Changes in Brain Functioning From Infancy to Early Childhood: Evidence From EEG Power and Coherence During Working Memory Tasks

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Using measures of EEG power and coherence with a longitudinal sample, the goal of this study was to examine developmental changes in brain electrical activity during higher order cognitive processing at infancy and early childhood. Infants were recruited at 8 months of age and performed an infant working-memory task based on a looking version of the A-not-B task. At age 4.5 years, one half of the original sample returned for a follow-up visit and were assessed with age-appropriate workingmemory tasks. At infancy, working memory was associated with changes in EEG power from baseline to task across the entire scalp, whereas in early childhood, working memory was associated with changes in EEG power from baseline to task at medial frontal only. Similar results were found for the EEG coherence data. At infancy, working memory was associated with changes in EEG coherence from baseline to task across all electrode pairs and by 4.5 years of age, EEG coherence changed from baseline to working-memory task at the medial frontal/posterior temporal pairs and the medial frontal/occipital pairs. These EEG power and coherence longitudinal data suggest that brain electrical activity is widespread during infant cognitive processing and that it becomes more localized during early childhood. These findings may yield insight into qualitative changes in cortical functioning from the infant to the early childhood time periods, adjustments that may be indicative of developmental changes in brain specialization for higher order processes.

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Developmental researchers propose that the rudiments of many higher order child and adult cognitive processes have their foundations in infancy. For example, infants exhibit some level of executive functioning (Roberts & Pennington, 1996), readily perform tasks requiring working memory and inhibitory control (Bell & Adams 1999; Diamond, Prevor, Callender, & Druin, 1997), and employ effortful control of attention (Posner & Rothbart, 2000). The brain area associated with these types of cognitive processes in children and adults is the frontal lobe, a cortical area that many early EEG researchers thought was too immature to function in infancy (see Bell, 1998, for a discussion). However, contemporary researchers employing brain imaging techniques report that infants exhibit an increase in glucose metabolism in the frontal cortex during the last half of the first year of life (Chugani, 1994; Chugani & Phelps, 1986) and show increases in frontal EEG activity, as well as increases in other areas, during working-memory tasks (Bell, 2001, 2002). Thus, infants appear to display elementary forms of higher order cognitive behaviors, and these behaviors may be associated with some level of frontal functioning, although they are probably associated with other brain areas as well (Nelson, 1995). The purpose of this study was to examine the EEG activity associated with frontal functioning during infancy and early childhood. If infants exhibit fundamental forms of the higher order cognitive behaviors performed by young children, then it may be that infant EEG activity during cognitive processing is likewise a fundamental form of the EEG activity exhibited by young children.

Studies of the development of brain electrical activity do suggest age-related shifts in patterns of interconnections among different areas of the cortex. An example is Thatcher's research using baseline (i.e., not task-related) measures of EEG coherence, the frequency-dependent squared cross-correlation of electrical signals between two scalp electrode sites (Nunez, 1981; Thatcher, Krause, & Hrybyk, 1986). Thatcher has proposed that coherence is a designation of the strength and number of synaptic connections (Thatcher, 1994) and, thus, is reflective of the level of connectivity between two EEG recording sites (and, perhaps, two cortical areas). EEG coherence values follow a cyclical pattern of increases (greater connectivity) and decreases, and Thatcher has noted five growth periods in his cross-sectional coherence data. Period 1, from birth to age 3, is characterized as "topographically scattered developmental change" (Thatcher, Walker, & Giudice, 1987, p. 1113), with coherence values from each electrode pair across the scalp displaying no obvious developmental pattern. After this first period, coherence values from different electrode pairs become more synchronized and show simultaneous fluctuations. Thus, the infant brain may be organized differently and may have cortical connections that operate in a different manner than in the child brain.

Other studies of brain electrical activity have focused on EEG frequency or power values when describing developmental shifts. The classic longitudinal EEG data set begun by Lindsley (1939) and reanalyzed by Henry (1944) included both infants and children. These EEG data show a gradual change in the EEG toward

higher frequencies after 12 months of age and then sudden frequency changes prior to age 4. Cross-sectional data sets show changes in EEG activity around age 2 (Gibbs & Knott, 1949) or age 3 (Corbin & Bickford, 1955). These older data sets focused only on occipital scalp recordings.

More recent data sets have utilized whole head EEG baseline recordings. Hudspeth and Pribram (1992) reanalyzed the Matousek and Petersen (1973) cross-sectional data, one of the most analyzed EEG data sets, and reported evidence for stages or "growth spurts" in EEG development. The stages of EEG maturation reported by these researchers coincide with data on regional brain development (e.g., Huttenlocher, 1994). Thus, using both EEG power and EEG coherence data, there is evidence of qualitative changes in brain electrical activity during infancy and early childhood. Both the Matousek and Petersen (1973) EEG power data and the Thatcher (Thatcher et al., 1986; Thatcher et al., 1987) EEG coherence data were collected without cognitive or behavioral complements, however. Fischer has noted the need for precise and simultaneous brain–behavior assessments to detect continuities and discontinuities in brain and cognitive development during childhood (Fischer & Rose, 1994).

Working-memory tasks offer the possibility of simultaneous brain-behavior assessments in both infants and young children. Infant working-memory tasks include the traditional Delayed Response, which is perhaps the most consistently used measure of prefrontal functioning (Luciana & Nelson, 1998), and its corollary, the Piagetian A-not-B task. Diamond (1990) has reported that both human infants and nonhuman primate infants demonstrate identical developmental progression on Delayed Response and A-not-B. The two tasks are very similar, with the only difference being the rule for deciding in which of two locations an attractive toy is to be hidden. The pattern of hidings for A-not-B is infant driven, whereas the pattern of hidings for Delayed Response is experimenter driven. During the infant working-memory task, the research participants are required to remember information across a delay period and update memory representations of that information from trial to trial. As distraction, participants are not allowed to maintain attentional focus to the information during the delay and must do so in the presence of interference from information from the previous trial. These are requirements for classic working-memory tasks, and Delayed Response and A-not-B fulfill these requirements (Engle, Kane, & Tulholski, 1999; Kane & Engle, 2002).

Infant EEG recorded during the A-not-B infant working-memory task exhibits an increase in 6–9 Hz power values, relative to baseline, at both anterior and posterior scalp locations at 8 months of age (Bell, 2002). Other researchers have employed a hiding task similar to the A-not-B task in that it requires attentional focus during delay. That task likewise results in increases in 6–9 Hz EEG power, relative to baseline, at multiple anterior and posterior scalp locations at 8–10 months of age (Orekhova, Stroganova, & Posikera, 2001). Thus, during infant performance of working-memory tasks, brain electrical activity appears to be relatively widespread because changes in EEG power values across the entire scalp, rather than at specific scalp locations, are associated with cognitive processing.

To date, only one research study has examined task-related EEG during working-memory performance in early childhood, reporting an increase in ln 6–9 Hz EEG power from baseline to task for the frontal scalp electrodes only (Wolfe & Bell, 2004). Working memory was measured with the Day-Night Stroop test (Diamond et al., 1997; Gerstadt, Hong, Diamond, 1994), a widely used working-memory assessment for preschool children. During this preschool working-memory task, the research participants are required to hold two rules in mind across a series of trials and update memory representations of that rule information from trial to trial. As a distraction, participants are constantly given trials with conflicting information during which they must use the two rules and they must do so in the presence of interference from information from the previous trial. These task requirements are comparable to those of the infant working-memory task and although this task has not yet been studied in relation to brain function, it is hypothesized to require the functions of the dorsolateral prefrontal cortex (Diamond et al., 1997).

The paucity of brain–behavior research in preschool children is disturbing because early childhood is a time when many advances are being made in working-memory abilities (Diamond & Taylor, 1996; Diamond et al., 1997; Gerstadt et al., 1994; Luciana & Nelson, 1998; Welsh, Pennington, & Groisser, 1991). Considerably more studies of brain–behavior functioning have been accomplished with older, school-age children. For example, during working-memory tasks with children ages 8 to 10, lower frontal EEG power values were associated with poor task performance (Fernandez et al., 1998). fMRI studies with this age group demonstrate prefrontal involvement during verbal working-memory tasks (Casey et al., 1995) and prefrontal and posterior parietal involvement during spatial working-memory tasks (Klingberg, Forssberg, & Westerberg, 2002; Nelson, Monk, Lin, Carver, Thomas, & Truwit, 2000). Thus, it appears that cortical organization is more specialized for function during later childhood than during infancy.

Although there are systematic longitudinal investigations of the ontogeny of the EEG from infancy to childhood (see Bell, 1998, for a review), there are no longitudinal investigations of the development of higher order cognitive functioning, such as working memory, across infancy and childhood. The only infancy-to-childhood study of the development of working memory was reported by Diamond et al. (1997). However, that project had three groups of research participants—-infants, toddlers, preschoolers—-with short-term longitudinal methodology within each age grouping. In that Diamond study, the working-memory task for the infant participants was A-not-B and the working-memory task for the toddlers was A-not-B with invisible displacement, a variation of the infant A-not-B task in which the container with the object is hidden rather than just the object itself being hidden as in the infant A-not-B task. The working-memory task for the preschool participants was the Day-Night Stroop task, as well as Luria's tapping task, and the Three Pegs task (Diamond et al., 1997). Age-related performance within each developmental period is reported, but no across-developmental-period assessments were made.

Thus, the state of the literature is such that there are longitudinal investigations of EEG development spanning infancy and early childhood. There are reports of qualitative shifts in brain electrical activity during this time period, and based on Piaget's theory, we know that there are qualitative shifts in cognition from infancy to early childhood. But are these qualitative shifts in the EEG also evident when the same cognitive skill, such as working memory, is required for both infant and preschool tasks?

Using measures of EEG power and EEG coherence with a longitudinal sample, the goal of this study was to examine brain–behavior relations across these two periods in the life span and to determine whether there were changes in brain functioning during higher order cognitive processing (i.e., working memory) between infancy and early childhood. We predicted that EEG power values would show increased localization of cognitive processing between infancy and early childhood and that EEG coherence values would likewise highlight this increased specificity in brain–behavior functioning.

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 participants in this study and were recruited from birth announcements placed in the local news-paper. 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 8.75 months of age, so that only 3 weeks separated the oldest and youngest infants in the study. Parents were paid for their infants' participation in the study.

When the children were 4 years of age, it was possible to locate and contact 43 of the families. Twenty-seven families were still in the local area and 25 of these families agreed to participate in the study. (One family was too busy and one family reported that the child was too shy to participate.) The returning children were all Caucasian and returned to the lab between 52 and 56 months of age. Children were given a gift of markers and drawing tablet for participation in the study.

Procedures

EEG technique at infancy and early childhood. For both laboratory visits, EEG recordings were accomplished during baseline and during an

age-appropriate 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.

EEG was recorded using a stretch cap (Electro-Cap, Inc.) 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 gently rubbed. Following this, conductive gel provided by the cap manufacturer was placed in each site. Electrode impedances were measured and accepted if they were below 5K 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 1 to 100 Hz. Activity for each lead was displayed on the monitor of a 100 MHz acquisition computer. The EEG signal was digitized online 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.) and the raw data were stored for later analyses.

Baseline EEG at infancy and early childhood. At the infant visit, 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 talk to infants during the EEG recording.

During the child visit, baseline EEG was recorded for 1 min while the child sat in a chair and watched a Sesame Street film clip. Likewise, this procedure quieted the child and yielded minimal eye movements and gross motor movements. Again, mothers were instructed not to talk to children during the EEG recording. Immediately after baseline at infancy and early childhood, the recording of EEG continued as the working-memory task was administered.

Infant working-memory/inhibitory control task. The infant searched for a hidden toy by making an eye movement to one of two possible hiding locations. The task 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. The testing apparatus was a table measuring 90 cm (L) \times 60 cm (W) \times 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. Individual differences in task performance for the entire sample of infant participants (n = 50), along with EEG correlates of the individual differences, are reported elsewhere (Bell, 2005).

Briefly, 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 ("Good job! You found it!") they received 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. Two consecutive successful eye movements toward the same side (for example, 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 the infant was successful on the reversal trial or not, 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 and so on. In reality, most infants were not flawless in performance and some needed multiple same-side trials to achieve two consecutive successful eye movements prior to reversal trials (e.g., L-L-L-L-L-R-R-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 17 per infant (SE = .96), with the minimum number of trials being 12 and the maximum being 26.

An event marker was used in conjunction with the EEG recording so that it was possible to mark which portions of the EEG record were associated with the most cognitively demanding sections of the looking task. For this study, the task-related EEG used in data analyses included that associated with the simultaneous use of the cognitive skills of working memory and inhibition. This meant that the task-related EEG started with the covering of the hiding site and non-hiding 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, EEG 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 data from all trials (correct and incorrect) were used in these analyses.

Early childhood working-memory/inhibitory control tasks. The Day-Night Stroop-like task and the Yes-No task were used to investigate the working memory in the children when they were 4.5 years of age. Each task required the child to remember two rules throughout task performance and inhibit the dominant response. The Day-Night Stroop-like task has been used in the developmental literature with children ages 3.5 to 7 years (Diamond et al., 1997; Gerstadt et al., 1994). The Yes-No task was created in our research lab. Individual differences in performance on each of these tasks, along with EEG correlates of these individual differences, are reported elsewhere (Wolfe & Bell, 2004).

For the Day-Night Stroop-like task, the child was instructed to say "day" when shown a black card with a picture of a yellow moon and to say "night" when shown a white card with a picture of a yellow sun. Children were given two learning trials with response-appropriate feedback and testing did not begin until each child responded correctly on the two learning trials. Children were given a total of 16 test trials, 8 with the sun card and 8 with the moon card in a pseudorandom order.

For the Yes-No task, the child was instructed to say "yes" when the experimenter shook her head no and to say "no" when the experimenter nodded her head yes. The child was given two learning trials with response-appropriate feedback and testing did not begin until each child responded correctly on the two learning trials. Children were given a total of16 test trials, 8 with the experimenter either nodding yes or shaking her head no in a pseudorandom order.

An event marker was used in conjunction with the EEG recording so that it was possible to mark which portions of the EEG record were associated with the 16 test trials of each of the two tasks. The task-related EEG used in data analyses included that associated with the simultaneous use of the cognitive skills of working memory and inhibition. Thus, EEG data not included in the analyses were the data recorded when the experimenter was explaining the task, the child was practicing during the two learning trials, and when the experimenter was giving appropriate feedback after the learning trials. The artifact-free EEG data from all test trials (correct and incorrect) were used in the analyses. The EEG data for the Day-Night and Yes-No tasks were combined by weighting the amount of artifact-free EEG collected during each task.

EEG analysis at infancy and early childhood. Both infant and child EEG data were examined and analyzed using EEG Analysis System software developed by James Long Company (Canoga 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 inter-electrode distance as much as they reflect electrical potential. 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 uV or greater. Transfer of eye movements is reported to be significant in a frequency band from 0–6 Hz 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 maturational change in frontal EEG power. Selecting artifact-free data yielded a more accurate portrayal of the EEG developmental record (Somsen & van Beek, 1998).

The criterion for scoring movement artifact was a potential greater than 200 uV peak to peak. 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-sec 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 to 9 Hz (Bell, 1998; Bell & Fox, 1992, 1994), and this particular frequency band discriminates baseline EEG from task EEG (Bell, 2001), as well as correct from incorrect responses, during an infant working-memory task (Bell, 2002). The 6–9 Hz band remains the prominent frequency band in 4-year-old children (Marshall, Bar-Haim, & Fox, 2002), thus allowing for a direct comparison of the electrical activity in the band at two different ages in the life span. 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, Fletcher, and Michaels (1986).

Of the 25 4.5-year-old participants, complete EEG and working-memory data were available for 20 children (2 refused to wear the EEG cap, 1 wore the cap but rejected application of EEG gels, 1 accepted the cap and gels but would not participate in the working-memory tasks, and 1 visit was associated with equipment failure). Of these 20 children with complete data, 18 likewise had complete EEG and working-memory data in infancy (2 of the 20 had no EEG data at infancy). Thus, all analyses were accomplished on the 18 participants with complete EEG and working-memory data at both the 8-month and 4.5-year assessments.

Statistical analyses. To examine differences in baseline and task-related EEG power and coherence at infancy and early childhood, the analyses consisted

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of repeated-measures MANOVA with age (8 months, 4.5 years), condition (baseline, task), region (for the EEG power analysis), electrode pair (for the EEG coherence analysis), and hemisphere as the within-subjects factors. Of major interest for the initial power and coherence analyses were the main effects and interactions involving the age and condition within-subjects variables. For ease in examining any interactions involving these variables, follow-up MANOVAs were performed. A multivariate approach for assessing multivariate interaction effects has been suggested by Keselman (1998).

RESULTS

EEG Power

The means for EEG power during baseline and task at ages 8 months and 4.5 years are displayed in Figure 1. There were main effects for age (p = .006) and condition (p = .008). Two-way interactions involving the age or condition factors included age by condition (p = .006), age by region (p = .001), age by hemisphere (p = .01), and condition by region (p = .004). These interactions were superceded by a three-way interaction among age, condition, and region, multivariate F(7, 11) = 7.57, p = .002, $\eta_p^2 = .83$. To aid interpretation of this three-way interaction, a condition by region by hemisphere analysis of power values was conducted separately for each age. Of interest in the age-specific analyses were the main effect or interactions associated with the condition factor.

At 8 months of age, there was a main effect for condition, multivariate $F(1, 17) = 34.69, p < .001, \eta_p^2 = .67$. There were no interactions involving the condition factor. Power values were higher at task relative to baseline across electrode sites (see Figure 1, top).

At 4.5 years of age, there was a condition by region interaction, multivariate F(7, 11) = 9.36, p = .001, $\eta_p^2 = .86$. To determine the source of this interaction, each region was examined separately with a condition by hemisphere analysis of power values. Results revealed a main effect for condition only at medial frontal region (F3,F4), F(1, 17) = 6.15, p = .02, $\eta_p^2 = .27$. At medial frontal, power values were higher at task relative to baseline (see Figure 1, bottom).

EEG Power at Cz

During the EEG recording, all electrode sites were referenced to Cz and then the data were re-referenced via software to an average reference configuration for analysis (Lehmann, 1987). In order to examine the EEG power values at Cz, the data were transformed mathematically to extract EEG power at this midline recording site. The means for EEG power at Cz during baseline and task at 8 months and 4.5 years of age are displayed in Figure 2. There was a main effect of condition, multivariate F(1, 17)



8 months

4.5 years



FIGURE 1 EEG power values for baseline and working-memory tasks in the same children at 8 months (top) and 4.5 years of age (bottom).

= 8.84, p = .009, η_p^2 = .34. At each age, power values at Cz were higher during task than during baseline. There was no age by condition interaction (p = .21).

EEG Coherence

The means for EEG coherence during baseline and task at 8 months and 4.5 years of age are displayed in Figure 3. Two-way interactions involving the age or condition factors included age by condition (p = .009) and age by pair (p = .004). There



Cz

FIGURE 2 EEG power values at Cz scalp location during baseline and working-memory tasks in the same children at 8 months and 4.5 years of age.

was a trend toward a four-way interaction among age, condition, pair, and hemisphere, multivariate F(6, 12) = 2.32, p = .10, $\eta_p^2 = .54$. To aid interpretation of these interactions, a condition by pair analysis of coherence values was conducted separately for each age. Of interest in the age-specific analyses were the main effect or interactions associated with condition.

At 8 months of age, there was a main effect for condition, multivariate F(1, 17) = 4.90, p = .04, $\eta_p^2 = .22$. There were no interactions involving the condition factor. Coherence values were higher at baseline relative to task across electrode pairs (see Figure 3, top).

At 4.5 years of age, there was a condition by pair interaction, multivariate F(6, 12) = 4.42, p = .01, $\eta_p^2 = .69$. To determine the source of this interaction, each homologous electrode pair was examined separately with a condition by hemisphere analysis of coherence values. Results revealed a main effect for condition at both the F3/T7 and F4/T8 pairs, F(1, 17) = 23.34, p < .001, $\eta_p^2 = .58$, and the F3/O1 and F4/O2 pairs, F(1, 17) = .6.88, p = .02, $\eta_p^2 = .29$. In these electrode pairs, coherence values were higher at task relative to baseline (see Figure 3, bottom).

DISCUSSION

These EEG power and coherence longitudinal data suggest that there is widespread brain electrical activity during infant working-memory processing and that it becomes more localized during early childhood working-memory processing. These findings may yield insight into qualitative changes in cortical functioning



8 months

4.5 years



FIGURE 3 EEG coherence values for baseline and working-memory tasks in the same children at 8 months (top) and 4.5 years of age (bottom).

from the infant to the early childhood time periods, adjustments that may be indicative of developmental changes in brain specialization for higher order processes.

At 8 months of age, working memory is associated with increases in EEG power from baseline to task across the entire scalp. This increase in 6–9 Hz power replicates previous work on infant EEG and working memory (Bell, 2001, 2002), with additional electrodes at temporal and central scalp locations being used in the current study. When the children were 4.5 years of age, however, working memory was associated with increases in EEG power from baseline to task at medial frontal only. Thus, at 8 months of age, the children appear to demonstrate global cortical

involvement in working-memory processing, with more specialized involvement of frontal scalp electrodes by age 4.5 years.

There is a similar pattern of results for the EEG coherence data. At 8 months of age, working memory is associated with decreases in EEG coherence from baseline to task across all electrode pairs. According to Thatcher and colleagues (1986, 1994), decreased coherence is associated with decreased coupling between populations of neurons, indicative of the involvement of widespread groups of neurons during the working-memory task. In contrast, at 4.5 years of age, the medial frontal/posterior temporal and medial frontal/occipital electrode pairs exhibited increases in EEG coherence from baseline to task, indicative of the increased coupling associated with a more spatially localized allocation of neuronal resources being involved in the working-memory task. These coherence data complement the EEG power data by indicating wide-spread brain electrical activity that was not specific to any particular cortical region during the working-memory task at 8 months of age. By 4.5 years of age, brain activity is more localized as the cortex becomes more efficient and less complex.

Thus, it does appear that EEG patterns in infancy and early childhood are different during cognitive processing, even when the same cognitive skill (e.g., working memory) is required for problem solving in both infancy and early childhood. Why, however, would the infant time period be associated with widespread cortical processing, whereas the early childhood time period associated with more localized cortical involvement? One possibility may be that the infant brain is a profusion of synapses, many generated by the anticipation of species-specific expected experiences (Greenough & Black, 1992). Coherence is theorized by Thatcher (1994) to reflect the strength and number of synaptic connections, whereas the EEG itself results from summated postsynaptic potentials (Davidson, Jackson, & Larson, 2000; although see Nunez, 1981).

Another possibility may involve the development of language. Dynamic shifts in cortical organization have been documented over the developmental time period associated with language acquisition (Bates, Thal, & Janowsky, 1992; Mills, Coffey-Corina, & Neville, 1997; Neville & Bavelier, 1998; Neville, Coffey, Lawson, Fischer, Emmorey, & Bellugi, 1997; Neville et al., 1998). For example, different regions of the cortex may be involved in the acquisition of language during the later stages of infancy than are critical for language in older children and adults (Johnson, 1998). Thus, the infant without language has a brain that may be organized differently than the brain of a child with language. As the infant acquires language, this species-specific experience may serve to help organize the cortex in such a way as to allow more specialized processing of other cognitive information, such as that in working-memory tasks. Working memory is correlated with verbal ability in young children (Gathercole, Willis, Emslie, & Baddeley, 1992; Hughes, 1998; Wolfe & Bell, 2004).

These data suggest a cortical reorganization from infancy to early childhood that is reflected in changes in the EEG recorded during working-memory tasks.

They demonstrate that brain electrical activity is widespread during infant cognitive processing and that it becomes more localized during early childhood. These data represent a critical first step in the examination of the development of higher order cognitive functioning during the transition from infancy to childhood. They lay the foundation for the study of how brain activity during this type of cognition might change with development.

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