6 The Use of the Electroencephalogram in Research on Cognitive Development

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INTRODUCTION

The field of developmental psychophysiology provides the methodology for examination of age-related changes in the functioning of the brain. The electroencephalogram (EEG) is an efficient, non-invasive, and relatively inexpensive method for studying brain development in infants and children and for relating brain development to changes in cognitive behaviors. Utilizing EEG allows for examination of these developmental changes without dramatic interference with normal ongoing behaviors. All of these characteristics make the EEG one of the more favorable methods for investigating brain-behavior relations with young populations (Casey & de Haan, 2002; Taylor & Baldeweg, 2002).

The EEG discussed in this chapter is sometimes called "quantitative EEG" and is used for basic research on brain activity during cognition or emotion and for basic research on brain maturation. Typically, quantitative EEGs used for basic research are digital records that are converted from the time domain to the frequency domain by means of spectral analysis, yielding spectral power at specific frequencies, or by means of phase coherence analysis, yielding the degree to which the EEG signals at two distinct scalp locations are in phase at a specific frequency. This quantitative methodology differs from the traditional use of the EEG in the clinical setting to localize seizures or tumors. It also differs from event-related potentials, or ERPs, which are brain electrical responses that are time locked to a specific set of stimuli. ERP methodology and research is reviewed in Chapters 2 and 4 of this volume.

Thus, the purpose of this chapter is to highlight the value of the EEG for the study of cognitive development in infancy and childhood. We begin with an overview of the EEG and, then, a review of the classic EEG development literature to highlight the longstanding history of this methodology in the...
study of brain maturation. The actual method associated with EEG data collection is reviewed in Chapter 2 of this volume. We then examine the recent use of the EEG in studies of infant, toddler, and child cognition by providing selective examples of research findings from the developmental psychophysiology literature that highlight our interests in working memory. It is our intent to provide the reader with basic information for synthesizing research in this exciting area of developmental science.

EEG Overview

The EEG represents spontaneous electrical activity recorded from the scalp, with the assumption that the origin of these electrical signals is in the brain itself. Although once thought to be the product of action potentials, there now is general agreement among psychophysicists that the scalp signal is the summation of postsynaptic potentials (Nelson & Monk, 2001). Although the EEG signal is spontaneous, it also is context-related, with the signal generated during quiet rest very different from that generated during mental activity. The EEG signal has excellent temporal resolution, potentially on the order of hundreds of milliseconds or better, depending on the frequency examined. Thus, postsynaptic changes are reflected rapidly in the EEG, making this methodology outstanding for tracking rapid shifts in behavior.

Limitations of EEG

Although EEG is one of the more favorable brain imaging methods for use with infants and children, there are some drawbacks to this methodology. We note these limitations early in this chapter so that the reader can keep them in mind as we review the classic infant/child EEG developmental literature and some of the most current EEG developmental research. Although the EEG signal has excellent temporal resolution, it has poor spatial resolution. There are at least three reasons for this shortcoming (Davidson, Jackson, & Larson, 2000). First, even with multiple electrodes, there are gaps between electrodes on the scalp. These gaps disallow a complete electrical mapping of the scalp. Second, the skull behaves like a low-pass filter and distorts the underlying brain electrical activity over a large area of the scalp. Finally, scalp potentials are likely generated by multiple groupings of cortical and subcortical generators spread across a relatively wide area. Thus, an electrode is likely detecting electrical activity generated from non-local groups of neurons.

Another drawback is that the EEG is prone to some distortion because of motor movement. Artifact may result from such gross motor activity as motion of the arms and legs, or from motor activity as fine as a simple eye
movement. Although adult research participants are generally cooperative when requested to sit without moving, young children often have difficulty in refraining from gross motor movements. Researchers must ensure that their expectations for the behavior of young children in EEG paradigms are developmentally appropriate. Researchers who conduct EEG research with infants must take special care in designing cognitive tasks that result in behavioral stilling for the infants.

**EEG Rhythms**

There is a rhythmic quality to the EEG signal, although there is some disagreement as to the source of this rhythmicity. Some researchers view the EEG rhythms as driven by the thalamus, whereas others propose that the drivers reside in the pyramidal cells in the cortex (Davidson et al., 2000). In adults, the EEG rhythmicities are reliably observed and are defined in terms of the number of cycles per second (frequency) and size of the signal (amplitude).

The *alpha rhythm* is the predominant frequency band and is readily observable during quiet rest, especially when the eyes are closed. This signal cycles at 8–13 Hz and has a relatively large amplitude. When an adult is engaged in cognitive activity, the alpha rhythm is no longer visible, especially at specific electrode sites. These sites are dependent upon the nature of the cognitive task. For example, engagement in a verbal task tends to be associated with the attenuation of alpha activity in frontal and central areas of the left hemisphere, whereas engagement in a spatial task tends to be associated with attenuation of alpha activity in parietal areas of the right hemisphere (e.g., Bell & Fox, 2003; Davidson, Chapman, Chapman, & Henriches, 1990).

During adult cognition and the attenuation of the alpha rhythm, it appears that alpha activity is replaced by the *beta rhythm*, which cycles at 18–30 Hz and has smaller amplitude than alpha. Beta activity signifies alertness or attentiveness. Brain electrical activity in the 30–70 Hz range or higher is designated as *gamma rhythm*. Gamma activity in adults appears to be associated with the integration of stimuli into a logical whole, with gamma activity differentiating between important and inconsequential stimuli (Stern, Ray, & Quigley, 2001).

*Theta rhythms* cycle at 4–8 Hz and also figure prominently in cognitive activity. Adults tend to exhibit increases in theta activity during memory and attention tasks, with these increases even greater for correct as opposed to incorrect responses (e.g., Burgess & Gruzelier, 2000; Klimesch, Doppelmayr, Schimke, & Ripper, 1997). Interestingly, theta also is associated with drowsiness or sleep onset. These disparate findings have led to the suggestion that
there are two different types of theta activity (Schacter, 1977). One type of theta associated with drowsiness and the other is associated with attention and active cognitive processing, leading to the possibility that these two types of theta activity have different sources.

*Delta rhythm* is of low frequency (1–4 Hz) and is associated with sleep in adults, especially deep sleep. Of interest is that this particular frequency range is the prominent frequency in infants during the first few months of postnatal life, gradually developing into the adult-like frequency patterns over time (Bell, 1998a). We trace the development of the EEG in the sections below. First, we summarize the classic infant and child EEG literature and then we report on current work on EEG and cognitive development in infancy and childhood.

**Classic EEG Development Literature**

By placing electrodes on the scalp, Berger (1929) was the first to demonstrate that the EEG was related to brain activity rather than other physiological processes. It was Berger’s (1932) publication highlighting EEG differences among infants, children, and adults that began the interest in developmental aspects of these scalp recordings. These differences are readily observable in EEG tracings from our research lab (see Figure 6.1). Infant EEG has much
greater amplitude, as evidenced by the eye blinks highlighted in these two tracings. Infant EEG also cycles at a lower frequency than adult EEG, with the average adult frequency being 10 Hz and the average infant frequency ranging from 3 Hz to 7 Hz, depending upon the infant’s age. From Berger’s time, researchers have assumed that EEG differences among infants, children, and adults reflect differences in brain maturation. Working with paper tracings and keen eyesight, these early researchers studied EEG developmental changes across the scalp.

*Developmental Changes in the EEG During Infancy*

We have completed a comprehensive review of the classic longitudinal and cross-sectional studies that are the basis of our current knowledge of EEG development during infancy and childhood (for these details, see Bell, 1998a). There have been four longitudinal samples of EEG recorded from awake infants in the classic EEG literature. Two of these were accomplished in the 1930s and appear to have been a result of Berger’s (1932) publication examining EEG differences between children and adults. The EEG samples collected by Smith (1938a, 1938b, 1939, 1941) and by Lindsley (1939; later republished by Henry, 1944) were examined by visual analysis and give us identical information as to the developmental changes associated with the EEG. Both noted the emergence of a rhythm over the occipital area around 3 months of age and termed this rhythm “alpha” because its waveform is visually similar to the adult 8–13 Hz alpha wave. Measured by hand, Smith and Lindsley reported that this waveform oscillated at 3–5 Hz. Each speculated as to the significance of the appearance of this oscillation and agreed that it was associated with visual capacities of the occipital cortex (Lindsley, 1939; Smith, 1938b). The Lindsley (1939) and Smith (1938b, 1939, 1941) EEG data also showed that this occipital activity gradually increased to 6–7 Hz by 12 months of age. In addition to the occipital rhythm, Smith (1941) noted the emergence of a 7 Hz signal at central scalp locations around 3 months of age and hypothesized links between the appearance of this rhythm, the disappearance of primitive reflexes, and the emergence of voluntary muscular control associated with reaching. This central activity remained stable for several months, not increasing in frequency until 10 months of age (Smith, 1941).

With the aid of technological advancements, the other two longitudinal samples of EEG in awake infants were measured mechanically in terms of frequency and amplitude. The EEG data collected by Hagne (1968, 1972) and Mizuno (Mizuno, Yamaguchi, Inuma, & Arakawa, 1970) were accomplished via frequency analysis that divided the EEG into preselected frequency bands, but these researchers gave an account of EEG frequency development
during the first postnatal year that was consistent with the reports of Smith and Lindsley. Hagene (1968, 1972) reported a decrease in amplitude at 1.5–3.5 Hz, with a corresponding increase in amplitude at 3.5–7.5 Hz during the first year at central, temporal, parietal, and occipital locations. Reporting on EEG recorded at the right occipital scalp location, Mizuno and colleagues (1970) showed a predominance of 2.0–4.15 Hz activity at 3 months and 3.5–8.6 Hz activity at 12 months. Interestingly, Hagene (1968) made note of individual differences in amplitude in same-age EEG recordings. She also stated that these individual differences persisted throughout the first year.

Mizuno and colleagues (1970) made detailed observations of each infant’s physical development, noting weight, height, head and chest circumference, and physical milestones (e.g., holding up head, sitting, standing, walking) at each EEG recording session. No attempt was made however to relate physical development with EEG maturation. Hagene (1972), on the other hand, did neurological and developmental assessments on each infant in association with each EEG recording. She reported correlations between peak frequency (frequency where the infant displayed the greatest amplitude) at parietal/occipital scalp locations and total score on the Griffiths Scale of Mental Development at 4 months, and between peak frequency at central scalp locations and Griffiths score at 10 months of age. Hagene also reported a correlation between 4-month EEG activity at 1.5–7.5 Hz, temporal and central locations, and total score on the Griffiths Scale.

**Developmental Changes in the EEG During Childhood**

The early infant longitudinal studies of Smith, Lindsley, and Henry were remarkable in that they also contained longitudinal samples of children. Smith (1938a, 1938b, 1939, 1941) continued to obtain EEG recordings from many in his infant sample until they were 4.5 years of age. There were also 95 children from ages 3 to 16 years from whom he made single EEG recordings (Smith, 1941). Using visual inspection, Smith noted that the occipital EEG had a frequency of almost 8 Hz by 30 months of age. This period of rapid EEG development during infancy and early childhood was followed by a more gradual change in EEG during childhood (Smith, 1941). EEG frequency of 9 Hz at occipital locations was not obtained until 8 years of age (Smith, 1938b), while the adult mean of 10 Hz at occipital scalp locations was not seen until 16 years of age (Smith, 1941). Smith made note that Lindsley’s data showed 10 Hz occipital EEG in some 12-year-old children (Smith, 1941), although Lindsley’s (1939) data tables revealed that 10 Hz activity was displayed by some children as early as 6 years of age. These early data sets appear to demonstrate a range of individual differences in EEG development.
The child EEG reported by Smith, Lindsley, and Henry may appear to be inconsistent with the work by Mizuno and colleagues (1970) summarized earlier, who reported that by 12 months of age infants already were exhibiting 3.5–8.6 Hz EEG activity. The apparent inconsistency is due to research methodology, however. The early EEG work by Smith, Lindsley, and Henry was accomplished with visual analysis of paper EEG tracings and the variable of interest was peak frequency, or the fastest individual rhythm (i.e., of 1 Hz width) exhibited by infants of a certain age. The work by Mizuno was accomplished with a frequency analyzer using preselected frequency bands that summed EEG activity across multiple frequencies. Thus, the variable of interest was power, or the amount of electrical activity (in microvolts) at a specific frequency interval. The report of infants of 12 months exhibiting EEG activity within a 3.5–8.6 Hz range does not tell us the peak frequency exhibited by the infants, exemplifying why caution must be taken when comparing EEG findings across different analysis methodologies.

One of the most informative EEG data sets is the one begun by Lindsley (1939) and reanalyzed by Henry (1944). This valuable data set included 95 infants and children ranging in age from 3 months to 19 years. Each child contributed a minimum of 5 recordings, collected over a minimum of 5 years, to the data set. Until 1 year of age, recordings were made every 3 months. From ages 1 to 5, recordings were done every 6 months and then every year thereafter. Recordings were made from occipital and central sites and analyzed using visual inspection. Lindsley (1939) reported that occipital amplitude began to decrease after 12 months of age, with the sharpest decline occurring near the 2nd birthday. He suggested that sharp decline around 2 years of age was due to the closing of the fontanelle because the drop in amplitude was not accompanied by a change in frequency. Lindsley (1939) further suggested that the continued drop in amplitude evident throughout childhood was associated with maturational increases in skull thickness.

Henry (1944) reported some sudden frequency changes at occipital recordings sites prior to age 4, but after age 6 most children exhibited an occipital EEG in the 9–11 Hz range. Henry also noted that individual differences in the maturation of the adult-like EEG frequency were evident in his visual analysis of the EEG data. Some children appeared to reach this mature frequency at a young age, while others showed slow increases in frequency throughout childhood. Individual differences in dominant frequency tended to be stable. Children with faster dominant frequencies (>11 Hz), and those with slower dominant frequencies (<9 Hz), tended to be at the maximum and minimum levels of the group mean throughout their participation in the longitudinal study (Henry, 1944). Thus, individual differences between the
children in the Henry data set and those in the Smith data set appear to be the reason that the Smith children did not demonstrate 9 Hz occipital EEG until 8 years of age. Individual differences in EEG power values have been the focus of our research program on cognitive development that we report in a later section of this chapter.

One of the best-known data sets of EEG development in children and adolescents was published by Matousek and Petersen (1973). Originally, Petersen and Eeg-Olofsson used visual analysis to report on EEG development in children from 1 to 15 years of age (Petersen & Eeg-Olofsson, 1971) and in adolescents from 16 to 21 years of age (Eeg-Olofsson, 1971). Recordings were made from frontal, central, temporal, parietal, and occipital scalp locations. Later, the EEG data were submitted for a frequency analysis by Matousek and Petersen. This work confirmed earlier cross-sectional reports by Petersen and Eeg-Olofsson (1971) of decreases in 1.5–3.5 Hz activity with age and increases in 9.5–12.5 Hz activity with age. Matousek and Petersen (1973) reported that EEG development occurred more quickly at posterior scalp locations than central ones. They also noted that age-related EEG changes were linear during childhood and logarithmic during adolescence.

John and colleagues (John et al., 1980) compared a data set of 306 children, aged 6 to 16 years with the Matousek and Petersen’s data set of 324 children, aged 6 to 16, and confirmed the notion of linear changes in the EEG as age increases. Again, EEG activity in the 1.5–7.5 Hz frequency band decreased with age, while EEG activity greater than 7.5 Hz increased with age.

These earlier notions of linear changes in EEG development were questioned with a graphical display of the EEG data by Epstein (1980). Examining EEG activity reported longitudinally by Smith (1938b), Lindsley (1939), and Henry (1944), and cross-sectionally by Matousek and Petersen (1973), Epstein recalculated the EEG changes across age to reflect biennial increments in 8–13 Hz activity. Epstein reported that this reconfiguration of the data revealed 5 stages of EEG development that correlated with the stages of brain growth with respect to gross weight of the brain.

With these classic EEG data sets, we have a great deal of information concerning the ontogeny of the EEG during infancy and childhood. What these data sets do not tell us, however, is whether there is functional significance to these age-related EEG changes. It was assumed by these researchers that age-related changes in EEG were associated with changes in cognition, but this assumption was never tested except by Hagie (1972). More recently, a correspondence between Piaget’s stages of cognitive development and stage-like patterns of brain development has been posited by Fischer (Fischer & Rose, 1994). Fischer has noted the need for precise and simultaneous
brain-behavior assessments to detect correlations between brain maturation and cognitive development during childhood (Fischer & Rose, 1994). Current EEG work is heeding that call.

Perhaps one of the biggest contributions of these early researchers is the acknowledgment of individual differences in EEG development. Interestingly, there was no speculation regarding the implications of these individual differences, except for Henry (1944). He examined correlations between EEG peak frequency and IQ and reported low to moderate correlations. Current infant and child basic EEG research is incorporating cognitive and emotion behaviors into the EEG recording sessions. Although most of this work is focused on age-related effects, there is a growing trend toward the examination of individual differences in EEG and corresponding behavioral correlates.

Next we turn to an examination of infant EEG frequency bands. If work is to progress on brain-behavior development, researchers need to have precise EEG definitions with which to work.

**Infant EEG Frequency Bands**

Psychophysiologists working with child, adolescent, and adult populations examine the theta (4–8 Hz), alpha (8–13 Hz), and beta (13–20 Hz) rhythms and note their associations with cognitive behaviors (e.g., Davidson et al., 1990; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Roberts & Bell, 2002). In the infant psychophysiology literature, however, there is no standardization of EEG rhythms as found in adult EEG work (Pivik et al., 1993). As a result, we know little concerning the associations of specific frequencies with cognitive behaviors during infancy.

In a set of recommendations for recording and analyzing EEG in research contexts, Pivik et al. (1993) noted that traditional frequency bands used with adults may not apply to studies of infant EEG. Two approaches were suggested. In the first, EEG analyses can be accomplished on a wide frequency band that includes all frequencies in which there is evidence of power. This approach has been used in some studies of infant emotion, where differences in baseline frontal EEG asymmetries in the 3–12 Hz band have been reported between infants with depressed mothers and infants with non-depressed mothers (e.g., Field, Fox, Pickens, & Nawrocki, 1995; Jones et al., 1998). The wide band method, however, is not commonly used in infant research. Given the rapid changes in EEG development during the first postnatal year, the wide frequency band may not be very informative.

In the second approach to infant EEG frequency bands noted by Pivik and colleagues (1993), individual spectra are examined and frequency bands are
determined that center around the peaks in the spectrum. We have used this second approach with our infant EEG data. In a longitudinal study examining relations between frontal brain electrical activity and cognitive development from 7 to 12 months of age, we began by doing spectral plots of each EEG lead for each longitudinal participant for every monthly testing session. The plots generally revealed a dominant frequency for most infants in the data set in all lead at all ages at 6–9 Hz (Bell & Fox, 1992). There were individual differences in this peak, however. Figure 6.2 (top) shows the spectral plots for F3 and F4 for one infant who exhibited a sharp peak at 5–8 Hz at 8 months of age. This is contrasted with another 8-month-old infant who does not exhibit this peak (Figure 6.2, middle). These two infants exhibited these same patterns monthly through 12 months of age.

We verified this peak at 6–9 Hz by performing spectral analysis on a different data set which included the EEG recordings of a group of 74 eight-month-old infants (Bell & Fox, 1997). The group mean spectral plot for F3 is shown in Figure 6.2 (bottom). Although the peak at 6–9 Hz is evident, it is much smaller in amplitude than the peak exhibited by the infant in Figure 6.2 (top), yet much larger in amplitude than the non-peak exhibited by the infant in Figure 6.2 (middle), demonstrating that group data can obfuscate individual differences in the EEG. Thus, within any infant EEG data set, researchers can expect a wide range of individual differences in spectral power among same-age infants.

The spectral plot approach was also used by Marshall with a longitudinal data set that included resting baseline EEG from a group of children at 5, 10, 14, 24, and 51 months of age (Marshall, Bar-Haim, & Fox, 2002). Marshall and colleagues reported a peak in the spectra in the 6–9 Hz frequency band that emerged across multiple scalp locations. This frequency range was consistent across all scalp locations by 10 months of age and continued to be the predominant frequency band through 51 months of age. The earliest EEG recordings at 5 months of age showed 6–9 Hz to be prominent at central scalp locations, with the lower 4–6 Hz band more prominent at posterior locations. For individual infants, there was an increase in the peak frequency across the four-year study reminiscent of the data reported in the classic infant EEG research reports.

Infant EEG and Cognitive Development

Working Memory and Inhibitory Control Tasks
The 6–9 Hz frequency band is of little intrinsic value unless it can be shown to be correlated with behavior. Based on the individual spectral plots in our own data set, we focused on the 6–9 Hz band and noted that changes
Figure 6.2. Spectral plots of frontal EEG for 8-month-old infants demonstrating individual differences in infant EEG and group means. (top) One infant with a well-defined peak frequency band between 5 and 9 Hz (Bell & Fox, 1992, data set). (middle) One infant without a peak frequency band between 5 and 9 Hz (Bell & Fox, 1992, data set). (bottom) Group mean data for 74 infants (Bell & Fox, 1997, data set).
in resting baseline frontal EEG power values from 7 to 12 months of age were associated with changes in performance on a classic infant cognitive task which requires the infant to search manually for a hidden toy in one of two hiding sites (Bell & Fox, 1992). It has been proposed that spatial working memory and inhibitory control, among other cognitive behaviors, are essential for performance on this type of task (Diamond, Prevor, Callender, & Druin, 1997; Nelson, 1995). Many of these cognitive behaviors are associated with the dorsolateral prefrontal cortex (Diamond et al., 1997), although the EEG cannot be that specific with respect to brain location.

Next, we assessed a group of same-age infants and found that individual differences in 6–9 Hz baseline frontal EEG at 8 months of age were related to differences in performance on the classic reaching spatial working memory task (Bell & Fox, 1997). Higher levels of performance were associated with greater baseline EEG power values at both frontal and occipital scalp locations. We then designed an infant looking task that was similar to the classic infant reaching task so that we could record EEG during task performance. On this looking task, infant performance at 8 months of age was associated with EEG activity at 6–9 Hz (Bell, 2001). Infants with high levels of performance on the visual spatial working memory task exhibited task-related EEG power values at 6–9 Hz which were higher than their baseline power values. Infants with low levels of performance had task-related EEG power values that were similar to their baseline values.

Thus, in our studies of infant cognition, increases in EEG power values at 6–9 Hz have been associated with higher levels of performance on cognitive tasks. In the adult EEG literature, researchers have long focused on the 8–13 Hz peak in the adult spectrum. As previously noted, it is commonly reported that alpha activity (8–13 Hz) exhibits decreased power values during increased cortical processing, although there are some reports of alpha increased power values during long-term memory tasks (Klimesch, Doppelmayr, Schweiger, Auinger, & Winkler, 1999). Recently, researchers have noted that adult theta activity (4–7 Hz) exhibits increases in power during memory and attention tasks (e.g., Burgess & Gruzelier, 2000; Klimesch et al., 1997). Thus, for the mature EEG signal, specific patterns of fluctuations in power levels at the defined frequency bands are associated with different types of cognitive processing. This type of information is lacking with respect to infant EEG.

Based on the spectral plots we had done in the past, and based on factor analysis of one of our infant EEG data sets (Bell, 1998b), we decided to compare the task-related EEG activity at 6–9 Hz with activity at both 3–5 Hz and 10–12 Hz (Bell, 2002). After a baseline EEG recording, a group of
8-month-old infants performed our spatial working memory looking task while we continued to record EEG. Thus, we had both baseline and task-related EEG data. Our first analysis was a comparison of baseline and task EEG at each of the three frequency bands. All three bands (3–5 Hz, 6–9 Hz, 10–12 Hz) discriminated between baseline and task activation at all electrode locations. At each frequency band, power values were higher during the memory task than during baseline.

Next, we analyzed the three frequency bands during the different processing stages of the cognitive task. We proposed that the processing stages involved an attention component, a working memory and inhibitory control component, and an emotion component associated with a task reward. Both the 3–5 Hz and the 6–9 Hz bands differentiated among various processing stages at specific electrode sites (see Figure 6.3). The 10–12 Hz band did not.

Perhaps the most intriguing results involved comparisons of the EEG during correct and incorrect responses. Only the 6–9 Hz band made this distinction. Power values were greater during correct responses than during incorrect responses. Thus, the 6–9 Hz band appears to be most informative concerning spatial working memory during infancy. With this band, there were differences between baseline and task EEG data, variations in power
among the processing stages of the task, and power value differences between correct and incorrect responses (Bell, 2002).

**Attention Tasks**

Similar results have been reported by other researchers who specialize in infant EEG and cognitive development. Infants between 8 and 11 months of age exhibited a peak in 6.0–8.8 Hz EEG at frontal scalp locations during sustained visual attention to an interesting stimulus (Stroganova, Orekhova, & Posikera, 1999). Similarly, infants between 8 and 11 months with longer anticipatory attention spans had higher 6.8 Hz alpha amplitude values (EEG was divided into 0.4 Hz bins) at posterior scalp locations than infants with shorter anticipatory attention spans (Orekhova, Stroganova, & Posikera, 2001). Those EEG data were recorded while infants were in a state of internally controlled attention; that is, they were waiting or anticipating the reappearance of a social stimulus.

Other infant EEG studies have focused on the 4–6 Hz frequency band, suggested by Marshall to be more appropriate for younger infants (Marshall et al., 2002). Increases in power at 4–6 Hz during internally controlled or anticipatory attention were evident in both 7–8-month-old (Stroganova, Orekhova, & Posikera, 1998) and 8–11-month-old infants (Orekhova, Stroganova, & Posikera, 1999). In both of these reports, it is the EEG data at frontal scalp locations that were most associated with the attention condition.

These studies may begin to form the foundation for defining EEG frequency bands that are appropriate for use with infants and for understanding the function of these EEG frequency bands during cognitive activities. It is also crucial to the field of developmental psychophysiology to know whether the infant frequency bands are appropriate for use with young children and with what age it is expedient to begin to use adult-defined EEG frequencies.

It is also crucial to determine the ontogeny of the 6–9 Hz frequency band. During infant cognitive processing, this frequency band performs as theta (4–7 Hz) does during adult cognition. It is intriguing to note that the 6–9 Hz band during infancy also behaves similarly to adult alpha (8–13 Hz) during eyes closed (or "lights off" for infant research participants). Stroganova and colleagues (Stroganova, Orekhova, & Posikera, 1999) have reported that in 8- and 11-month-old infants, the amplitude of occipital EEG at 5.2–9.6 Hz increases during total darkness. Thus, the functional significance of the infant 6–9 Hz frequency band encompasses characteristics of both adult theta and adult alpha. Whether this infant 6–9 Hz oscillation has different generators depending on if it behaves like adult theta or adult alpha is unknown, but
perhaps source analysis can eventually be used to differentiate these two different functions. One of the more intriguing research agendas will be to sort out the ontogeny of infant EEG and trace the transition from infant EEG to child and then adult-like brain activity patterns.

**Toddler EEG and Cognitive Development**

The field of developmental psychophysiology is lacking with respect to EEG data from children during the second year after birth. Although children of this age are well known for having an independent spirit that might not translate into cooperation during an EEG laboratory session, these data are crucial for bridging the infant and early childhood EEG literatures. The longitudinal resting baseline 6–9 Hz EEG data from 5 months to 4 years reported by Marshall and colleagues (2002) contain EEG at the 14-month time point, making this a valuable and unique EEG data set.

Resting EEG data have been utilized in an examination of the joint attention skills of 14-month-old toddlers. Joint attention refers to the coordination of attention between two social partners. The developmental literature focuses on infant and toddler attempts to initiate joint attention as well as respond to the attention bids of others. The tendency for the toddlers to initiate joint attention bids with the experimenter was associated with left frontal EEG power values (Mundy, Card, & Fox, 2000).

Currently, we are collecting baseline and task-related EEG with a group of 24- to 25-month-old children. These children are members of a longitudinal data set that we have assessed on spatial working memory tasks twice when they were infants. As toddlers, they are participating in both spatial and verbal working memory assessments. As would be expected, each toddler is participating in the spatial working memory task, where we are seeing individual differences in task performance. Participation in the verbal working memory task is possible only if the toddler has sufficient spoken language. Our first examination of the data will involve the 6–9 Hz frequency band, as per the findings of Marshall and colleagues (2002). We anticipate that these task-related EEG data will be an important addition to the brain-behavior developmental literature.

**Early Childhood EEG and Cognitive Development**

During the early childhood years, significant changes in attention, executive, and self-control processes are clearly identifiable (e.g., Diamond et al., 1997; Posner & Rothbart, 2000). These changes are inarguably associated with transformations in cortical function and organization. It has been suggested
that the most salient changes in brain anatomy (i.e., growth in brain weight, increased myelination, glucose utilization, and synaptic growth) take place in the first four years (Van Baal, De Geus, & Boomsma, 1996). There are few EEG studies of cognition in early childhood, however. This is particularly surprising because early childhood is a time when many advances are being made in cognitive and related behavioral skills, particularly in the executive function domain. The paucity of EEG literature is further intriguing as EEG is one of the more favorable methodologies for brain imaging investigations with this age population (Casey & de Haan, 2002).

In our research lab, we are attempting to provide a systematic, developmental view of the cognitive skills of working memory and inhibitory control and their associated electrophysiology by extending our infant work on spatial working memory (e.g., Bell, 2001, 2002) to the preschool years. From the work of Diamond, we know that many advances are being made in certain executive function skills during the early childhood years (Diamond et al., 1997). For example, children are unable to successfully perform working memory and inhibitory control tasks, such as the day-night Stroop-like task, at 3.5 years. By age 4, however, performance has increased to competent levels (Diamond et al., 1997).

Recently, we have investigated the EEG correlates of working memory and inhibitory control in 4.5-year-old children (Wolfe & Bell, 2004). As did Marshall and colleagues (Marshall et al., 2002), we found the 6–9 Hz frequency band to be informative with this age group. The children with higher performance on the day-night Stroop-like task of working memory and inhibitory control had higher baseline and task-related EEG power values at frontal scalp locations than did children with lower performance on the task. This finding is similar to our infant EEG results and highlights the value of individual differences research within the field of developmental psychophysiology.

Middle/Late Childhood EEG and Cognitive Development

There is an extensive developmental psychophysiology literature focusing on cognitive development in middle and late childhood. Most of this work focuses on associations between EEG and constructs such as intelligence and school-related skills (e.g., Roberts & Kraft, 1990; Schmid, Tirsch, & Scherb, 2002), although there is some focus on specific cognitive skills such as mental rotation (e.g., Roberts & Bell, 2000, 2002). These studies tend to utilize adult EEG frequency band definitions of alpha, theta, and beta. In our own work, we have demonstrated the alpha frequency band to be appropriate for
8-year-old children, although the power values of this age children are greater than the power values of adults (Roberts & Bell, 2000, 2002).

Working memory performance also has been associated with adult-like EEG frequencies in children 8–10 years of age. EEG power values at 8–9.5 Hz were higher at frontal scalp locations for correct responses on a verbal working memory task than they were for incorrect responses (Fernandez et al., 1998). In another study, the 10–12 Hz EEG associated with short-term memory performance of 12-year-old children did not differ from the EEG of adults completing the same task, suggesting that brain-behavior memory systems might be fully developed by age 12 (Krause, Salminen, Sillanmaki, & Holopainen, 2001).

Conclusion

In this chapter, we have highlighted the value of the EEG for the study of cognitive development in infancy and childhood by focusing on research on working memory. These studies suggest that not only does cognition change dramatically during this time period, but also the EEG is undergoing major developmental changes. We have focused on the need to combine brain-behavior measures in developmental research and have proposed that the EEG is the ideal methodology for this purpose.

We have also highlighted two areas of the developmental psychophysiology literature that deserve more attention. First, continued work on defining standardized EEG frequency bands that are developmentally appropriate for infants and young children is essential to interpreting any EEG research results. Second, the paucity of EEG research with toddlers and young preschool-age children severely limits our knowledge of EEG development during this crucial phase of brain-behavior development. Most valuable would be longitudinal studies that encompass the infancy to childhood time periods and examine changes in task-related EEG.

Developmental psychophysologists have a wide variety of research methods available for the study of age-related changes in the functioning of the brain and associated cognitive behaviors. The EEG remains one of the most efficient and relatively inexpensive methodologies for examining developmental change.

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References


