and were used as predictors. Ten imputed datasets were generated, and imputed values were averaged for each variable.

Analyses

Preliminary analyses consisted of examining the frequencies and distributions of all study variables. Descriptive statistics for the observed attention and EEG coherence variables can be found in Table 2, Table 3, and Table 4 respectively. Due to high kurtosis, square root transformations were performed on both the 5- and 10-month average look away variables. Correlations between demographic and observed attention variables indicated that infant sex and parent education were correlated with some of the observed attention variables (see Table 5).

Table 2. Descriptive Information for Observed Attention Variables

Variables	Min.	Mean	Std. Dev.	Max.	Variance	Skew	Kurtosis
Total shifts (5m)	1.00	8.68	4.31	26.00	18.54	.76	1.15
Total shifts (10m)	1.00	11.65	4.60	30.00	21.18	.63	1.06
Total shifts (ch)	-14.00	2.98	5.86	25.00	34.34	.07	.44
Percent twds. (5m)	1.77	67.31	22.76	100.00	517.90	-.58	-.38
Percent twds. (10m)	6.50	68.99	18.38	100.00	337.72	-.65	.03
Percent twds. (ch)	-67.58	1.69	25.90	84.73	671.05	.20	.06
Peak look twds. (5m)	1.37	16.72	10.83	49.25	117.40	1.03	.50
Peak look twds. (10m)	1.00	13.06	7.55	46.68	56.99	1.71	4.04
Peak look twds. (ch)	-40.14	-3.67	12.11	31.63	146.61	-.64	1.00
Avg. look away (5m)	.00	3.63	3.39	37.87	11.46	4.34	33.60
Avg. look away (10m)	.00	2.57	1.74	11.64	3.02	2.06	5.95
Avg. look away (ch)	.00	-1.06	3.47	9.73	12.06	-2.54	14.93
Avg. look away (5m)$_t$	.00	1.76	.74	6.15	.55	.95	4.42
Avg. look away (10m)$_t$	.00	1.53	.49	3.41	.24	.83	1.75
Avg. look away (ch)$_t$	-3.33	-0.23	.82	2.24	.68	-.30	1.54

$_t$ = transformed variable. ch = change score (10m – 5m).

Table 3. Descriptive Information for 5-Month EEG Coherence Variables

Pair	Min.	Mean	Std. Dev.	Max.	Variance	Skew	Kurtosis
F1F3	.02	.49	.20	.99	.04	.36	.01
F1F7	.00	.47	.16	.93	.03	-.17	.68
F1P7	.05	.27	.09	.65	.01	.33	.59
F1P3	.04	.28	.10	.62	.01	.36	.42
F3F7	.02	.51	.20	1.00	.04	.17	-.35
F3C3	.01	.26	.14	.92	.02	.97	1.76
F3P7	.03	.23	.10	.57	.01	.29	.04
F3P3	.00	.22	.11	.61	.01	.56	.22
F7C3	.01	.16	.11	.83	.01	1.85	6.46
F7P7	.01	.19	.08	.46	.01	.36	-.19
F7P3	.02	.22	.09	.59	.01	.48	.83
F2F4	.01	.46	.19	.97	.04	.23	.00
F2F8	.02	.47	.16	.89	.02	-.43	.17
F2P8	.03	.29	.10	.57	.01	.29	.42
F2P4	.04	.31	.10	.67	.01	.11	.49
F4F8	.01	.56	.25	1.00	.06	.00	-.82
F4C4	.01	.23	.14	.94	.02	1.38	3.44
F4P8	.02	.24	.11	.91	.01	1.73	6.39
F4P4	.03	.24	.10	.57	.01	.47	.52
F8C4	.01	.15	.10	.78	.01	1.68	5.20
F8P8	.02	.20	.09	.47	.01	.39	-.03
F8P4	.01	.24	.09	.57	.01	.32	.48

Table 4. Descriptive information for 10-Month EEG Coherence Variables

Pair	Min.	Mean	Std. Dev.	Max.	Variance	Skew	Kurtosis
F1F3	.03	.54	.18	1.00	.03	.14	.38
F1F7	.01	.52	.15	.93	.02	-.42	1.15
F1P7	.03	.31	.11	.70	.01	.63	.76
F1P3	.02	.33	.11	.57	.01	-.28	-.06
F3F7	.06	.57	.22	1.00	.05	.33	-.43
F3C3	.03	.26	.13	.80	.02	.85	1.39
F3P7	.03	.29	.11	.67	.01	.69	.59
F3P3	.03	.27	.11	.60	.01	.20	-.35
F7C3	.00	.16	.10	.57	.01	.91	1.19
F7P7	.03	.21	.10	.99	.01	1.64	8.55
F7P3	.03	.26	.10	.58	.01	.44	.16
F2F4	.05	.53	.18	.99	.03	.07	.01
F2F8	.01	.54	.16	.94	.02	-.70	.95
F2P8	.02	.32	.11	.73	.01	.55	1.11
F2P4	.00	.35	.11	.63	.01	-.37	.08
F4F8	.07	.56	.23	1.00	.05	.24	-.61
F4C4	.01	.23	.12	.99	.01	1.31	4.62
F4P8	.03	.29	.11	.93	.01	1.01	3.78
F4P4	.03	.29	.11	.64	.01	.12	-.09
F8C4	.01	.16	.10	.55	.01	1.24	2.04
F8P8	.02	.21	.09	.49	.01	.24	-.33
F8P4	.02	.28	.10	.66	.01	.13	.13

Table 5. Pearson Correlations among Demographic and Observed Attention Variables.

Variables	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Sex	-.06	-.06	.13*	.17*	.04	-.12*	-.01	.10*	-.14*	-.09	.06	.07	-.13*	-.13*
2. Minority		-.29**	.01	-.05	-.05	.03	-.02	-.04	.02	.04	.01	-.01	.01	.02
3. College			-.08	-.04	.03	.21**	.21**	-.04	.13*	.13*	-.04	-.14*	-.18*	.01
4. Total shifts (5m)				.14*	-.63**	-.38**	-.19*	.20**	-.68**	-.14*	.52**	-.15*	.08	.18*
5. Total shifts (10m)					.69**	-.10*	-.31**	-.14*	-.16*	-.61**	-.24**	-.02	-.23**	-.08
6. Total shifts (ch)						.20**	-.11*	-.25**	.37**	-.38**	-.57**	.00	-.23**	-.19*
7. Percent twds. (5m)							.22**	-.72**	.76**	.19*	-.56**	-.72**	-.17*	.62**
8. Percent twds. (10m)								.52**	.19*	.66**	.24**	-.12*	-.78**	-.27**
9. Percent twds. (ch)									-.53**	.31**	.67**	.55**	-.40**	-.74**
10. Peak look twds. (5m)										.17*	-.79**	-.39**	-.09	.33**
11. Peak look twds. (10m)											.47**	-.07	-.33**	-.17*
12. Peak look twds. (ch)												.30**	-.13*	-.35**
13. Avg. look away$_t$ (5m)													.21**	-.87*
14. Avg. look away$_t$ (10m)														.30**
15. Avg. look away$_t$ (ch)														

*$p < .05$. ** $p < .01$. $_t$ = transformed variable. ch = change score.

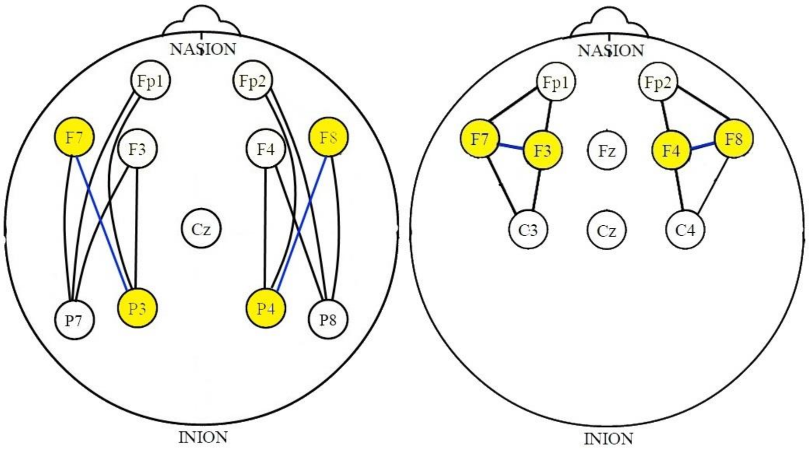
Table 6. Descriptive Information for EEG Coherence Change Scores

Pair	Min.	Mean.	Std. Dev.	Max	Variance	Skew	Kurtosis	% <0
F1F3	-.79	.04	.27	.84	.08	-.09	.28	40.1
F1F7	-.78	.04	.22	.55	.05	-.37	1.55	38.6
F1P7	-.44	.04	.14	.41	.02	-.10	.03	37.2
F1P3	-.53	.05	.15	.42	.02	-.30	.23	34.8
F3F7	-.64	.07	.25	.88	.06	.08	.21	38.3
F3C3	-.70	.07	.23	.58	.05	-.29	.43	35.4
F3P7	-.36	.03	.14	.52	.02	.26	.94	38.9
F3P3	-.46	.04	.15	.53	.02	-.19	.17	36.6
F7C3	-.76	.05	.30	.87	.09	.09	-.12	44.8
F7P7	-.65	.00	.17	.66	.03	-.10	1.63	46.3
F7P3	-.39	.05	.14	.57	.02	.09	.42	34.8
F2F4	-.45	.05	.14	.45	.02	-.17	.17	35.1
F2F8	-.79	.00	.32	.84	.10	.05	-.21	51.6
F2P8	-.72	.00	.17	.73	.03	-.15	2.13	51.6
F2P4	-.70	.05	.16	.74	.03	-.33	4.26	32.4
F4F8	-.42	.05	.15	.49	.02	-.18	.37	36.0
F4C4	-.59	.00	.13	.47	.02	-.32	1.67	47.8
F4P8	-.34	.02	.13	.76	.02	.52	2.67	44.8
F4P4	-.32	.04	.12	.43	.02	.13	-.03	38.3
F8C4	-.63	.00	.14	.40	.02	-.62	2.24	43.1
F8P8	-.38	.02	.12	.41	.02	.01	.22	42.5
F8P4	-.36	.04	.14	.44	.02	-.07	.23	35.4

Note: change scores were calculated by subtracting 5-month values from 10-month values

To assess whether there are age-related changes in attention, a series of paired samples *t* tests were run on the observed attention variables. These tests specifically assessed whether there were significant differences between the mean values for each variable at the two time points. To assess whether there were age-related changes in EEG coherence, a series of paired samples *t* tests were run on the EEG coherence variables. These tests specifically assessed whether there were significant differences between the mean EEG coherence values at the two time points. Tests were run for hypothesized as well as neighboring coherence pairs for comparison purposes (see Figure 2). To assess whether changes in EEG coherence were associated with changes in observed attention behaviors, a series of multivariate multiple regression tests were run. Because observed attention behaviors were highly correlated (see Table 3), multivariate multiple regression analysis was the most powerful and parsimonious way to assess the relations between the EEG coherence variables and observed attention variables. 10-Month observed attention behaviors served as the dependent variables; EEG coherence change scores (10-month – 5-month) and 5-month attention behaviors served as independent variables. Separate tests were run for intra-frontal and fronto-parietal regions and for left and right hemispheres, resulting in 4 total tests. Significant univariate tests were followed up with multiple linear regression analyses.

Figure 2. Analyzed Coherence Pairs.



Note: hypothesized pairs are filled in yellow with blue connecting lines

Are there age-related changes in attention across the second half of the first year? Because attentional control is theorized to come online during the second half of the first year of life, it was expected that attention behaviors at 10 months of age would be more controlled than at 5 months of age. Specifically, it was hypothesized that at 10 months, peak look towards the video, total percent looking towards the video, and total number of shifts would be greater and that the average look away would be lesser than at 5 months. Results from the paired samples *t* tests are presented in Table 7. Consistent with the hypothesis, total visual shifts were significantly greater at 10 months than at 5 months, M_D = 2.98, SD = 5.86, *t*(338) = 9.36, p < .001, and the average look away was significantly lesser at 10 months than at 5 months, M_D = .023, SD = .82, *t*(338) = -5.09, p < .001. However, total percent looking (towards the video) was not significantly different between the two time points, M_D = 1.69, SD = 25.90, *t*(338) = 1.20, p = .23, and peak look duration towards the video was significantly *lesser* at 10 months than at 5 months, $M_{D =}$ -3.67, SD = 12.11, $t(338) = -5.57$, $p = <.001$, the opposite direction of the hypothesis.

Are there age-related changes in EEG coherence across the second half of the first year? Because attention networks are thought to undergo significant maturation during the second half of the first year, it was hypothesized that EEG coherence values between medial frontal – lateral frontal (F3F7, F4F8) and lateral frontal – medial parietal (F7P3, F8P4) pairs would be significantly greater at 10 months than at 5 months. Results from the paired samples *t* tests are presented in Tables 8 and 9. Within the frontal region, EEG coherence values between all left frontal sites (F1F3, F1F7, F3F7) were significantly greater at 10 months than at 5 months. In the right hemisphere, only coherence between frontal polar and medial frontal (F2F4) and lateral frontal (F2F8) sites were significantly greater at 10 months than at 5 months. Across hemispheres, coherence values between frontal and central sites (F3C3/F4C4, F7C3/F8C4) were not significantly different between the two time points. For all fronto-parietal coherence pairs, in both hemispheres, 10-month EEG coherence values were significantly greater 5-month values. Effect sizes (Cohen's *d*) for these differences ranged from small to medium.

Are there longitudinal relations between changes in EEG coherence and changes in attention across the second half of the first year? Because the maturation of neural attention networks is theorized to underlie the changes in attention during the second half of the first year, it was hypothesized that as coherence values between medial frontal –

lateral frontal (F3F7, F4F8) and lateral frontal – medial parietal (F7P3, F8P4) increased, the observed attention variables would also change in the hypothesized directions. Across all four tests, EEG coherence variables were not significant predictors of the set of observed attention behaviors. However, univariate tests indicated that some of the EEG coherence change scores were significantly associated with changes in peak look duration. Follow-up multiple linear regression tests were conducted with 10-month peak look duration as the dependent variable; 5-month peak look duration and days between visits were entered in at the first step; EEG coherence change scores were entered in at the second step. Results from these follow-up tests are presented in Tables 10, 11, and 12. For intra-frontal pairs, the left medial frontal – lateral frontal (F3F7) change score was positively associated with peak look duration towards the video at 10 months ($\beta = .13$, $p = .04$). For left fronto-parietal pairs, the F1P7 change score was negatively associated with 10-month peak look duration ($\beta = -.20$, $p = .008$). For right fronto-parietal pairs, the F2P4 and F4P8 change scores were positively associated with 10-month peak look duration ($\beta = .22$, $p = .007$; $\beta = .15$, $p = .04$). However, across these tests, EEG coherence change scores did not explain a significant amount of *unique* variance above and beyond 5-month peak look duration.

Table 7. Paired-Samples *t* Tests for Observed Attention Variables

Behavior	Mean Difference	Std. Deviation	Std. Error Mean	*t*	*d*
Total shifts	2.98	5.86	0.32	9.36**	.67
Percent twds.	1.69	25.90	1.41	1.20	.08
Peak look twds.	-3.67	12.11	.66	-5.57**	-.39
Avg. look away$_t$	-.23	.82	.04	-5.09**	-.36

**p* < .05. ** *p* < .01; $_t$ = transformed variable; *df* = 338 across tests; *d* = Cohen's *d*

Table 8. Paired-Samples *t* Tests for Intra-frontal EEG Coherence Variables

Pair	Mean Difference	Std. Deviation	Std. Error Mean	*t*	*d*
F1F3	.04	.27	.01	2.96**	.23
F2F4	.07	.25	.01	5.22**	.38
F1F7	.04	.22	.01	3.84**	.29
F2F8	.07	.23	.01	5.39**	.42
F3F7	.05	.30	.02	3.20**	.24
F4F8	.00	.32	.02	-.15	-.01
F3C3	.00	.17	.01	.23	.02
F4C4	.00	.17	.01	-.34	-.03
F7C3	.00	.13	.01	-.12	-.01
F8C4	.00	.14	.01	.62	.05

**p* < .05. ** *p* < .01; *df* = 338 across tests; *d* = Cohen's *d*

Table 9. Paired-Samples *t* Tests for Fronto-parietal EEG Coherence Variables

Pair	Mean Difference	Std. Deviation	Std. Error Mean	*t*	*d*
F1P7	.04	.14	.01	4.58**	.35
F2P8	.03	.14	.01	3.37**	.25
F1P3	.05	.15	.01	6.26**	.48
F2P4	.04	.15	.01	4.73**	.38
F3P7	.05	.14	.01	7.19**	.52
F4P8	.05	.16	.01	5.89**	.45
F3P3	.05	.14	.01	6.30**	.45
F4P4	.05	.15	.01	6.17**	.48
F7P7	.02	.13	.01	2.54*	.19
F8P8	.02	.12	.01	2.69*	.20
F7P3	.04	.12	.01	5.87**	.41
F8P4	.04	.14	.01	5.50**	.42

**p* < .05. ** *p* < .01; *df* = 338 across tests; *d* = Cohen's *d*

Table 10. Univariate Multiple Regression Predicting 10-Month Peak Look Duration from Left Intra-frontal EEG Coherence Change

Variable	Model 1			Model 2		
	B	SE	β	B	SE	β
Days between visits	.00	.03	.00	.01	.03	.02
Peak look twds. (5m)	.12	.04	.17**	.12	.04	.17**
F1F3 change score				-.10	1.68	.00
F1F7 change score				1.11	2.17	.03
F3F7 change score				3.35	1.61	.13*
R^2			.03**			.05**
R^2 Δ			.03**			.02
F for R^2 Δ			4.99**			2.52

Note: *p < .05. ** p < .01; *df* = 338 across tests; *d* = Cohen's *d; R^2 is adjusted*

Table 11. Univariate Multiple Regression Predicting 10-Month Peak Look Duration from Left Fronto-parietal EEG Coherence Change

Variable	Model 1			Model 2		
	B	*SE B*	*β*	*B*	*SE B*	*β*
Days between visits	.00	.03	.00	.01	.03	.01
Peak look twds. (5m)	.12	.04	.17	.12	.04	.17
F1P7 change score				-10.55	3.96	-.20**
F1P3 change score				3.12	3.87	.06
F3P7 change score				4.62	4.14	.08
F3P3 change score				-6.39	4.17	-.12
F7P7 change score				1.97	3.71	.03
F7P3 change score				3.54	4.56	.06
R^2			.03**			.06**
R^2 Δ			.03**			.03
F for R^2 Δ			4.99**			1.58

*$p < .05$. **$p < .01$

Table 12. Univariate Multiple Regression Predicting 10-Month Peak Look Duration from Right Fronto-parietal EEG Coherence Change

Variable	Model 1			Model 2		
	B	SE	*β*	B	SE	*β*
Days between visits	.00	.03	.00	-.01	.03	-.01
Peak look twds. (5m)	.12	.04	.17**	.12	.04	.18**
F2P8 change score				-5.96	3.82	-.11
F2P4 change score				10.81	3.98	.22*
F4P8 change score				7.14	3.43	.15*
F4P4 change score				-4.29	4.32	-.08
F8P8 change score				-2.80	4.14	-.05
F8P4 change score				-.34	4.45	-.01
R^2			.02**			.06**
R^2 Δ			.03**			.03
F for R^2 Δ			4.99**			1.79

$^*p < .05$. $^{**}p < .01$

CHAPTER IV

DISCUSSION

The present study aimed to investigate the developmental changes in attention and EEG coherence across the second half of the first year of life and the longitudinal associations between these changes. Because attention is considered foundational for the development of many later social, emotional, and behavioral competencies, understanding the factors that are associated with its development is particularly important area of inquiry. The maturation of attention networks is theorized to underlie the developmental changes in attention across the first year of life (Colombo, 2001; Posner & Petersen, 1990). However, very few researchers have attempted to empirically demonstrate the development of these networks in infancy or their relation with developing attention skills. EEG coherence is an indicator of the phase consistency between the brain electrical activity at two spatially separated neuronal populations that can be attributed to underlying network properties (Thatcher, 2012). By analyzing changes in EEG coherence across infancy in relation to developing attention skills, this study makes an important first step towards providing empirical support for attention network models. The findings presented provide extended information regarding the changes in attention and brain organization that are taking place during the latter half of the first year, and the interrelations between these changes.

Overview and Implications of Main Findings

The first research question asked in the current study was whether there are significant changes in observed attention behaviors between 5 and 10 months. It was expected that by 10 months of age, infants would exhibit greater sustained attention and controlled attention shifting while watching a dynamic video clip. Consistent with this hypothesis, at 10 months of age, the total number of visual shifts was significantly greater and the average look away from the video was significantly lesser than at 5 months. These findings suggest that by 10 months of age, infants were better able to flexibly disengage and shift their attention. However, the total percent looking was not significantly different across the two time points, and contrary to the hypothesis, peak look duration towards the video was significantly *lesser* at 10 months than at 5 months. This particular finding is inconsistent with previous research that has found linear increases in peak look duration during this time when viewing complex visual stimuli (Courage, Reynolds & Richards, 2006). These results are more consistent with developmental changes in look duration towards *simple* stimuli, which has been found to exhibit linear declines during this time due to improvement in processing speed (Rose, Feldman & Jankowski, 2002). Despite using similar stimuli as previous research in this area (see Richards, 2010), it does not appear that this task elicited sustained attention from most infants in this study. However, on average, infants in this study exhibited improvement in attentional flexibility and overall processing speed between 5 and 10 months of age.

The second research question addressed in the current study was whether there are significant changes in EEG coherence across the latter half of the first year. It was predicted that EEG coherence values for medial frontal – lateral frontal (F3F7, F4F8) and lateral frontal – medial parietal (F7P3, F8P4) pairs, specifically, would be significantly greater at 10 months than at 5 months, as these regions have been implicated in attention networks that are supposedly maturing during this time. Consistent with the hypothesis, coherence values for left medial frontal – lateral frontal (F3F7) pairs and for lateral frontal – medial parietal (F7P3, F8P4) pairs were significantly greater at 10 months than at 5 months, suggesting that synaptic connections between these regions were growing during this time. However, more than just the hypothesized pairs exhibited this pattern; most intra-frontal and all neighboring fronto-parietal pairs included in the analyses exhibited significant mean increases in EEG coherence across the two time points, suggesting that synaptic growth is not unique to the hypothesized regions. This is not surprising, as brain growth in infancy is particularly widespread and more than just attention skills are developing during this time. However, it does not appear that specific neural networks are developing during this time but that synaptic connections—both short- and long-range—are rapidly growing throughout the infant brain.

One of the few pairs that failed to exhibit significant mean differences in EEG coherence values across the two time points was right medial frontal – lateral frontal (F4F8) pairs, which was specifically hypothesized. This suggests that, on average, synaptic connections between these regions did not significantly increase in strength and/or number during this time. However, this does not necessarily indicate an overall lack of growth or change. For any single coherence pair, between one-third to one-half of the sample had change scores less than zero (see Table 6); and for this particular pair (F4F8) roughly half of the sample had negative change scores. As mentioned previously, many researchers have proposed that there is initially an overproduction of synaptic connections that are subsequently pruned (Greenough et al., 1987). Theoretically, coherence values would decline if unused or unnecessary synaptic connections were being pruned away. If the infants in this study were in different phases of brain growth, coherence values could have significantly changed for most infants just not all in the same direction. Because this period of time has been theorized to involve the emergence of skills, mean level increases in EEG coherence were expected. Consistent with expectations, significant mean level *increases* were found for most intra-frontal and all fronto-parietal pairs analyzed in this study, supporting the hypothesis that synaptic connections are increasing in strength and/or number between 5 and 10 months of age.

The third research question asked in this study was whether changes in EEG coherence would be longitudinally associated with changes in observed attention behaviors. Based on theoretical models of attention development, it was expected that as EEG coherence change values for medial frontal – lateral frontal (F3F7, F4F8) and lateral frontal – medial parietal (F7P3, F8P4) pairs increased, there would be linear increases in observed attention behaviors indicative of sustained attention and controlled attention shifting. Because the 10-month observed attention behaviors were highly correlated at both time points ($r > .3$), multivariate multiple regression tests were run to assess whether changes in EEG coherence were associated with changes in the set of attention behaviors as a whole. Multivariate tests were not significant, indicating that the attention behaviors, although highly correlated, were not collectively associated with changes in EEG coherence.

Results from univariate follow-up tests indicated that changes in EEG coherence were only predictive of the change in peak look duration. Results from these tests were partially in support of the hypothesis. Consistent with expectations, as coherence between left medial frontal – lateral frontal (F3F7) pairs increased, peak look duration also tended to increase. This suggests that synaptic growth between these regions was associated with improvement in sustained attention. Further, because this association was not found for neighboring pairs (F1F3, F1F7), it would seem to lend support to neural network models that have implicated the medial and lateral frontal regions specifically in the development of attentional control. However, contrary to the hypothesis, changes in right intra-frontal EEG coherence was not associated with changes in attention. This is inconsistent with attention network models and theoretical assertions that the right hemisphere is particularly involved in sustained visual attention (Petersen & Posner, 2012).

Changes in both left and right fronto-parietal coherence were also significantly associated with changes in peak look duration, however, not for the hypothesized pairs (F7P3, F8P4). Rather, as coherence values for right frontal polar – medial parietal (F2P4) and medial frontal – lateral parietal (F4P8) pairs increased, peak look duration also increased. This suggests that as synaptic connections between these regions increased, infants were able to sustain longer peak looks towards the video. However, in the left hemisphere, the direction of this relation was reversed: as coherence values between frontal polar and lateral parietal (F1P7) regions increased, peak look duration *decreased*. Given that most infants in this sample exhibited declines in peak look duration over time, likely due to improvement in overall processing speed, one interpretation of this finding is that infants who showed increases in left fronto-parietal coherence were better able to disengage and shift attention at 10 months. However, it is unclear why this would have impacted peak look duration and not total visual shifts. Collectively, these findings provide only meager support for the importance of fronto-parietal networks and developing attentional control. Further, they specifically do not support attention networks models that have uniquely emphasized lateral frontal regions in these networks. Rather, results from this study suggest that frontal polar (F1/F2) regions may be more strongly associated with attention development.

Changes in EEG coherence between 5 and 10 months of age, although significantly associated with changes in peak look duration, did not account for a significant amount of additional variance in the model to be considered meaningful predictors. Further, all of the significant longitudinal relations between EEG coherence and attention in this study involved the peak look duration score. Although on average, peak look duration declined between the two time points, roughly two-fifths of the sample had increases in peak look duration between visits, suggesting that infants in this sample may have been at different developmental levels. Perhaps if the infants in this study were observed at slightly older ages (e.g., 7 and 12 months) the majority of infants would have exhibited the expected direction of change. Understanding the mechanisms underlying these group differences will be an important aim for future research.

Strengths, Limitations, and Future Directions

The current study adds to an already large body of literature documenting changes in observed attention behaviors across infancy. The relatively large size and socioeconomic diversity of the current sample make it an especially unique addition to this literature. However, the observed attention measures used in this study were a serious limitation. For one, it is not necessarily the case that they are exclusively due to endogenous attention processes. Infants who frequently looked towards their mother during the task, for example, could have the same total visual shifts as those who were distracted by things in the room. Even if these kinds of looks had distinguished by coders, there is still no way to be certain that a look is an internally controlled look. Second, because peak look duration did not change in the expected direction, its significant associations with changes in EEG coherence in this study are not entirely clear. The reliance on measures of looking behavior as indicators of endogenous attention has been criticized by many researchers (see Aslin, 2007 for a review). Unless researchers can find a reliable way of distinguishing exogenous and endogenous looks their continued use will not advance scholarship in this area. More innovative methodologies are needed to fully understand the development of this important skill.

Although EEG coherence has been analyzed in relation to cognitive functioning in infants and young children, very few have analyzed it longitudinally. Thus, this study also makes an important contribution to a surprisingly small body of literature on brain development in infancy. By exploring mean differences in EEG coherence across 5 and 10 months, the data provide information regarding the changes in brain organization that are taking place during this time. Results indicated that for most infants, synaptic connectivity is rapidly increasing during the second half of the first year—both within the frontal region and between frontal and parietal regions. Although data were only assessed at two time points, this is consistent with existing literature on human brain development in infancy (Huttenlocher, 1979).

As mentioned previously, although mean level trends were observable across the entire sample, there was considerable individual variation in how both attention and EEG coherence changed between 5 and 10 months. For a given EEG coherence pair, around one-third of infants exhibited declining values; regarding the observed attention measures, between one-third and two-fifths of infants changed in the opposite direction of the mean pattern of change. Individual variation is important for detecting the relations between variables; however, variation in the direction of change can be problematic when relying on mean based analytic procedures. Perhaps infants who exhibit sustained attention at earlier ages show unique patterns of brain growth that were not captured in this particular study. Future research in this area should conduct similar analyses using group-based trajectory modeling techniques in order to better understand individual differences in these associations.

Most importantly, the current study makes an important contribution towards a very underdeveloped body of literature in providing empirical support for the development of attention networks in infancy. By relating changes in attention to changes in EEG coherence across the second half of the first year, this study was able to directly test the theoretical assertions made by Posner, Colombo and their colleagues regarding the role of neural networks in the emergence of endogenous, attentional control. Although the results from this study did find statistically significant associations between changes in EEG coherence and observed attention behaviors, the effect sizes were quite small, and they did not account for a significant amount of unique variance in predicting 10-month peak look duration. Changes in brain organization may account for a greater portion of variance in attention development among infants who are developing along similar trajectories. Future studies should investigate whether changes in EEG coherence during this time are predictive of attention at later ages (e.g., 24 months).

Although the theories that were being tested in this study have proposed that changes in brain organization underlie changes in attention across the first year, it is entirely possible that the reverse is also true. That is, changes in attention could also contribute towards changes in brain organization. Theoretical perspectives on brain development have acknowledged that experience plays a critical role in the pattern of formation and pruning of synaptic connections (Greenough et al., 1987). Further, most psychobiological approaches to the study of early behavioral development consider the functioning across multiple levels of analysis to be bidirectional (Gottlieb, 2007). Future studies that aim to investigate the developmental relations between brain organization and attention should entertain both possibilities.

In conclusion, the development of controlled attention is critical for the learning that occurs in infancy, and foundational for the development of higher-level cognitive and self-regulatory skills. Identifying the factors that account for variation in the emergence of this capacity is an important aim for developmental scientists. Attention network models are cited frequently in the cognitive development literature, yet have received very little attention from researchers in terms of empirical validation. Results from the current study do not provide much support for the role of neural networks in the development of attentional control. Much additional research is needed to fully understand the nature of individual differences in this domain of neurobehavioral development. Hopefully, the results, implications, and acknowledged limitations of this study can provide guidance for future investigations.

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