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Development of the EEG from 5 months to 4 years of age

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Abstract

Objectives: This report provides a systematic longitudinal analysis of the EEG from infancy into early childhood. Particular emphasis is placed on the empirical confirmation of a 6–9 Hz alpha-range frequency band that has previously been used in the infant EEG literature.

Methods: EEG data in 1-Hz bins from 3 to 12 Hz were analyzed from a longitudinal sample of 29 participants at 5, 10, 14, 24, and 51 months of age.

Results: Inspection of power spectra averaged across the whole sample indicated the emergence of a peak in the 6–9 Hz range across multiple scalp regions. Coding of peaks in the power spectra of individual infants showed a clear developmental increase in the frequency of this peak. A rhythm in the 6–9 Hz emerged at central sites that was independent of the classical alpha rhythm at posterior sites. The relative amplitude of this central rhythm peaked in the second year of life, when major changes are occurring in locomotor behavior.

Conclusions: The 6–9 Hz band is a useful alpha-range band from the end of the first year of life into early childhood. The findings also complement other research relating the infant central rhythm with the adult sensorimotor mu rhythm.

Keywords: Electroencephalogram; Development; Infant; Mu rhythm; Alpha rhythm

1. Introduction

Since Berger (1932) documented the first study of the electroencephalogram (EEG) in infants and children, there have been numerous investigations of the development of the EEG across infancy and childhood (for reviews see Bell, 1998; Dreyfus-Brisac and Curzi-Dascalova, 1975; Schmidt and Fox, 1998). In general, early studies such as those of Smith (1938a,b, 1941), Lindsley (1938, 1939), and Henry (1944) focused on the development of the occipital alpha rhythm over infancy and childhood. Using visual quantification techniques, these authors noted the emergence of a 3–5 Hz occipital rhythm at around 3 months of age. The frequency range in which this oscillation occurred was seen to increase to around 6–7 Hz by the end of the first year of life. The oscillations in early infancy were labeled as ‘alpha’ by these original authors because of a visual resemblance to the classical adult alpha rhythm. Alpha rhythm is the most prominent rhythm observed in awake adults, occurring in the 8–12 Hz frequency range. The classical adult alpha rhythm is most pronounced at occipital and parietal recording sites, but can be recorded in a weaker form at other locations on the scalp, and it is stronger when the eyes are closed and is desynchronized (blocked) when the eyes are opened. Lindsley (1938) observed that the infant alpha rhythm was blocked by visual stimulation even in infants a few months of age, suggesting a functional as well as a visual similarity between infant alpha at posterior sites and the adult alpha rhythm. This was also clearly shown for 7–12 month old infants by Stroganova et al. (1999), who found a pronounced increase in 6–8 Hz rhythmic activity at parieto-occipital sites under a condition of total darkness, compared with a condition of quiet attention with illumination.

Computerization of EEG analysis flourished in the 1960s and 1970s, particularly following the development of the fast Fourier transform (FFT; Cooley and Tukey, 1965). Studies of normally developing infants and children using such techniques have shown a developmental pattern in terms of an increase in the prevalence of higher frequency (e.g. 6–12 Hz) oscillations compared to low-frequency (e.g. 1–5 Hz) activity (e.g. Corbin et al., 1955; Gibbs and Knott, 1949; Hagne, 1972; Matousek and Petersen, 1973; Mizuno et al., 1970; Srinivasan, 1999). Such a pattern is clearly consistent with a developmental increase in the frequency of the alpha rhythm. More recently, Stroganova et al. (1999) in a study of 7–12 month old infants, detected changes in alpha frequency over a period of 3 months towards the end

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of the first year of life. Studies of EEG frequency development have tended to focus on the classical occipital alpha rhythms. However, certain researchers have also described rhythmic activity in the alpha frequency band at other sites that may be functionally independent of the occipital rhythm. Smith (1939, 1941) noted the appearance in the awake EEG of a 7 Hz rhythm at central sites at around 4 months of age. He labeled this rhythm 'central alpha' and using a cross-sectional sample, observed that the mean frequency of this rhythm remained around 7 Hz over the first year of life, increased to 8 Hz by 18 months of age, then to 9 Hz by 4 years of age, and stabilized at around 10 Hz in mid-adolescence (Smith, 1941). Hagne et al. (1973) confirmed Smith's (1941) infancy findings with a longitudinal sample of infants over the first year of life. In the data of Hagne et al. (1973), a central rhythm was not visible at 4 months of age but is clearly seen at 6 Hz in the power spectra from 6 until 12 months of age, by which time the peak had moved to a frequency of just above 7 Hz. Both Smith (1941) and Hagne et al. (1973) speculated that the development of the central rhythm in infants is associated with the development of motor and locomotor skills. More recent work has indeed suggested a functional relation between the 6 and 9 Hz central rhythm in infants and young children and the sensorimotor 'mu' rhythm found in adults (Galkina and Boravova, 1996; Stroganova et al., 1999). In adults, the classical mu rhythm occurs in the 7–13 Hz range, appears maximally over central sensorimotor areas, and is attenuated or blocked by movement or intended movement of the contralateral side of the body (Gastaut et al., 1954; Kuhlman, 1978). Niedermeyer (1997) summarizes the contemporary view that both the classical occipital rhythm and the central mu rhythm are two distinct kinds of sensory-specific alpha rhythms in the awake adult EEG. However, the relation of the infant mu rhythm to the classical adult mu rhythm is not clear, and more developmental work is needed to elucidate the dynamics of this salient central rhythm from infancy to early childhood and beyond.

Some studies examining the developmental course of the EEG have extrapolated the commonly accepted adult frequency bands back to infancy and childhood in order to calculate the developmental trajectories of power in these conventional bands (e.g. Hagne, 1968, 1972; John et al., 1980; Matousek and Petersen, 1973). However, given the developmental changes in alpha peak frequency documented previously, it is very likely that alternative frequency bands are needed for developmental work, or at least that the functional meaning of the adult bands needs to be reconsidered for infants and children. An example of the modification of the conventional adult frequency bands is that of Orekhova et al. (2001) who used a frequency band of 6.4–10.0 Hz as the 'alpha range' in a sample of infants aged 7–12 months. They conceptualized this band as encompassing both central sensorimotor and posterior alpha rhythms, and chose the 6.4 Hz cutoff to minimize contamination of the alpha band from theta activity.

The lack of clear identification of an alpha frequency band in infants and young children has led to a variety of bands being employed in developmental studies relating EEG to behavior (see Table 1). Despite this plethora of developmental EEG publications utilizing various frequency bands, a longitudinal examination of EEG development from infancy to early childhood has not been undertaken. In this article we trace the development of the EEG from infancy into early childhood. Of the frequency bands presented in Table 1, a 6–9 Hz band or a close derivative (e.g. 6–8 Hz) has been predominant, and it is this band that will be further investigated here. This comprises two main steps: first, we examine the distribution of peaks in power spectra in the waking EEG in infancy and early childhood, with the aim of identifying trends in peak dynamics over electrode sites and ages. Given the findings from this preliminary examination, we then consider the consistency of the 6–9 Hz band across infancy and also determine its developmental course in a longitudinal analysis from 5 months to 4 years of age.

2. Methods

2.1. Participants

The participants in the current study were part of a longitudinal sample of infants who were participating in a study of psychophysiological aspects of social and emotional development. The participants were all Caucasian, of middle-class background, and were living in the greater Washington, DC area. Families with young infants were initially contacted by mail using commercially available

Table 1
Frequency bands used in recent developmental studies relating EEG to behavior in infants and young children up to 4 years of age

Frequency band (Hz)	Authors	Age range
1–12	Davidson and Fox, 1982	10 months
3–12	Fox and Davidson, 1988	10 months
3–11	Fox and Davidson, 1987	10 months
1–6	Field et al., 1998	3 months
2–6	Jones et al., 1997	1 months
4–6	Schmidt and Fox, 1996	4 months
	Calkins et al., 1996	9 months
	Fox et al., 2001	9 months
	Henderson et al., 2001	9 months
6–8	Davidson and Fox, 1989	10 months
	Fox et al., 2001	14, 24 months, 4 years
	Fox et al., 1995	4 years
6–9	Bell and Fox, 1992, 1996, 1997; Fox and Bell, 1990; Fox et al., 1992; Bell, 2002	7–12 months
	Dawson et al., 1992a,b, 1997, 1999	11–21 months
	Galkina and Boravova, 1996	2–3 years
6–10	Orekhova et al., 2001	8–11 months
7–10	Finman et al., 1989	3 years

lists of names and addresses compiled from the birth records of area hospitals. Interested parents were asked to complete a brief background survey. Families were excluded from further participation if one or both parents were left-handed (in order to avoid handedness effects in the EEG), if the infant was pre-term, if the infant had experienced any serious illnesses or developmental problems since birth, or if the infant was on any long-term medication.

Infants were seen in a home visit at 4 months of age ($N = 255$), and a subset of 72 infants was selected for longitudinal follow-up based on high or low levels of motoric and affective reactions to visual and auditory stimuli presented during the 4 month home visit. Full details of the selection procedure are given in Fox et al. (2001). The selected infants were subsequently brought to the laboratory at 5, 10, 14, 24 months and 4 years of age for a visit that included the collection of EEG data. Informed consent was obtained from all families at every age of assessment.

In this article we first examine overall power spectra and then we report longitudinal analyses of EEG band power. All analyses concern the 29 infants (17 boys, 12 girls) who had complete data at all 5 age points. The mean age of the 29 infants at each time point was 5.17 (SD = 44), 9.52 (0.41), 14.25 (0.46), 24.30 (0.36) and 50.98 months (2.25).

2.2. Procedures

At every age of assessment, each infant visited the laboratory with his or her mother for a visit lasting 1–2 h, the first part of which involved the collection of psychophysiological data. The EEG data were collected while the infant or child was alert and quietly attending to combined visual and auditory stimuli.

At 5 and 10 months of age, the infant was seated in the mother's lap, while at 14 and 24 months of age, infants were seated in an infant seat next to their mother. At each of these ages, a bingo wheel was placed on the table directly in front of the infant. An experimenter placed different numbers of brightly colored balls (1, 3, or 7) in the wheel and spun the wheel for a series of trials each lasting 10 s. This experimental protocol has proved very useful in standardizing behavioral and attentional state during EEG collection in awake infants (e.g. Calkins et al., 1996). There were 6 trials at 4 months of age and 9 trials at 9, 14, and 24 months of age. These trials were separated by 10 s intervals in which the experimenter tapped the balls on the outside of the bingo wheel in order to keep the infant's attention between trials. EEG data were recorded for the entire bingo period, but only the data from epochs in which the wheel was being spun were subjected to further processing and analysis.

When the children were 4 years of age, EEG data were collected during a quiet period as the seated child watched a computer-generated video display of abstract patterns that was accompanied by a simple musical soundtrack. The duration of the display was just under 80 s.

Prior to the recording of EEG from each subject at each age, a 50 μV 10 Hz signal was input into each of the channels and this amplified signal was recorded for calibration purposes. Lycra stretch caps were used which had tin EEG electrodes sewn in according to the 10–20 system of electrode placement. A small amount of abrasive gel was inserted into each of the active sites on the cap, which included F3, F4, C3, C4, P3, P4, O1, and O2 as well as the reference site at the vertex (Cz). EEG was also recorded from F7 and F8 at all age points except 4 years of age, but these sites are not included in the developmental analyses in this article. Following gentle abrasion, a small amount of electrolytic conducting gel was inserted in each site. Impedances were measured at each site and were considered acceptable if they were at or below 5000 Ω. One channel of electro-oculogram (EOG) was recorded from the right eye using two mini-electrodes, one placed lateral to the eye at the outer canthus and the second placed in the supra-orbital position below the eye.

The EEG and EOG channels were amplified with Grass Model 7p511 amplifiers (high pass 1 Hz, low pass 100 Hz) and digitized at 512 Hz using Snapshot-Snapstream acquisition software (HEM Data Corp.). All subsequent processing and analysis of the EEG signal was carried out using the EEG Analysis System from James Long Company (Caroga Lake, NY, USA).

2.3. EEG data reduction

The EEG channels were re-referenced in software to an average reference configuration. The average reference has been used in much of the literature concerning the relations of EEG to emotional and cognitive development. While there is some controversy about using the average reference with small electrode arrays (e.g. Hagemann et al., 2001), the scalp distribution of the electrodes in the present study was extensive enough to justify the use of this reference configuration. After re-referencing, the digitized EEG data were displayed graphically for artifact scoring. Portions of the EEG record marked by eye movement or motor movement artifact were removed from all channels of the EEG record prior to subsequent analysis.

The re-referenced, artifact-scored EEG data were submitted to a discrete Fourier transform analysis (DFT) using a 1 s Hanning window with 50% overlap between adjacent windows. Spectral power in 1 Hz frequency bins from 3 to 12 Hz was computed for each of the electrode sites. The central frequency of each bin was an integer, e.g. the 5 Hz bin extended from 4.5 to 5.5 Hz. Across the 29 infants, the mean number of artifact-free DFT windows was 83 (SD = 65) at 5 months, 81 (32) at 10 months, 69 (21) at 14 months, 70 (37) at 24 months, and 67 (20) at 51 months of age.

All analyses were carried out on relative power scores, which are expressed as the percentage of power in a specific frequency bin at each electrode site relative to total power (in all frequency bins) at the same electrode site. For instance, relative power for the 4 Hz bin at F3 at 10 months of age is calculated as: ((spectral power in 4 Hz bin for F3 at 10 months of age/total 3–12 Hz spectral power at F3 at 10 months of age)*100). Whether EEG band power should be analyzed as absolute power or relative power has been the subject of some debate. Changes in bone thickness, skull resistance and impedance have been put forward as reasons for not using absolute power in developmental studies (e.g. Benninger et al., 1984). John et al. (1980) suggested that relative power has better test–retest reliability than absolute power. However, there are multiple viewpoints on the subject, and some research groups have even reported both absolute and relative power values in developmental studies (e.g. Clarke et al., 2001; Gasser et al., 1988). However, Clarke et al. (2001) concluded that relative power was more sensitive than absolute power to changes in the frequency composition of the EEG with age.

3. Results

3.1. Spectral analysis of relative power data

Fig. 1 shows power spectra (averaged across the 29 participants) for each site for each of the 5 age points. These spectra primarily show a general developmental decrease in low-frequency power (below approximately 6 Hz) and a concurrent increase in higher frequency power that was concentrated in a band from around 6 to 10 Hz.

The relative power spectra also show the development of a clear peak at central sites that emerges at 10 months of age and rises to maximum relative power at 14 or 24 months of age before declining to a lower level at 4 years of age. The peak frequency of this central rhythm also shows a clear pattern in the power spectrum, rising from 7 Hz at 10 months of age to 9 Hz at 4 years of age. Aside from the central rhythm, there are peaks in the 6–9 Hz range in the averaged power spectra for other electrode sites, although these peaks appear to follow a different development course, and none reaches the levels of relative power shown by the central peaks.

3.2. Peak frequency

An independent coder examined individual power spectra for each of the 29 participants at each of the 8 electrode sites across the 5 age points (for a total of 1160 spectra). The coder looked for a peak in the 3–10 Hz range in each spectrum, and classified the spectrum into one of 3 categories: no peak, single peak, or multiple peaks. Inter-rater reliability was performed on 10% of the spectra and Cohen's kappa was 0.87 for peak classification. For spectra showing single peaks, the maximum relative power value was identified across the 1 Hz bins from 3 to 12 Hz, and the value of the dominant frequency (the frequency value at which this maximum occurred) was noted. The majority (80%) of individual spectra showed single peaks. The number of spectra showing no peak declined with age (10% of spectra at 5 months showed no peak, 4% at 10 months, 2% at 14 months, 3% at 24 months, and 2% at 51 months of age) and did not show differential patterns among electrode sites. The number of spectra showing multiple peaks neither showed differential occurrence across sites, nor showed a clear developmental pattern (31% of spectra at 5 months showed multiple peaks, 23% at 10 months, 16% at 14 months, 22% at 24 months, and 37% at 51 months of age). Cases with no peaks or multiple peaks were not subject to further analysis. The distribution of the dominant frequencies of single peaks is shown in Fig. 2, which illustrates the developmental increase towards higher dominant frequencies at all electrode sites. At 5 months of age, modal peak frequencies tended to be lower at parietal and occipital sites than at frontal and central sites. The modal peak frequency at parietal and occipital sites at 5 months of age was 4 Hz, with the exception of P3, which showed equally frequent peaks at 4 and 7 Hz. Across frontal and central sites, the modal peak frequency varied between 5 and 7 Hz at 5 months of age. At 10 months of age, there was less variation between anterior and posterior sites in terms of the modal peak frequency, although posterior sites tended to show a more diffuse pattern (lack of a clearly dominant frequency) compared to frontal and central sites, which showed clear modes at 7 or 8 Hz. The distribution of peak frequencies was especially narrow at central sites compared to posterior sites. For example, out of the 26 spectra showing single peaks at C3 at 10 months of age, 24 had peaks at 7 or 8 Hz, while out of 23 spectra at C4, 20 had peaks at 7 or 8 Hz. This is in contrast to the distribution of peak frequencies at occipital sites, which had a more even distribution across a wider range of peak frequencies (4–9 Hz at O1 and 4–8 Hz at O2). At O2 at 10 months of age, the modal peak frequency was still 4 Hz.

At 14 months of age, the modal peak frequency was 8 Hz at frontal and central sites, and 7 or 8 Hz at parietal and occipital sites. At 10 months, frontal and central sites showed clearer modal frequencies, with the majority of infants showing peaks at 7 or 8 Hz in these regions, and at parietal and occipital sites, the distribution of infant peaks was again wider. At 24 months of age, the dominant peak frequency at all sites was 8 Hz. At this age, parietal and occipital sites showed less variability, with the majority of toddlers showing peaks at 8 Hz. At 51 months of age, all of the 4 frontal and central sites showed modal peak frequencies of 9 Hz. At parietal and occipital sites, the modal peak frequency was 8 Hz except for P4, which showed a modal frequency of 9 Hz.

3.3. Correlations of band power across ages

Table 2 shows Pearson correlation coefficients for relative power in the 6–9 Hz band across contiguous age points. After 10 months of age, 6–9 Hz relative power showed moderate to high consistency, with only 3 out of 24 possible correlation coefficients (3 age epochs for 8 sites) falling below $r = 0.50$. In contrast, none of the 8 correlations for the 5–10 month interval reached $r = 0.50$, and only 3 were statistically significant. The relative instability of 6–9 Hz power across this age range suggests that this frequency band at 5 months is not homologous with the same band at later ages.

3.4. Development of power in the 6–9 Hz frequency band from 10 to 51 months of age

In line with previous studies, and in accordance with the exploratory spectral analyses presented previously, relative

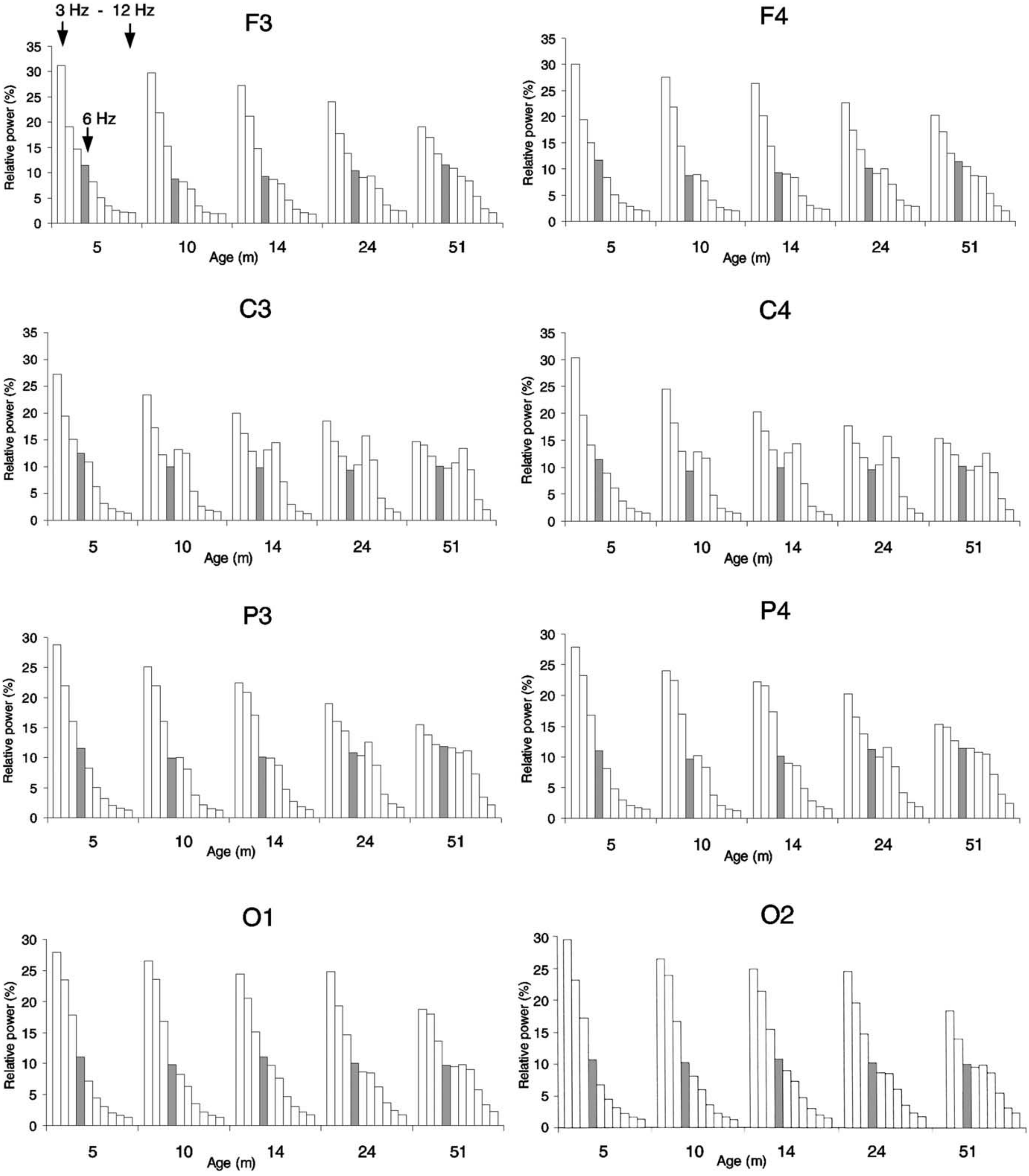

Fig. 1. Power spectra for relative power in the 3–12 Hz bins at each age point (5, 10, 14, 24, and 51 months of age). The 6 Hz bin is indicated in gray.

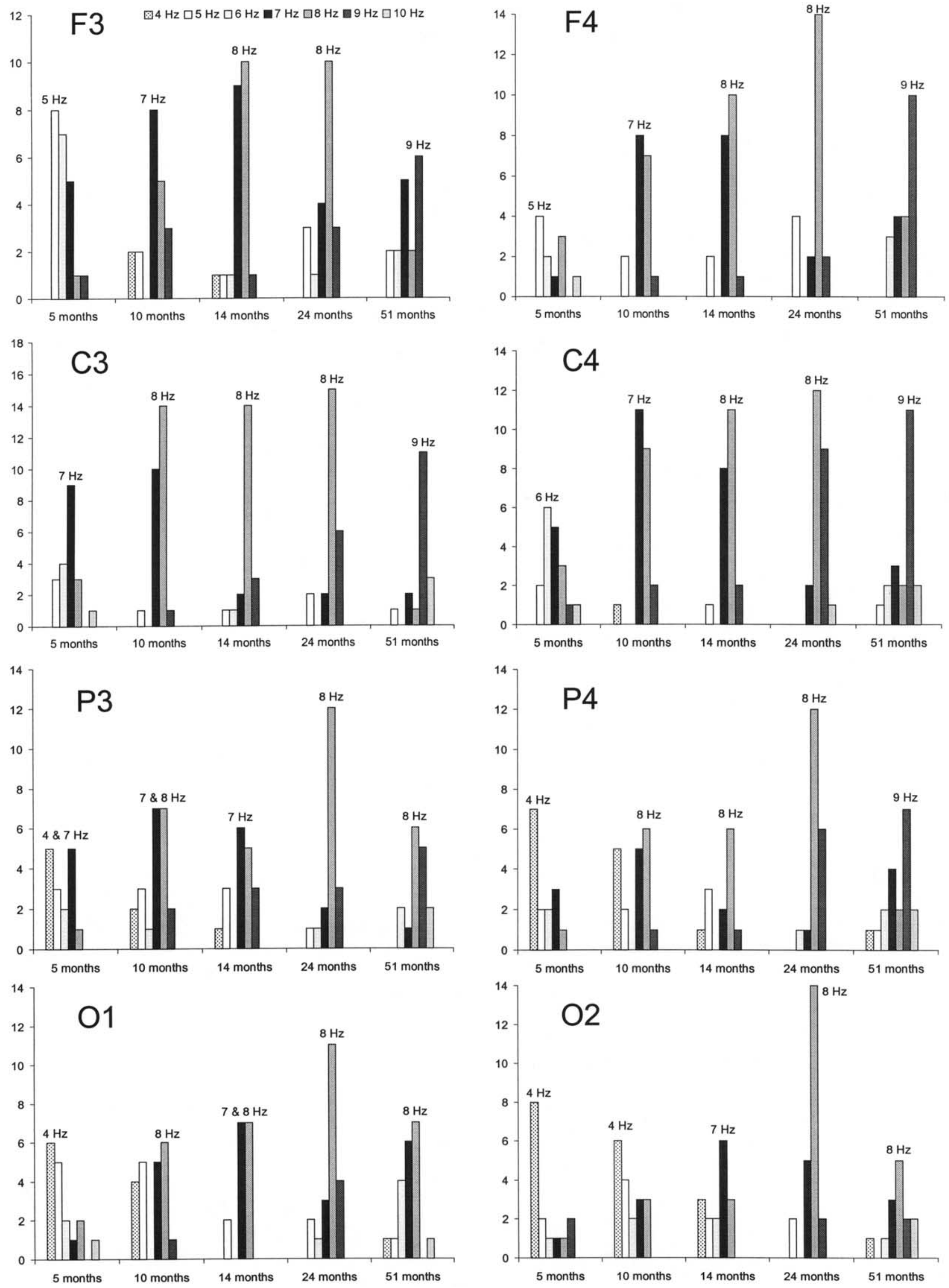

Fig. 2. The distribution of the peak frequency of relative power within the 3–10 Hz range for each electrode site at each age point. The bars indicate the number of participants whose peak frequency fell in each 1 Hz bin. Modal frequencies are indicated for each site and age.

Table 2
Pearson correlation coefficients for relative power in the 6–9 Hz band across contiguous age points[a]

	5–10 months	10–14 months	14–24 months	24–51 months
F3	0.37*	0.63**	0.67***	0.75***
F4	0.23	0.53**	0.63***	0.70***
C3	0.44*	0.43*	0.51**	0.74***
C4	0.26	0.65***	0.70***	0.77***
P3	0.29	0.36	0.39*	0.67***
P4	0.34	0.67***	0.65***	0.59**
O1	0.22	0.59**	0.68***	0.68***
O2	0.37*	0.56**	0.50**	0.54**

[a] $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

power in the 6–9 Hz band was calculated for each site at each assessment point from 10 to 51 months of age. Both the peak detection procedure and correlational analyses suggested that the 6–9 Hz range at 5 months of age is not comparable to the same frequency band at later ages. For this reason, the 5 month age point was not included in further analysis of the development of 6–9 Hz power.

Fig. 3 shows the development of mean relative power in the 6–9 Hz frequency band at each electrode site. For the analysis of these data, a repeated-measures analysis of variance (ANOVA) was carried out. The within-subjects factors were region (frontal, central, parietal, occipital), hemisphere (left, right), and age (10, 14, 24, 51 months). Similar analyses were also carried out with sex as a between-groups factor in the 3 ANOVAs. There were no significant main effects or interactions involving the sex of the child, and these analyses will not be considered further.

There were highly significant main effects of region ($F(3,29) = 69.1$, $\varepsilon = 0.605$, $P < 0.001$) and age ($F(3,29) = 20.57$, $\varepsilon = 0.813$, $P < 0.001$). The region by age interaction term was also significant ($F(9,29) = 11.92$, $\varepsilon = 0.626$, $P < 0.001$). There were no other significant main effects or interactions.

In terms of the main effects, overall means and significant differences (as determined using contrasts) are presented in Table 3. The main effect of age was due to an increase in power in the 6–9 Hz band with age. The most salient contributing factor to the main effect of region was that central and parietal sites had higher 6–9 Hz relative power compared to frontal and occipital sites. Contrasts showed that relative power at central sites was not significantly different than relative power at parietal sites, and that relative power at central and parietal sites was significantly higher than at frontal and occipital sites.

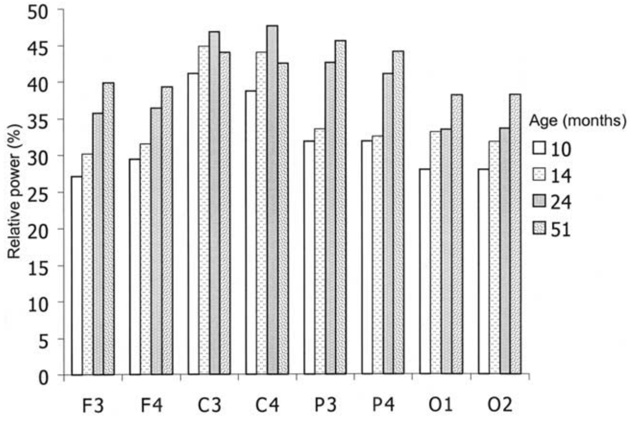

Fig. 3. Mean relative power at each electrode site for the 6–9 Hz frequency band at 10, 14, 24, and 51 months of age.

The significant region by age interaction refers to differential developmental changes in 6–9 Hz relative power between scalp regions. As shown in Fig. 3, relative power in this band at central sites showed a distinct developmental pattern compared with other scalp regions: 6–9 Hz relative power at C3 and C4 increased from 9 to 24 months, and then showed a decrease to 51 months of age. At all other electrode sites, relative power in the 6–9 Hz band increased from 24 to 51 months of age.

4. Discussion

4.1. Frequency band selection in developmental EEG studies

The results of the spectral analysis, peak detection procedures and correlational analyses suggest that 6–9 Hz was a meaningful and consistent frequency band from the latter part of the first year of life into early childhood, across all assessed scalp regions. In contrast, frequency band selection in early infancy may depend on the region and phenomenon of interest. A 6–9 Hz band should certainly capture central sensorimotor rhythms from 5 months of age onwards, but given the lower modal peak frequencies and more diffuse peak frequency distributions at posterior sites in the first year, a slightly lower band (e.g. 4–6 Hz) may also be suitable in early infancy, especially in terms of capturing posterior alpha rhythms. This is certainly the case at 5 months of age, although the 10 month data for occipital sites in the present study are ambiguous, and do not suggest a clear choice of a 4–6 Hz band over a 6–9 Hz band at this age. However, other data using a condition of reduced illumination suggest that the peak frequency of posterior alpha at

Table 3
Mean relative power (with standard errors), and significant differences for the main effects in a repeated-measures ANOVAs of region by hemisphere by age, for the 6–9 Hz frequency band from 10 to 51 months of age[a]

Region	Frontal	33.6 (1.3)	
	Central	43.7 (1.7)	C > F***, C > O***
	Parietal	37.9 (1.4)	P > F***, P > O***
	Occipital	33.0 (1.2)	
AGE (months)	10	32.0 (1.6)	
	14	35.1 (1.3)	14 > 10 months*
	24	39.6 (1.6)	24 > 14 months**
	51	41.4 (1.7)	50 > 24 months +

[a] $+P < 0.10$, $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

around 1 year of life falls at or above 6 Hz (Stroganova et al., 1999). These data, together with our own, suggest that 6–9 Hz may be more suitable for capturing posterior alpha rhythms at around 10 months of age. After the end of the first year, the picture is much clearer in that 6–9 Hz band clearly encompasses both central sensorimotor and posterior alpha rhythms over the remainder of infancy, through toddlerhood, and into early childhood. The results also suggest that the 6–9 Hz band may reach a useful limit at around 4 years. The observation that many children had spectral peaks at 9 Hz at 51 months of age even suggests that an extended band of 6–10 Hz may better capture alpha-type rhythms at this age.

The suggestion of the 6–9 Hz frequency band confirms the predominant band used in previous EEG research with infants and children. The 6–9 Hz band or a close derivative (e.g. 6–8 Hz) has been used extensively in the literature concerning the relations of EEG power with affective and cognitive development in infancy and early childhood (e.g. Bell and Fox, 1992, 1997; Davidson and Fox, 1989; Dawson et al., 1992a,b, 1997, 1999; Fox and Bell, 1990; Fox et al., 1992, 1995, 2001).

4.2. Developmental changes in the EEG

A further finding that both replicated and extended previous work was the general developmental decrease in low frequency (<6 Hz) and concurrent increase in higher frequency power (<6 Hz) over infancy and into early childhood. More specific information about this shift was also given by the analysis of dominant frequencies in the relative power spectra of individual participants. Over all scalp regions, the dominant frequency in the power spectra showed a steady developmental shift towards higher frequencies. There are a variety of possibilities for the neural processes underlying the developmental shifts in the EEG power spectrum, including general neuronal maturation and the development of myelination across the cortex. Other possible contributing factors include changes in the physical orientation and density of neuronal assemblies, and morphological changes related to the skull and other supportive tissue.

4.3. Development of the central 6–9 Hz rhythm in infancy

Relative power in the 6–9 Hz band at central sites showed a unique pattern compared to the other scalp regions. The averaged power spectra clearly show the development of a peak at central sites that emerged at 10 months of age and reached maximum amplitude at 24 months of age. The analysis of peak frequency in individual participants complements these data by illustrating the increase in peak frequency at central sites in the 3–12 Hz range. Among the infants with complete data sets, the dominant frequencies expressed by the largest proportion of infants steadily increased from 6–7 Hz at 5 months of age, to 7–8 Hz at 10 months of age, to 8 Hz at 14 and 24 months of age, and then to 9 Hz at 4 years of age.

The rhythm described by the preceding observations appears to be the same central rhythm observed in infants by other researchers such as Smith (1939, 1941), Hagne et al. (1973), Galkina and Boravova (1996) and Stroganova et al. (1999). Smith (1941) reported that the infant central rhythm was not blocked by eye-opening, an observation that suggested a functional dissociation of the central rhythm from the occipital alpha rhythm. Galkina and Boravova (1996) found that under a condition of quiet attending, a central rhythm clearly emerged in the second year of life, with a spectral peak at 8 Hz that remained at around the same level until the last age point in the study, which was 38–40 months of age. Interestingly, Galkina and Boravova (1996) also found that this spectral peak at central sites showed a decrease in magnitude under a separate condition of decreased illumination. As may be expected, occipital rhythms were much less prominent in the quiet attention condition compared with a separate condition of reduced illumination. Similar results were also described for an earlier age range by Stroganova et al. (1999), who observed a distinct peak at around 7 Hz at precentral sites in their longitudinal sample of infants aged 7–12 months of age. This peak was larger in magnitude during a condition of quiet visual attention compared to a condition of darkness, which again suggests that the central rhythm is not simply part of the classical occipital alpha rhythm. On this evidence, Galkina and Boravova (1996) and Stroganova et al. (1999) imply a functional relation between the 6–9 Hz central oscillation in infancy and early childhood with the adult mu rhythm, which is also found primarily at central sites and is also promoted by a quiet, attentive state. The adult mu rhythm is attenuated by voluntary movement and somatosensory stimulation, but is minimally affected by changes in visual stimulation. In this sense, mu has been considered by some to be a ‘somatosensory alpha rhythm’ (Kuhlman, 1978) that is sensitive to somatic afferent input. While evidence suggests that the infant central rhythm may be related to the adult mu rhythm, the precise nature of these relations is not clear. There is only very sparse information concerning the amplitude development of the central rhythm in childhood and beyond. Smith (1941) made a careful analysis of frequency changes in central rhythms over infancy and childhood, but he did not document amplitude changes in such detail. The few studies addressing this topic suggest that power in the mu frequency range at central sites increases over childhood. According to Niedermeyer (1997), rolandic mu is on the rise until a peak is reached in early adolescence. In a longitudinal sample from 4 to 11 years, Benninger et al. (1984) found an increase in 7.5–12.5 Hz power and a decrease in 3.5–7.5 Hz power at central leads. However, no previous study has looked specifically at development of relative power at central sites in a longitudinal sample from early infancy to early childhood. In the current analyses, modal peak frequency at central sites moved from 8 Hz at 24 months to 9 Hz at 4 years of age, with very few children showing a dominant frequency of 10 Hz at 4 years of age. In addition, the overall power spectra indicated a decrease in the magnitude of the broad peak at central sites from 24 months to 4 years of age. This points to a decrease in the saliency of the central sensorimotor rhythm from 2 to 4 years of age, rather than a developmental shift of the rhythm to higher frequencies above the 6–9 Hz band. It may not be coincidental that maximum relative power for this central rhythm occurs during toddlerhood, which is a time of intense development of locomotor ability. Both Smith (1941) and Hagne et al. (1973) speculated that the development of the central rhythm in infants is associated with the development of motor and locomotor skills. However, their respective studies said little about the developmental changes in the salience of the central rhythm. Our data clearly show that the central rhythm peaks in relative magnitude at a time when key developmental patterns in motor and sensorimotor cortex are being shaped.

4.4. Correlations of 6–9 Hz band power between ages

Bell and Fox (1994) report mixed findings for stability of 6–9 Hz EEG power between 7 and 12 months of age, although interpretation of these correlations is hampered by a small sample size. In the current dataset, correlations of relative power in the 6–9 Hz band between contiguous age points were moderate to strong, especially after 10 months of age.

Along with the other evidence presented throughout this article, the high level of consistency suggests that the 6–9 Hz band or a close derivative is a statistically reliable and empirically substantiated frequency band for use in developmental EEG research from the end of the first year of life into early childhood. The functional meaning and interpretation of this band depends on age and the scalp region of interest (e.g. occipital vs. central), but it is suggested that the 6–9 Hz band in infants and young children corresponds to sensory rhythms in the alpha and mu frequency range in adults. Recent research has also begun to explore other infant frequency bands (e.g. theta, Stroganova et al., 1998), which along with the research presented in the current article, points towards a possible synthesis of the functional and spatial dynamics of different EEG bands across infancy and early childhood.

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