Using Electroencephalography (EEG) to Measure Maturation of Auditory Cortex in Infants: Processing Pitch, Duration and Sound Location

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Introduction

The auditory system serves three main functions: identifying and locating objects, perceiving music, and understanding language. All of these rely on efficient processing of basic sound features. *Electroencephalography (EEG)* can be used to measure, for example, how auditory cortex processes pitch, fine temporal differences and sound location in infants. In particular, the brain's response to a sound event (the *event-related potential or ERP*) changes across age in morphology (i.e., what positive and negative peaks are present at which recording sites on the scalp) and in the amplitude and latency of the peaks present.[1] ERPs can also be analyzed developmentally in the frequency domain in terms of changes across age in phase-locked and non-phase-locked activity in different frequency bands such as alpha, beta and gamma.[2,3] Many factors likely contribute to these changes. Processes such as waves of *myelination*, *synaptic proliferation*, *synaptic pruning*, and the presence and amounts of various *neurotransmittors* are largely under genetic control.[4,5] These processes enable the development of more efficient circuits for processing auditory features. At the same time, the details of the networks formed are largely affected by experiential factors, such that synaptic connections receiving concurrent input are strengthened while others are weakened or eliminated. Thus, specific experience with sounds with pitch, with sound containing fine timing differences, and with sound from different spatial locations all affect auditory development. At a higher level, the specific musical system and language to which the infant or child is exposed also contribute substantially to auditory maturation, enabling efficient processing of certain musical pitch systems, rhythmic structures and phonemic categories.[6] Here we outline the dramatic changes seen in ERPs during development and indicate how these changes could be used as diagnostic indicators of early abnormal auditory development.

Subject

Basic auditory abilities are crucial for the linguistic and music acquisition that will enable communication and healthy social and emotional development. Auditory ERPs derived from EEG recordings in response to sound can track the development of auditory processing. Here we describe what is known about the normal development of ERP responses to basic auditory features, how they change with age, and how they are affected by musical experience. Auditory ERPs could be used as a diagnostic indicator of early abnormal central auditory development.

Problems

Diagnosing auditory processing difficulties early in development would be very useful as the earlier problems are identified, the greater the chance for successful remediation. Currently, hearing thresholds can be established with the *auditory brainstem response (ABR)* in newborns[7] and with behavioural measures such as *conditioned head turn* in older infants.[8] However, ABR does not give information about processing sound features such as pitch, duration and sound location, and it also does not address cortical sound processing. Behavioural measures are limited in that they typically do not have the power and experimental control to give reliable information about individual infants. Due to movement constraints and the noise of the scanner, functional Magnetic Resonance Imaging (fMRI) is very difficult to run with infants and young children. Thus, ERPs derived from EEG recordings are a method of choice for examining early auditory development and the maturation of auditory cortex.

Research Context

In adults, the presentation of a sound results in a series of obligatory evoked potentials (EPs) that originate in auditory areas. Because auditory cortex is located around the *Sylvian fissure*, synchronous depolarizations of neurons whose axons span cortical layers tend to create electrical fields at the scalp with opposite polarity at frontal and occipital sites. The series of EPs include the P1 (first frontally positive potential) around 50 ms after stimulus onset, the N1 around 100 ms and the P2 around 180 ms. Attention to the stimulus and performing a stimulus-related task result in further EP components. One other obligatory or preattentive component is the *mismatch negativity (MMN)*. MMN is elicited in an *oddball paradigm* in which repeated (standard) sounds (or tokens from a category) are occasionally replaced with a different (deviant) sound (or token from a different category).[9] The deviant sound elicits an additional negativity between 150 and 250 ms after its onset. MMN is of particular interest as it is thought to reflect an automatic change detection mechanism.

Key Research Questions

What are the developmental trajectories for the P1, N1, P2 and MMN? Is their development affected by experience? Can the maturation of auditory cortex be determined by measuring ERPs to sound?

Recent Research Results

Despite the fact that N1 and P2 are obligatory responses in adults, they are not seen clearly in children until after 4 years of age in response to music tones and sine tones.[10,11] Interestingly, N1 and P2 increase in amplitude and decrease in latency with age, reaching a maximum amplitude around ages 10 to 12. Amplitude decreases thereafter, reaching adult levels around 18 years of age. The developmental trajectory of N1 and P2 appear to be related to maturation of neural connections in layers II and upper III.[12] Data from human autopsies show that neurofilament expression, which enables fast transmission of neural signals, only begins to be expressed in these layers around 5 years of age, and does not reach adults levels until 12 years of age. The majority of connections to other cortical areas arise in these layers, suggesting that this protracted immaturity may be related to immature top-down processing or executive control of auditory perception. Interestingly, preschool children engaged in music lessons show N1 and P2 components equivalent to children 2 to 3 years older, suggesting that music lessons affect auditory executive control.[11]

Although N1 and P2 are difficult to measure in infants, MMN can be measured very early in development.[1,13] Interestingly, our research shows that in very young infants, occasional changes in the pitch, size of a temporal gap, or location of a sound result in an increase in the amplitude of a slow frontal positivity. This component is not present in adults. Some months after birth, an adult-like MMN (faster frontally negative component) emerges in the ERP. For simple pitch discrimination, MMN is present by 3 months,[14,15] but for hearing the pitch of the missing fundamental, MMN is not seen until 4 months,[16] and for hearing changes in a pitch pattern, the immature slow positive response remains at 6 months.[17] For detection of small silent gaps in a tone, the adult-like MMN emerges around 4 to 6 months.[18] Sound localization remains immature for a very long time, such that even by 8 months the slow positive response is still present, but not the adult-like MMN.[19] Thus, the age at which adult-like MMN emerges depends on the sound feature under investigation.

Research Gaps

There are few studies in this area to date, so our knowledge of normal developmental trajectories is still quite limited. Furthermore, there are few studies concerning multisensory interactions and how they develop. One promising area of recent research is to examine the development of oscillatory activity through frequency analysis of EEG data. Early data suggest protracted developmental time courses for activity in beta and gamma frequencies, and effects of musical training.[2,3] Finally, in order to understand how the functional development of the auditory cortex is related to anatomical development, interfaces between human and animal studies will need to take place.

Conclusions

Auditory development and the maturation of auditory cortex can be examined for different sound features with event-related potentials (ERPs) derived from EEG recordings. Auditory cortex shows a very protracted developmental trajectory, with completely mature responses to simple sounds not achieved until about 18 years of age. At the same time, the brain’s responses to occasional changes in a repeating auditory stimulus can be measured in very young infants. When adult-like ERP morphology for detecting sound changes emerges depends on the particular sound feature, with early emergence for pitch (3 months), later emergence for small temporal changes (4-6 months), and latest emergence for pitch patterns and sound localization (after 8 months).

Implications for Parents, Services and Policy

Early detection of central auditory processing problems (when hearing thresholds are normal) is critical because much language and musical acquisition takes place during infancy. ERPs derived from EEG offer the potential for identifying the age norms at which various developmental milestones are achieved. These could be used to assess whether individual infants are on a normal maturational trajectory.

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