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A frequency band analysis of two-year-olds' memory processes

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ABSTRACT

Research on the functional meaning of EEG frequency bands during memory processing has only examined two developmental periods: infancy and from late childhood to adulthood. The purpose of this study was to examine changes in EEG power for three toddler EEG frequency bands (3–5 Hz, 6–9 Hz, 10–12 Hz) during a verbal recall task. To this end, we asked three questions: (a) Which frequency band(s) discriminate baseline from memory processing?; (b) Which frequency band(s) differentiate between memory encoding and retrieval processes?; (c) Which frequency band(s) distinguish toddlers with high and low verbal recall performance? Analysis of 2-year-olds' ($n = 79$) power values revealed that all three frequency bands differentiated the retrieval and encoding phases from the baseline phase; however, the particular regions that exhibited this dissociation varied. Retrieval-related increases in 3–5 Hz (theta) power were widespread. Only the 3–5 Hz and 6–9 Hz bands distinguished encoding and retrieval processes; retrieval power values were higher than encoding power values. High and low verbal recall performers were discriminated by all frequency bands; high performers had greater power values than low performers. Thus, the 3–5 Hz (theta) and 6–9 Hz (alpha) bands were most informative about 2-year-olds' memory processes. Theta and alpha rhythms are critical to memory processes during late childhood and adulthood, and our findings provide initial evidence that these rhythms are also intricately linked to memory processing during toddlerhood. These findings are discussed in relation to behavioral changes in memory processes.

1. Introduction

The encoding and retrieval of declarative memories—essential processes for normal cognitive functioning—are intricately linked to activity of the medial temporal lobe (MTL) and the prefrontal cortex (PFC; Ghetti et al., 2010; Ofen et al., 2007). Substantial behavioral research has revealed age-related changes in memory encoding and retrieval from infancy through adulthood (see Kail, 1984; Rovee-Collier and Cuevas, 2008; Schneider and Pressley, 1997, for reviews). Neuroscience research, on the other hand, has only examined these processes during two developmental periods: infancy and from late childhood through adulthood. Thus, there is a significant gap in our current understanding of the neural correlates of memory encoding and retrieval during early to middle childhood.

In the present study, we were particularly interested in the emergence of verbal recall around 2 years of age because (a) toddlerhood marks a transitional period between infancy and childhood; (b) this is the youngest age that verbal recall can be assessed; and (c) a high degree of variability in verbal recall is likely to be evident at this age, which is optimal for examining relations between psychophysiological measures and individual differences in verbal recall. To this end, we recorded electroencephalography (EEG) during memory encoding and retrieval, calculated EEG power (i.e., a measure of neural activity), and used a multiple frequency band approach to identify which toddler frequency band(s) are functionally related to memory processing. In the following sections, we first discuss the development of EEG frequency bands during infancy and toddlerhood and then review related psychophysiological memory research findings.

1.1. Development of EEG frequency bands

In general, adult EEG frequency bands are clearly defined and their functional significance is widely accepted. The same cannot be said for infant and toddler EEG frequency bands. Early longitudinal research demonstrated that infant and toddler EEG is at a much lower frequency than adult EEG (see Bell, 1998; Bell and Fox, 1994, for reviews). Consequently, developmental EEG researchers have questioned the appropriateness of using traditional adult frequency bands (Pivik et al., 1993; Stroganova and Orekhova, 2007).

For adults, the dominant EEG rhythm during quiet wakefulness is the 8–13 Hz alpha rhythm. The frequency of the alpha rhythm is postulated to increase early in development (Lindsley, 1939). Accordingly, the alpha rhythm during early childhood functions as the alpha rhythm during adulthood, just at a lower frequency. Two lines of research have suggested that the infant and toddler 6–9 Hz band is analogous to the adult alpha rhythm. Using spectral analysis to examine longitudinal baseline data, Marshall et al. (2002) found that 6–9 Hz was the dominant

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frequency across most scalp electrode sites from infancy to 4 years of age. Thus, both the infant/toddler 6–9 Hz rhythm and the adult 8–13 Hz alpha rhythm are prominent during quiet wakefulness. Additional research suggests that the infant/toddler and adult alpha rhythms exhibit similar functional dissociations. During "eyes closed" baseline, the adult alpha rhythm typically exhibits increases in amplitude over the occipital cortex. The same pattern of findings has been found for the infant 5.2–9.6 Hz rhythm during a "lights off" period that was hypothesized to be equivalent to the "eyes closed" baseline (Stroganova et al., 1999).

In line with other developmental EEG researchers (e.g., McLaughlin et al., 2010; see Stroganova and Orekhova, 2007, for a review), we consider the infant/toddler 6–9 Hz band to be analogous to the adult alpha rhythm, and use this as a reference point when interpreting the meaning of lower and higher toddler frequency bands. The adult 8–13 Hz alpha rhythm, for instance, is centered between the lower, adjacent 4–8 Hz theta rhythm and the upper, adjacent ≈ 13–25 Hz beta rhythm. Accordingly, the infant/toddler 3–5 Hz and 10–12 Hz bands, which are adjacent to the 6–9 Hz band, are likely analogous to the adult theta and beta rhythms, respectively (McLaughlin et al., 2010; Orekhova et al., 2006; see Stroganova and Orekhova, 2007, for a review). In sum, the present study's multiple frequency band analysis of 2-year-olds' neural activity (i.e., EEG power) during memory encoding and retrieval provides the essential framework for future developmental investigations of memory processes.

1.2. Memory processes: Neural activity

Functional magnetic resonance imaging (fMRI) research with adults and older children (i.e., 8 years and older) has emphasized the role of the MTL and PFC during memory encoding and retrieval (Ghetti et al., 2010; Ofen et al., 2007). Similar fMRI research has not been completed with younger children because of the technique's extreme sensitivity to motor artifacts. EEG, on the other hand, is a non-invasive imaging technique that is relatively resistant to motor artifacts, making it the preferred brain imaging technique during infancy and early childhood (Casey and de Haan, 2002). Although EEG does not have the spatial resolution of fMRI, it does have superior temporal resolution.

EEG research with adults and older children has revealed changes in neural activity (i.e., EEG power) during memory encoding and retrieval. Specifically, memory-related changes in EEG power (as compared to a baseline/reference interval) have been found for the theta, alpha, and beta rhythms (Babiloni et al., 2004; Klimesch et al., 1996, 1997, 1999; Krause et al., 2001, 2007; Mölle et al., 2002; Sederberg et al., 2003). Similar multiple band frequency analyses of memory processes have not been completed during infancy or early childhood. Clearly, our understanding of behavioral changes in encoding and retrieval are limited by a gap in the literature about corresponding changes in neural activity.

To our knowledge, only one infant/toddler study has examined changes in EEG power associated with declarative memory processes. Morasch and Bell (2009) analyzed 6–9 Hz EEG during the encoding and retrieval stages of a deferred imitation task (i.e., nonverbal declarative memory task). They found that 10-month-olds with high recall performance (i.e., ordered recall) exhibited baseline-to-retrieval increases in EEG power at temporal sites. No retrieval-related changes were found for low performers (i.e., no ordered recall). A similar nonsignificant pattern (i.e., high performers, $p = .10$) was displayed at frontal sites. However, neither high nor low performing 10-month-olds displayed changes in EEG power during encoding at frontal or temporal electrode sites. Because of the single frequency band approach, it is unknown whether these findings reflect general or frequency-specific developmental phenomena. Clearly, additional infant and toddler multi-frequency band EEG research is essential to understanding age-related changes in neural activity during memory processing.

1.3. Research questions

The present study analyzed changes in EEG power associated with 2-year-olds' memory encoding and retrieval for three different frequency bands: 3–5 Hz (theta), 6–9 Hz (alpha), 10–12 Hz (beta). Although research with adults and older children has revealed changes in EEG power for theta, alpha, and beta rhythms during memory encoding and retrieval (Babiloni et al., 2004; Krause et al., 2001, 2007; Mölle et al., 2002; Sederberg et al., 2003) as well as differences in power between memory encoding and retrieval for theta and alpha rhythms (Babiloni et al., 2004; Krause et al., 2001, 2007), it is unknown whether 2-year-olds will exhibit similar changes in neural activity. Infant memory research has failed to reveal encoding-related changes in 6–9 Hz EEG power, and retrieval-related changes in 6–9 Hz power varied as a function of performance (Morasch and Bell, 2009). To this end, the current study addressed three questions: (a) Which frequency band(s) discriminate baseline from memory processing?; (b) Which frequency band(s) differentiate between memory encoding and retrieval processes?; (c) Which frequency band(s) distinguish toddlers with high and low verbal recall performance? The answers to these questions will enhance our understanding of the neural correlates of memory encoding and retrieval during toddlerhood.

2. Materials and methods

2.1. Participants

A total of 122 two-year-old children (62 girls, 60 boys; 5 Hispanic, 117 Non-Hispanic; 112 Caucasian, 1 African American, 9 Multi-Racial) participated in our immediate recall task as part of a longitudinal study examining cognitive development from infancy through early childhood. Children were seen between 2 years 0 months and 2 years 4 months of age ($M = 2$ years 1 month, $SD = 23$ days). All children were born within 2 weeks of their expected due dates and had no diagnosed neurological problems or developmental delays. For parents who reported educational information (120 mothers, 115 fathers), all completed a high school education (7.5% and 4.3% technical degree; 41.7% and 34.8% bachelor's degree; 26.7% and 32.2% graduate degree; respectively). Average maternal and paternal age at birth was 30.0 and 33.6 years ($SD = 4.9$ and 6.9), respectively. Children were given a small gift and parents were paid for the laboratory visit.

2.2. Procedure

2.2.1. EEG recordings

Continuous EEG recordings were collected throughout a battery of tasks in an ongoing longitudinal examination of cognitive development. Recordings made during baseline and the memory task are described and reported in the current study.

EEG was recorded during baseline and during the memory task. Recordings were made from 16 left and right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), central (C3, C4), temporal (T7, T8), medial parietal (P3, P4), lateral parietal (P7, P8), and occipital (O1, O2). All electrode sites were referenced to Cz during recording. EEG was recorded using a stretch cap (Electro-Cap, Inc.; Eaton, OH) with electrodes in the 10/20 system pattern (Jasper, 1958; Pizzagalli, 2007). During the electrode application, a research assistant entertained and distracted the toddler by playing with age-appropriate toys. This entertainment period also served to help the toddler "warm up" to the laboratory setting. After the cap was placed on the toddler's head, recommended procedures regarding EEG data collection with children were followed (Pivik et al., 1993). Specifically, a small amount of abrasive was placed into each recording site and the scalp gently rubbed. Following this, conductive gel was placed in each site. Electrode impedances were measured and accepted if they were below 10 K ohms.