

Power changes in infant EEG frequency bands during a spatial working memory task

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Abstract

Developmental psychophysiologicalists working with infants have no commonly accepted frequency definitions of EEG waves or rhythms. The purpose of this study was to investigate the task-related power changes in three infant EEG frequency bands during the performance of a spatial working memory task by 8-month-old infants. EEG data were divided into three frequency bands: 3–5 Hz, 6–9 Hz, and 10–12 Hz. Although all three frequency bands showed some level of discrimination of baseline from task and among different processing stages of cognitive activity, only the 6–9 Hz band consistently exhibited these capabilities and distinguished the correct from incorrect responses. These data may form the foundation for defining EEG frequency bands that are appropriate for use with infant research participants and for understanding the function of these frequencies during cognitive activity.

Descriptors: Infancy, Electroencephalography, Spatial working memory, Frontal lobe

Developmental psychophysiologicalists working with infants have no commonly accepted frequency definitions of EEG waves or rhythms. Psychophysiologicalists working with child, adolescent, and adult populations have examined the theta (4–8 Hz), alpha (8–13 Hz), and beta (13–20 Hz) rhythms, among others, and noted their associations with cognitive and emotional behaviors (e.g., Crawford, & Barabasz, 1996; Davidson, Chapman, Chapman, & Henriques, 1990; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Ray & Coles, 1985; Roberts & Bell, 2000; Schmidt, 1999). 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 and emotional behaviors during infancy. The purpose of this research was to investigate the functional meaning of infant EEG frequencies associated with cognitive processing, specifically spatial working memory.

Interest in the normal developmental course of the EEG began with Berger's (1932) report of EEG differences among infants, young children, and adults. This work immediately generated longitudinal studies of EEG development during infancy and childhood (Henry, 1944; Lindsley, 1939; Smith, 1938a, 1938b). These pioneering researchers used visual inspection of EEG records to describe the appearance of a 3–5 Hz rhythm over the occipital area at 3 months of age that increased to a frequency of 6–7 Hz by 12 months of age. Later use of frequency analyzers confirmed this

original work (Hagne, 1968, 1972; Mizuno, Yamaguchi, Iinuma, & Arakawa, 1970). More recently, researchers have noted, based on these earlier studies, that by the second half of the first year of life, the majority of infant EEG activity can be found in the 3–12 Hz band (Fox & Davidson, 1987, 1988). Furthermore, there appears to be a peak in EEG activity at 6–9 Hz during this same time period (Bell, 1998a; Bell & Fox, 1992, 1994).

This period of rapid EEG development during the first year of life continues into early childhood and is then followed by a more gradual change in EEG. In longitudinal studies of EEG development during childhood, frequencies of 9–10 Hz at occipital locations have been reported by 8 years of age (Lindsley, 1939; Smith, 1938b; see Bell, 1998a, for a review of the ontogeny of EEG during infancy and childhood).

In a set of recommendations for recording and analyzing EEG in research (i.e., nonclinical) contexts, Pivik et al. (1993) stated that traditional frequency bands used with adults may not apply to studies of infant EEG. Two approaches were noted in the guidelines. 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 most often in studies of infant emotion, where frontal EEG asymmetries in the 3–12 Hz band have been reported with respect to the display of discrete facial expressions (Fox & Davidson, 1988). Differences in baseline frontal EEG asymmetries have also been reported between infants with depressed and infants with nondepressed mothers (Field, Fox, Pickens, & Nawrocki, 1995; Jones et al., 1998). In these wide-band studies, activity at the 1–2 Hz level was eliminated due to high levels of variability that the researchers deemed unlikely to be task relevant, such as head and eye movement artifact (Field et al., 1995; Fox & Davidson, 1988). The wide-band method, however, is not commonly used in infant research.

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In the second approach to infant EEG frequency bands noted by Pivik et al. (1993), individual spectra are examined and frequency bands are determined that center around the peaks in the spectrum. This technique has been used in many infant studies of cognition and emotion. In a longitudinal study examining relations between frontal brain electrical activity and cognitive development from 7 to 12 months of age, Bell and Fox (1992) did spectral plots of each EEG lead for each longitudinal participant for every monthly testing session. The plots generally revealed a dominant frequency in all leads at all ages at 6–9 Hz. Based on individual spectral plots, Bell and Fox focused on the 6–9 Hz band and noted that changes in baseline frontal EEG power values from 7 to 12 months of age were associated with changes in performance on a classic infant cognitive task, the Piagetian A-not-B search task. This particular task, which requires the infant to manually search one of two hiding sites for a hidden toy, has been demonstrated to show the same developmental progression as the classic Delayed Response task (Diamond, 1990a, 1990b). It has been proposed that spatial working memory and inhibitory control, among other cognitive behaviors, are essential for performance on A-not-B and Delayed Response tasks (e.g., Diamond, Prevor, Callender, & Druin, 1997; Funahashi, Bruce, & Goldman-Rakic, 1993; Goldman-Rakic, 1987; Nelson, 1995). Many of these cognitive behaviors are subserved by the dorsolateral prefrontal cortex (Diamond, 1990a, 1990b; Diamond et al., 1997).

In an age-held-constant design, individual differences in 6–9 Hz baseline frontal EEG at 8 months of age were found to be related to differences in performance on the classic reaching A-not-B 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. On an oculomotor version of the A-not-B search task, infant performance at 8 months of age was associated with EEG activity at 6–9 Hz (Bell, 2001). Specifically, infants with high levels of performance on the visual spatial working memory task exhibited task-related EEG power values at 6–9 Hz that 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. Similarly, infants at 8 and 11 months of age exhibited increases in 6.0–8.8 Hz EEG power during sustained visual attention (Stroganova, Orekhova, & Posikera, 1999).

Studies of infant brain electrical activity during emotion expression and regulation have also focused on the 6–9 Hz frequency band. For example, researchers have noted frontal EEG asymmetries at 6–9 Hz associated with different emotion-eliciting situations (e.g., left frontal asymmetry—lower left hemisphere power values—for approach emotions and right frontal asymmetry for avoidance emotions; Bell & Fox, 1994; Dawson, Panagiotides, Klinger, & Hill, 1992; Fox, Bell, & Jones, 1992; Fox & Davidson, 1987), as well as group differences in 6–9 Hz frontal EEG asymmetry scores between infants of depressed mothers and infants of nondepressed mothers (i.e., right frontal asymmetry for the former and left frontal asymmetry for the latter; Dawson et al., 1999; Dawson, Klinger, Panagiotides, Hill, & Spieker, 1992; Dawson, Panagiotides, Klinger, & Spieker, 1997). For one of these studies (Dawson et al., 1999), EEG data in the 3–5, 6–9, and 10–12 Hz bands were examined, but only data in the 6–9 Hz band were analyzed.

Thus, there appear to be two patterns for 6–9 Hz activity during infancy. In studies of emotion, decreases in EEG power values in one hemisphere relative to the other are associated with emotion expression or emotion regulation. In studies of cognition, increases

in EEG power values are 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. It is commonly reported that alpha activity (8–13 Hz) exhibits desynchronization (decreased power values) during increased cortical processing, both cognitive and emotional; although there are some reports of alpha synchronization (increased power values) during long-term memory tasks (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999). Recently, researchers have noted that adult theta activity (4–7 Hz) exhibits synchronization 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 the infant EEG signal.

In this study, infant EEG was recorded during baseline and during an oculomotor spatial working memory and inhibition task. Based on previous developmental literature utilizing wide band and narrow band analyses and on recent factor analyses of infant EEG data sets (Bell, 1998b; Marshall & Fox, 2001), EEG data were divided into three frequency bands: 3–5 Hz, 6–9 Hz, and 10–12 Hz. The aim of this study was to investigate the functional meaning of these three bands by answering the following questions: (1) *Does the frequency band discriminate between baseline and task activation?* This is the classic marker of cortical activation in the adult literature. There is some indication that power in the 6–9 Hz band may increase from baseline to task for infants who perform well on a working memory and inhibition task (Bell, 2001), but possible fluctuations in the other two bands are unknown. (2) *Does the frequency band differentiate among various cognitive processing stages during the task?* In the adult EEG, the relative power values of both theta and alpha rhythms vary with specific cognitive processes (Burgess & Gruzelier, 2000; Klimesch et al., 1997, 1999). It is unknown whether this will occur in the infant EEG bands. (3) *Does the frequency band distinguish correct from incorrect responses?* Theta power increases during correct responses in adults (Klimesch et al., 1997). In infants, power at 6–9 Hz increases from baseline to task for infants who excel at spatial working memory task performance, but not for infants who do poorly on the task (Bell, 2001). It may be that this particular frequency band fluctuates with correct and incorrect responses. Because there is so little information concerning the functional meaning of different infant EEG frequency bands, the answers to these three questions may form the foundations of our knowledge of task-related changes in infant EEG power values.

Methods

Participants

Sixty-two healthy 8-month-old infants (33 male, 29 female; 53 Caucasian, 5 Black, 3 Asian, 1 Hispanic) were participants in this study and were recruited from birth announcements placed in the local newspaper. Infants were born to right-handed parents, each of whom had at least a high school diploma (highest level of education for mothers: 18% high school diploma, 68% bachelor degree, 14% graduate degree; highest level of education for fathers: 27% high school diploma, 52% bachelor degree, 21% graduate degree). All infants were born within 3 weeks of their calculated due dates and were healthy at the time of testing. Infants were seen when they were between 8.0 and 8.5 months of age, so that only 2 weeks separated the oldest and youngest infants in the study. All infants were given a small toy for their participation in the study. One

additional infant was recruited for this study but cried and would not allow EEG electrode placement.

Procedures

EEG technique. EEG recordings were accomplished during baseline and during the oculomotor spatial working memory task. Recordings were made from 10 left and right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), parietal (P3, P4), and occipital (O1, O2). All electrode sites were referenced to Cz. EEG was recorded using a stretch cap (Electro-Cap) with electrodes in the 10/20 system pattern. After the cap was placed on the infant's head, recommended procedures regarding EEG data collection with infants 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 5 k Ω . EOG, digitized along with the EEG channels and used for subsequent artifact editing, was recorded using Beckman miniature 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 on-line at 512 samples per second for each channel so that the data were not affected by aliasing. The raw data were stored for later analyses.

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

Oculomotor spatial working memory task. The infant "searched" for a hidden toy by making an eye movement to one of two possible hiding locations. 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. After the toy was hidden, the infant's gaze to the hiding site was broken and brought to the experimenter's face at 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 counterbalanced among infants. Two consecutive successful eye movements toward the same side (for example, toward the infant's right) resulted in the toy then being hidden under the tub on the opposite side (toward the infant's left; i.e., right-right-left). Regardless of whether or not the infant was successful on the "reversal" trial, new "same-side" trials commenced at the reversal site and continued until two consecutive successful eye movements were executed, initiating another reversal (i.e., L-L-R). Thus, flawless performance by an infant would result in this pattern of trials: R-R-L-L-L-R-etc. In reality, most infants were not flawless in performance and some needed multiple same-side trials in order to achieve two consecutive successful eye movements prior to reversal trials (e.g., L-L-L-L-L-L-R-R-R-L-etc.). The average number of trials (combining same-side and reversals) from which EEG data were collected was 15 per infant ($SE = 0.67$), with the minimum number of trials being 6. Four infants (7% of the sample) did not receive reversal trials, three because they were unable to accomplish two consecutive successful same side trials and one because of experimenter error.

Infants who made an eye movement toward the correct tub on reversal trials in two out of three attempts were then tested with a delay. Fifteen infants (28% of the sample) were assessed with a delay.¹ The delay was initiated during the time the infant's gaze to the hiding site was broken and brought to the experimenter's face at midline. In the delay condition, the experimenter called the infant's name, counted out the delay period, and then asked, "Where's the toy?" Subsequent delays were initiated until the infant looked at the incorrect tub in two out of three reversal trials at any given delay. Delay was incremented in 2-s intervals throughout the study. In reality, even during the "no delay" trials at the beginning of the assessment, the infants experienced a brief delay as their gaze to the tub was broken and brought to midline. This brief delay was unavoidable because of the necessity of breaking the infant's gaze so that the direction of their first eye movement could be determined. Assessment terminated when the infant made an eye movement toward the incorrect tub in two out of three reversal trials at either no delay or a timed delay.

An event marker was used in conjunction with the EEG recording so that it was possible to mark the portions of the EEG record associated with the specific processing stage of each trial. Thus, the "display & hide" (*attention*) processing stage was the time period when the experimenter manipulated the mechanical toy to capture the infant's interest and then hid it under one of the two tubs. During "delay & search" (*working memory and inhibitory control*), the infant's gaze to the hiding site was broken and brought to the experimenter's face at midline by the experimenter calling the infant's name and asking, "Where's the toy?" This component of the task ended with the infant's first eye movement. "Retrieval & reward" (*emotion*) consisted of the experimenter praising the infant for a correct eye movement (or sighing in the event of an incorrect one) and retrieving the toy from the tub for

¹These data were collected as part of a study that examined individual differences in looking task performance among 8-month-old infants. Thus, the number of trial blocks varied with each participant and was dependent on infant performance. The data on the associations between individual differences in task performance and EEG activity at 6–9 Hz have been published elsewhere (Bell, 2001).

the infant to see. The experimenter talked to the infant during each of the three processing stages.

EEG analysis. The EEG data were examined and analyzed using software developed by James Long Company. First, the data were re-referenced via software to an average reference configuration (Lehmann, 1987; Lehmann & Skrandies, 1984). Average referencing, in effect, weighted all the electrode sites equally and eliminated the need for a noncephalic reference. Active (F3, F4, etc.) to reference (Cz) electrode distances vary across the scalp. Without the re-referencing, power values at each active site may reflect interelectrode distance as much as they reflect electrical potential. 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).

The average reference EEG data were artifact scored for eye movements using a peak-to-peak criterion of 100 μV or greater. Of concern to this study was the transfer of EOG artifacts into the EEG record. Transfer of eye movements is reported to be significant in a frequency band from 0 to 6 Hz and transfer for eyeblinks occurs as high as adult alpha band frequencies (Gasser, Sroka, & Mocks, 1985). However, blink artifacts were readily identified via visual inspection of the EEG and artifact scored. EOG correction algorithms are not appropriate for children because they remove power across the entire scalp across all frequency bands (Somsen & van Beek, 1998). Because of this, part of the maturational change in frontal EEG power is filtered out by EOG correction, so selecting artifact-free data yielded a more accurate portrayal of the EEG record (Somsen & van Beek, 1998).

Artifact associated with gross motor movements over 200 μV peak-to-peak was also scored. These artifact-scored epochs were eliminated from all subsequent analyses. The data then were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-s width and 50% overlap. Power was computed for frequency bands: 3–5 Hz (actually 2.5–5.5 Hz), 6–9 Hz (5.5–9.5 Hz), and 10–12 Hz (9.5–12.5 Hz). The power was expressed as mean square microvolts and the data within each frequency band transformed using the natural log (ln) to normalize the distributions.

Eight of the participants had incomplete EEG data (6 due to excessive gross motor artifact, either during baseline or task or both, and 2 due to EEG equipment failure). Thus, there were complete EEG (baseline and task) data on 54 of the participants. All statistical analyses were completed only on these 54 infants.

The artifact-free EEG data from all of the same-side and reversal trials (both correct and incorrect) were used in the analyses for research Questions 1 (Does the frequency band discriminate between baseline and task activation?) and 2 (Does the frequency band differentiate among various processing stages during the task?). Question 3 focused on task performance (Does the frequency band distinguish between correct and incorrect responses?) and, thus, differentiated between correct and incorrect eye movements.

Statistical analyses. To examine each of the research questions, the analyses consisted of repeated-measures MANOVAs with region, hemisphere, and activation (Question 1) or processing stage (Question 2) or response (Question 3) as within-subjects factors (Picton et al., 2000). Main effects and interactions with a p value of $\leq .10$ are noted in the tables for information purposes; however, only p values of $\leq .05$ are highlighted in the results section. Of

major interest for the specific analyses associated with each question were the main effect and the interactions involving the activation (Question 1), processing stages (Question 2), and response (Question 3) 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). A Bonferroni procedure was adopted to limit the familywise Type I error rate.

Results

Does the Frequency Band Discriminate between Baseline and Task Activation?

The means for EEG power during baseline and task are displayed in Figure 1 and the results of the MANOVA are displayed in Table 1. As can be seen from Figure 1, the three frequency bands

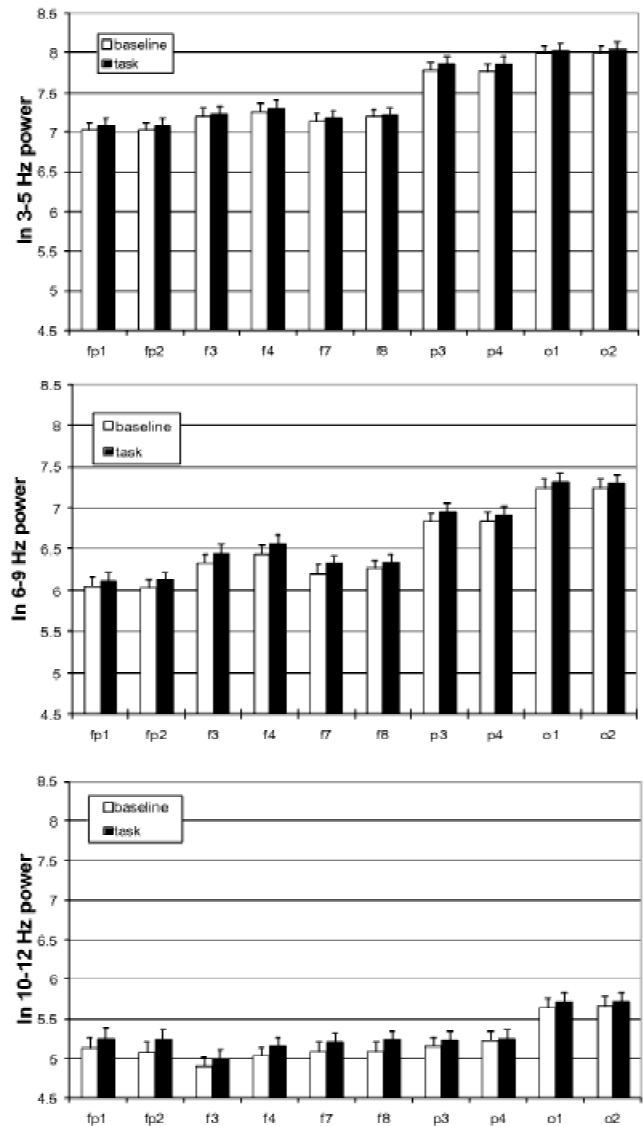


Figure 1. EEG ln power values for baseline and spatial working memory task in 8-month-old infants at 3–5 Hz (top), 6–9 Hz (middle), and 10–12 Hz (bottom).

Table 1. Summary of Multivariate Analyses *F* Values for Baseline and Task Activation Comparisons

| | Activation | Region | Hemi | Activ × Region | Activ × Hemi | Region × Hemi | Activ × Region × Hemi |
|-----------|------------|-----------|-------|----------------|--------------|---------------|-----------------------|
| <i>df</i> | 1,53 | 4,50 | 1,53 | 4,50 | 1,53 | 4,50 | 4,50 |
| 3–5 Hz | 6.20* | 244.51*** | | | | 2.13+ | |
| 6–9 Hz | 8.49** | 210.61*** | | | | 2.84* | |
| 10–12 Hz | 16.03*** | 54.64*** | 3.52+ | | 3.17+ | 2.67* | |

*** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; + $p \leq .10$.

exhibit very different power values in infants, with the 3–5 Hz band yielding the greatest power values and the 10–12 Hz band the lowest power values. The y axes in Figure 1 are on the same scale for each frequency band to highlight these differences.

There was a main effect for activation for the 3–5 Hz, 6–9 Hz, and 10–12 Hz bands. Power values were higher during task than during baseline.² There were no interactions involving activation for any frequency band.

Does the Frequency Band Differentiate among Various Processing Stages during the Task?

For these analyses, the processing stages factor had three levels that corresponded to the three sections of the oculomotor task: display & hide (the attention component of the task), delay & search (the working memory and inhibitory control portion), and retrieval & reward (the emotion portion). The means for EEG power during the three processing stages are displayed in Figure 2. The y axes for each frequency band in Figure 2 were chosen to highlight the power differences among the three conditions at each recording site; however, each y axis portrays the same relative scale. Results of the MANOVA are displayed in Table 2.

There was a main effect for processing stage for both the 3–5 Hz and 6–9 Hz bands, but not for the 10–12 Hz band. This main effect for processing stage was superseded by a two-way interaction between processing stage and region for both the 3–5 Hz and 6–9 Hz bands. At the 10–12 Hz band, there was a three-way interaction among processing stage, region, and hemisphere.

For ease in examining the two-way interactions involving the processing stages factor, separate follow-up MANOVAs were performed on the EEG power values at 3–5 Hz and 6–9 Hz for each of the five regions. The adjusted p value was $\leq .01$ ($.05/5 = .01$). For the follow-up MANOVAs that examined the overall two-way Processing Stage × Region interaction for the 3–5 Hz and 6–9 Hz bands, EEG power values were collapsed across hemisphere (because hemisphere was not a factor in the interaction); thus, the within-subjects factor in the MANOVA was processing stage.

At the 3–5 Hz band, there was a main effect for processing stage at lateral frontal, $F(2,52) = 7.33, p = .002$, parietal, $F(2,52) = 9.57, p \leq .001$, and occipital regions, $F(2,52) = 9.47, p \leq .001$. At both frontal pole and medial frontal regions, the p value failed to reach the adjusted significance level (both F s = 4.88, both p s = .011). Simple effects testing at these three regions was accomplished after adopting a Bonferroni procedure to control the overall level of significance (three regions with three comparisons at each

region; $p = .05/9 = .0056$). The delay & search stage had higher EEG power values than the retrieval & reward stage at lateral frontal, $t(53) = 3.83, p \leq .001$, parietal, $t(53) = 4.39, p \leq .001$, and occipital regions, $t(53) = 3.79, p \leq .001$. In addition, the delay & search stage had higher power values than the display & hide stage at occipital, $t(53) = 4.04, p \leq .001$.

Similar results were found at the 6–9 Hz band. There was a main effect for processing stage at lateral frontal, $F(2,52) = 16.19, p \leq .001$, parietal, $F(2,52) = 5.74, p = .006$, and occipital regions, $F(2,52) = 13.02, p \leq .001$. At both frontal pole and medial frontal regions, the p value failed to reach the adjusted significance level (both F s ≤ 4.83 , both p s = .012). Simple effects testing at these three regions was accomplished after adopting a Bonferroni procedure to control the overall level of significance (three regions with three comparisons at each region; $p = .05/9 = .0056$). The delay & search stage had higher EEG power values than the display & hide stage at lateral frontal, $t(53) = 5.69, p \leq .001$, parietal, $t(53) = 3.33, p = .002$, and occipital regions, $t(53) = 4.84, p \leq .001$. In addition, the delay & search stage had higher power values than the retrieval & reward stage at occipital, $t(53) = 4.10, p \leq .001$.

For ease in examining the three-way interaction among processing stage, region, and hemisphere at 10–12 Hz, separate MANOVAs were performed on the EEG power values for each of the five regions. Processing stage and hemisphere were the within-subjects factors. The adjusted p value was $\leq .01$ ($p = .05/5 = .01$). The only main effect or interaction involving processing stage was at lateral frontal, but that Processing Stage × Hemisphere interaction failed to reach the adjusted significance level, $F(2,52) = 4.10, p = .022$.

Does the Frequency Band Distinguish between Correct and Incorrect Responses?

For these analyses, the responses factor denoted correct and incorrect eye responses and the EEG was specific to the delay & search processing stage, when the infants' cognitive skills of working memory and inhibitory control were utilized. All 54 participants had same-side trials and 44 of the participants (81%) had artifact-free EEG data for both correct and incorrect same-side trials. However, only 18 participants (33%) had artifact-free EEG data for both correct and incorrect reversal trials. Thus, these analyses were conducted on the same-side trials. The amount of artifact-free data (i.e., the number of DFT windows) was identical for both correct and incorrect original trials, $t(43) = 0.38, p = .7$. Results of the MANOVA on the EEG power values are displayed in Table 3 and the means are displayed in Figure 3.

There was a main effect for response for the 6–9 Hz band only. The EEG power values were higher for correct trials than for incorrect trials. There were no interactions involving response at any frequency band.

²Analyses indicated that this effect was associated with individual differences in task performance. Infants were divided into high and low performance groups. High performers showed increases in 6–9 Hz EEG power from baseline to task. Low performers showed no task-related increases in EEG power. This individual differences analysis can be found in Bell (2001).

Table 2. Summary of Multivariate Analyses *F* Values for Processing Stages Comparisons

| | Stage | Region | Hemi | Stage × Region | Stage × Hemi | Region × Hemi | Stage × Region × Hemi |
|-----------|----------|-----------|-------|----------------|--------------|---------------|-----------------------|
| <i>df</i> | 2,52 | 4,50 | 1,53 | 8,46 | 2,52 | 4,50 | 8,46 |
| 3–5 Hz | 8.71*** | 276.70*** | 4.74* | 4.38*** | 2.52+ | | |
| 6–9 Hz | 11.91*** | 210.79*** | | 3.69** | | 3.46* | |
| 10–12 Hz | | 44.68*** | 4.88* | | | 3.39* | 2.68* |

****p* ≤ .001; ***p* ≤ .01; **p* ≤ .05; +*p* ≤ .10.

Summary of Findings

The 3–5 Hz band discriminated baseline from task activation and differentiated among some of the processing stages in some regions. This band did not distinguish between correct and incorrect responses, however.

The 6–9 Hz band discriminated baseline from task, as well as differentiating among some of the processing stages in some regions. The 6–9 Hz band also distinguished between correct and incorrect responses.

The 10–12 Hz band discriminated baseline from task, but did not differentiate among different processing stages during task. Neither did this band distinguish between correct and incorrect responses.

Discussion

The data in this study allowed examination of the dynamic brain electrical activity associated with cognitive processing during infancy. These data yielded valuable information concerning the functional meaning of three different infant EEG frequency bands and gave credence to infant frequency band selection.

The 6–9 Hz frequency band appeared to be most informative concerning spatial working memory. With this band, there were differences between baseline and task data, variations in power values among some of the processing stages of the cognitive task, and power value differences between correct and incorrect responses. In brief, power values at 6–9 Hz increased during cognitive challenge and increased during correct responses. Using an individual differences framework, Bell (2001) reported group differences in 6–9 Hz EEG power between infants who perform at a high level on a spatial working memory task and those who perform at a low level. The current data showed that beyond discriminating group differences in task performance, the 6–9 Hz band also distinguished correct responses. Researchers have hypothesized that brain activity is different during correct and incorrect trials; the 6–9 Hz data in this study confirm that hypothesis for infant cognition.

Given the behavioral neuroscience research on working memory (e.g., Funahashi et al., 1993), it could have been hypothesized that the power changes associated with this spatial working memory task would be specific to the frontal scalp locations. With these data, task-related changes in EEG power values at all three frequency bands were not specific to particular scalp locations. Bell (2001) reported group differences in frontal, parietal, and occipital 6–9 Hz EEG power values between infants who performed at a high level on a spatial working memory task and infants who performed at a low level. Ungerleider, Courtney, and Haxby (1998) reported frontal, parietal, and occipital activation during spatial working memory tasks in adult humans. Wilson, O Scalaidhe, and Goldman-Rakic (1993) highlighted the interconnections of the occipital and frontal lobes in nonhuman primates. Both anterior and posterior regions of the cortex have areas utilized for object identity and object location, essential components of a spatial working memory task. This supports Nelson’s (1995) admonitions that other brain areas subservise additional skills associated with performance on this type of infant spatial working memory task.

It is interesting to note the specific fluctuations associated with various processing stages of cognitive activity during the task. At the 3–5 Hz band, infants displayed greater power values during the delay & search (working memory and inhibitory control) component than during retrieval & reward (emotion). At the 6–9 Hz band, infants displayed higher power values during the delay & search (working memory and inhibitory control) component of the task than during display & hide (attention). This differentiation at both frequency bands was specific to the lateral frontal, parietal, and occipital locations. Perhaps this allows some speculation that the 3–5 Hz band may differentiate between the processing associated with working memory/inhibitory control and emotion and the 6–9 Hz band between working memory/inhibitory control and attention. The 10–12 Hz band did not contribute information concerning these processing stages.

In the results section, the focus was on main effects and interactions involving the activation, processing stages, and responses within-subjects variables. However, from a developmental psycho-

Table 3. Summary of Multivariate Analyses *F* Values for Correct/Incorrect Responses Comparisons

| | Response | Region | Hemi | Respon × Region | Respon × Hemi | Region × Hemi | Respon × Region × Hemi |
|-----------|----------|-----------|--------|-----------------|---------------|---------------|------------------------|
| <i>df</i> | 1,43 | 4,40 | 1,43 | 4,40 | 1,43 | 4,40 | 4,40 |
| 3–5 Hz | | 159.53*** | 5.87* | | | | |
| 6–9 Hz | 6.15* | 141.32*** | | | | 3.11* | |
| 10–12 Hz | | 35.33*** | 7.27** | | | | |

****p* ≤ .001; ***p* ≤ .01; **p* ≤ .05.

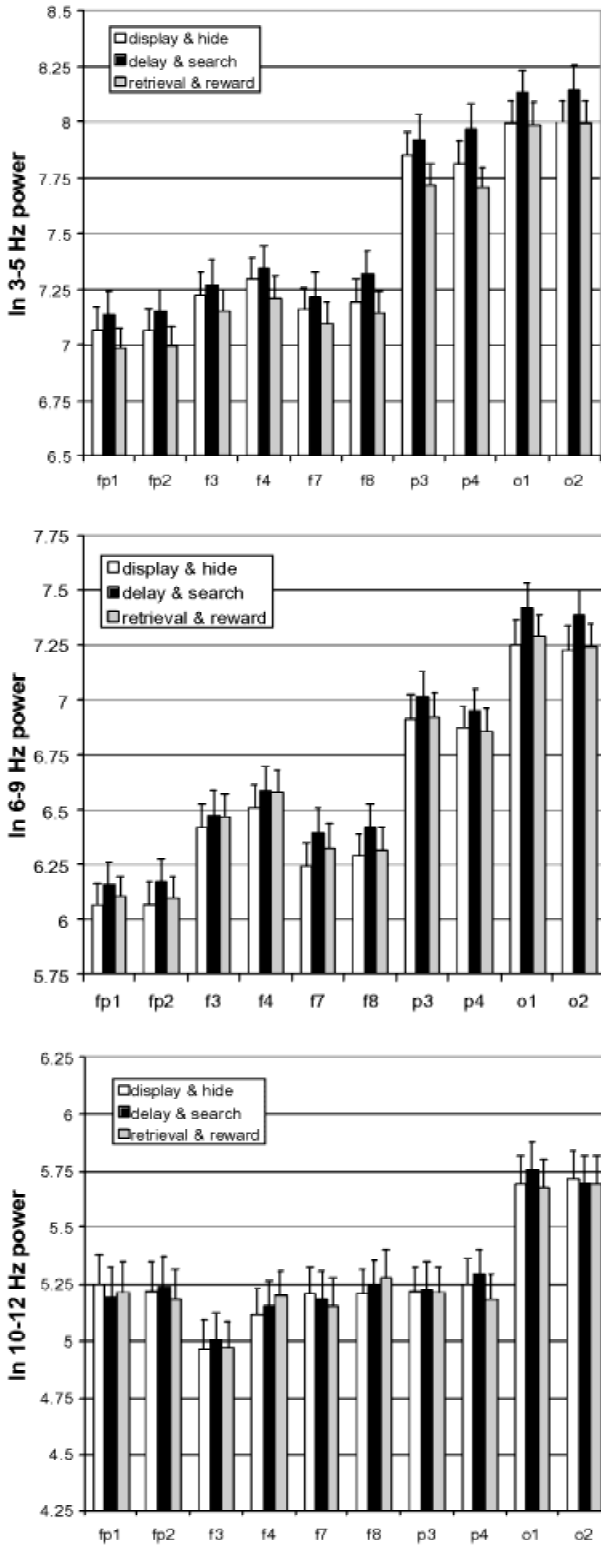


Figure 2. EEG ln power values for different processing stages during spatial working memory task at 8 months. Data are graphed with respect to frequency band: 3–5 Hz (top), 6–9 Hz (middle), and 10–12 Hz (bottom).

physiology point of view, the pattern of brain electrical activity at 10–12 Hz may provide valuable information for understanding infant EEG activity. The main effect for region found in the

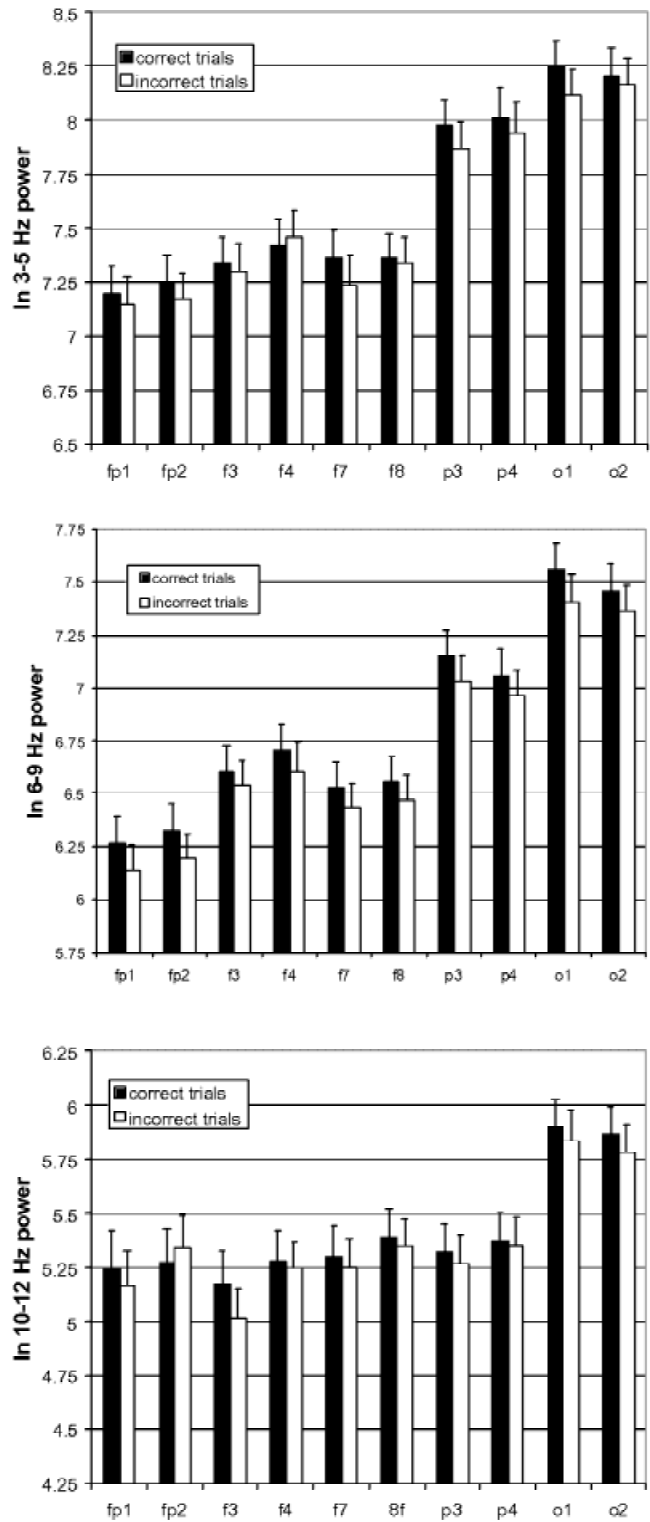


Figure 3. EEG ln power values for correct and incorrect responses during spatial working memory task with 8-month-old infants. Data are graphed with respect to frequency band: 3–5 Hz (top), 6–9 Hz (middle), and 10–12 Hz (bottom).

10–12 Hz data in all three of the analyses was driven by the higher power values at occipital locations. The parietal leads displayed elevated EEG power at both 3–5 Hz and 6–9 Hz but not at

10–12 Hz, where parietal power values are comparable to frontal values. This can be seen in all three figures. Power values at 10–12 Hz at the F3 and F4 locations did not display the same elevated pattern of power values with respect to other frontal locations that they do in the 6–9 Hz data. In fact, power values at F3 in particular appeared to be lower at 10–12 Hz relative to the other frontal scalp locations. This raises the question of the functional significance of the 10–12 Hz band. This band did not prove valuable for the research questions asked by this study. It may be, however, that the different patterns of brain electrical activity associated with the 10–12 Hz band may underlie other types of infant processing.

A word of caution is in order, however, for highlighting the lower power values at F3. This apparent asymmetry at 10–12 Hz may be an artifact of the use of average reference. Recently Hagemann et al. (2001) reported that this reference configuration might be inappropriate for measuring anterior alpha asymmetry in adult populations. Because of the topography of the adult alpha rhythm (low activity at anterior sites and higher activity at posterior sites), the signal-to-noise ratios appear to be low for anterior derivations. Thus, frontal asymmetry values obtained from average reference configuration may be as much artifact as they are a reflection of actual brain electrical activity. Although Hagemann et al. (2001) specifically investigated the adult alpha rhythm, their findings suggest caution with respect to any frontal asymmetry reports in infant or child EEG data sets utilizing the average reference. Replication of the findings of this study by using other reference configurations (e.g., average mastoids) would be a valuable endeavor.

Perhaps the most intriguing finding from this study was the ability of the 6–9 Hz frequency band to distinguish between correct and incorrect responses. Many studies of adult EEG have demonstrated fluctuations in power values associated with various cognitive demands (e.g., Burgess & Gruzelier, 2000; Davidson et al., 1990). Studies demonstrating fluctuations in power values associated with correct and incorrect responses are less common. Klimesch et al. (1997), however, reported increases in adult theta for words that were later correctly recognized and no increases for words that were later not recognized. The infant data in this study are similar to the Klimesch data in that correct searches during the spatial working memory task were associated with higher 6–9 Hz power values than incorrect searches. The ability of the 6–9 Hz band to discriminate correct from incorrect responses gives more specific information about this frequency band than the discrimination of baseline from task.

The data presented here allowed examination of the dynamic brain electrical activity associated with spatial working memory at 8 months of age. The 3–5 Hz, 6–9 Hz, and 10–12 Hz bands all exhibited different patterns of power values with respect to cognitive processing, with the 6–9 Hz band discriminating between processing stages and correct/incorrect responses. These data are a valuable first step toward defining EEG frequency bands that are appropriate for use with infant research participants and for understanding the functional meaning of these frequencies during cognitive activity.

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