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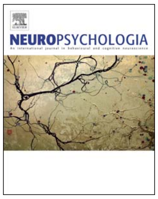

Hemispheric asymmetries in rapid temporal processing at age 7 predict subsequent phonemic decoding 2 years later: A longitudinal event-related potential (ERP) study

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ABSTRACT

The asymmetric sampling in time hypothesis (AST) suggests that the left and right secondary auditory areas process auditory stimuli according to different sampling rates (Poeppel, 2003). We investigated whether asymmetries consistent with the AST are observable in children at age 7 and whether they become more pronounced at age 9. Data were collected from 50 children who attended a 2-day research program at age 7 and were followed up 2 years later. At both time points, children were presented with tone-pairs, each composed of two 50 ms, 1000 Hz, sinusoidal tones separated by inter-stimulus intervals (ISIs) of 25, 50, 100, or 200 ms. Stimuli were presented binaurally whilst the EEG was recorded. The Ta and Tb, which are components of the auditory event-related potential (ERP), were used as electrophysiological indices of auditory processing. There was no significant effect of age on Ta or Tb responses. Tb responses to the second tone of tone-pairs indicated a left-hemisphere preference for rapidly presented stimuli (50 ms ISI) and a right hemisphere preference for more slowly presented stimuli (100 and 200 ms ISI). The results provide evidence that auditory areas of the left hemisphere preferentially respond to fast temporal rates, and those of the right hemisphere preferentially respond to slow temporal rates in children at age 7 and 9. In 7-year-old children, leftward lateralisation of responses to rapidly presented tones predicted better phonemic decoding ability 2 years later, which suggests that hemispheric specialisation may be a precursor for subsequent phonemic decoding skills.

1. Introduction

1.1. *Multi-time resolution framework of speech processing*

Speech is a rich composition of both temporal and spectral modulations. Temporal cues are known to contribute significantly to the intelligibility of speech (Luo and Poeppel, 2007), even when the signal is spectrally degraded. We use temporal cues to identify auditory objects such as phonemes and syllables, thus, sensitivity to temporal modulations in the phonemic and syllabic timescales is necessary for speech perception. Current research supports a multi-time resolution model of temporal processing for speech perception called the Asymmetric Sampling in Time (AST) hypothesis (Poeppel, 2003). The AST suggests that functional asymmetries of the left and right auditory areas facilitate the processing of the fast and slow modulations present in speech (phonemic/segmental and syllabic/suprasegmental). Poeppel (2003) proposed that temporal integration windows of either a short (25–50 ms) or long (200–250 ms) duration provide an intrinsic framework by which we sample auditory information in chunks or phonological units. He further postulated that the privileged sampling rates associated with the temporal integration windows are synonymous with the intrinsic oscillatory rates of neuronal ensembles in the left and right auditory areas. According to the AST, neuronal ensembles in both the left and right primary auditory areas are tuned to rapid temporal modulations 25–50 ms (20–40 Hz), which potentially facilitates the higher-order decomposition of the signal into fast and slow modulations. In the secondary auditory areas, the neuronal ensembles in the left and right hemispheres are differentially tuned to rapid (25–50 ms

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= 20–40 Hz), and slow (200–250 ms = 4–5 Hz) modulations, respectively. The AST hypothesis proposes a hierarchical, intrinsic neural framework, which is optimally suited to the segmental and suprasegmental timescales of speech, and is necessary for the perception of phonemes and syllables (Poeppel, 2003).

Numerous studies have investigated the predictions of the AST in adults using a range of neuroimaging techniques such as functional magnetic resonance imaging (fMRI; Boemio et al., 2005), electroencephalography (EEG; Clunies-Ross et al., 2015), simultaneous fMRI and EEG (Giraud et al., 2007), and magnetoencephalography (MEG; Luo and Poeppel, 2007, 2012). In general, results have supported the AST in that there is a leftward preference for the processing of rapid modulations and a rightward preference for slow modulations. For example, Giraud and colleagues (2007) used simultaneous EEG and fMRI to demonstrate that spontaneous fluctuations in EEG power in the gamma range (28–40 Hz) best correlated with endogenous neural activity in the left auditory cortex and fluctuations in the theta (3–6 Hz) range best correlated with endogenous neural activity in the right auditory cortex. Despite substantial evidence for asymmetric temporal processing in adults, the developmental trajectory of temporal processing asymmetries is still unknown. Importantly, the role such asymmetries may play in the development of complex linguistic abilities is poorly understood (Vanvooren et al., 2014).

1.2. Auditory ERPs and temporal processing

In the current study, we used EEG to investigate hemispheric asymmetries in temporal processing in children. As cortical processing of auditory signals occurs in the order of milliseconds, techniques such as EEG or MEG provide high temporal resolution which is necessary for the detailed analysis of such processes. However, previous research indicates that the activity of the auditory cortex gives rise to both tangential (vertical) and radial (lateral) dipoles (Ponton et al., 2002). Whilst EEG is sensitive to both tangential and radial dipoles, MEG is primarily sensitive to tangential dipoles (Irimia et al., 2012). This difference is particularly important as the tangential dipole has been localised to the superior surface of the temporal lobe (primary auditory cortex and belt areas of secondary auditory cortex), and the radial dipole has been localised to the lateral surface of the temporal lobe (parabelt areas of secondary auditory cortex) (Ponton et al., 2002; Ruhnau et al., 2011). The poor sensitivity of MEG to radial dipoles means that the use of this technique in auditory processing research may mask critical neural activity of secondary auditory areas. EEG is also a non-invasive, cost-effective neuroimaging technique that is suitable for use in a wide range of age groups, from infants to the elderly. It is therefore a valuable neuroimaging technique that can be used for a wide range of experimental paradigms and populations.

The obligatory ERPs elicited by auditory stimuli are divided into fronto-central, and temporal components, generated by the tangential and radial dipoles, respectively (Albrecht et al., 2000; Ponton et al., 2002). In previous years, it was suggested that the temporal components were simply an inversion of the components observed at fronto-central sites, however, differences in the maturation rates (Bishop et al., 2011) and source dipoles strongly suggest that fronto-central and temporal ERPs are dissociable (Ponton et al., 2002).

1.2.1. Fronto-central auditory ERPs

In adults, the fronto-central ERP waveform is the most often reported, and contains the P1 and N1. The P1 is a positive deflection that peaks between 50 and 150 ms in adults, and 100–300 ms in children. It is present from infancy and is thought to reflect early auditory processing in the cortex (Campbell et al., 2011; Shafer et al., 2015). The N1 is a negative deflection that peaks between 50 and 200 ms. It is the most well-studied of the auditory ERPs due to its prominence in adults, however, the N1 is not clearly observed in children until approximately 10 years of age (Ruhnau et al., 2011). The P1-N1 components are proposed to reflect acoustic feature processing (Wagner et al., 2013, 2017) predominantly in the primary auditory cortex (Albrecht et al., 2000; Bishop et al., 2011; Ruhnau et al., 2011).

1.2.2. Temporal auditory ERPs

The temporal ERP waveform contains the Ta, and Tb components, commonly referred to as the T-complex. It is the most prominent ERP component in children, and becomes less prominent throughout adolescence and adulthood when the N1 becomes more prominent. The Ta is a positive deflection that occurs between approximately 140–170 ms post-stimulus onset in childhood (Shafer et al., 2015). Whilst the T-complex is proposed to reflect the activity of secondary auditory areas due to the orientation of the dipole, some studies have localised the Ta to the primary auditory cortex (Bishop et al., 2011), and others report origins in secondary auditory areas (Ponton et al., 2002). The Tb is a negative deflection that peaks between 140 and 200 ms in children, and has been localised to the secondary auditory cortex (Albrecht et al., 2000; Shafer et al., 2015; Tonnquist-Uhlen et al., 2003).

The T-complex has been implicated as a potential component for identifying individuals at risk of language difficulties (Shafer et al., 2011; Tonnquist-Uhlen et al., 2003). Like the P1-N1, the T-complex reflects acoustic feature processing, but is also shown to respond differentially depending on the phonological content (Wagner et al., 2013) and temporal rate of stimuli (Clunies-Ross et al., 2015). The Ta appears less identifiable in individuals prior to the age of 7 years, and continues to increase in amplitude before reaching peak amplitude at age 11 (Shafer et al., 2015; Tonnquist-Uhlen et al., 2003). Some studies report that the Tb is identifiable from approximately 6 years of age (Tonnquist-Uhlen et al., 2003), whereas others report that it is more stable across individuals from age 7–8 years (Shafer et al., 2015).

1.2.3. Functional utility of auditory ERPs

As fronto-central and temporal ERP components reflect areas of the primary and secondary auditory areas, respectively, they can be used to differentiate between acoustic feature processing and higher-level auditory processing. Clunies-Ross et al. (2015) examined asymmetries in N1, Ta and Tb responses elicited by tone-pairs with inter-stimulus intervals (ISIs) of 50 and 200 ms. No asymmetries were observed for N1and Ta responses to rapid and slow tone-pairs. The asymmetries in the Tb component supported left hemisphere preference for the processing of rapidly presented stimuli (50 ms) and a right hemisphere preference for slowly presented stimuli (200 ms). Their findings indicated that stimuli are processed in a hierarchical manner according to temporal features and also showed that the Tb was particularly important when investigating functional asymmetries in temporal processing.

A previous study by Fox et al. (2012) examined the development of temporal processing in children using the fronto-central components. The children were tested at 7- and 9 years, and 2 years later, at 9 and 11 years. They used intra-class correlations (ICCs) to compare the fronto-central waveforms elicited by single-tones and tone-pairs with varying ISIs. High ICCs indicated a low degree of discrimination between tones, whilst low ICCs indicated a high degree of discrimination between tones. They observed significant changes from time 1 to time 2 in ICCs for rapidly presented tone-pairs, suggesting that the temporal discrimination of rapid tones improved between 7 and 9 years, and between 9 and 11 years. They also examined the relationship between rapid temporal processing and nonword repetition. They found that ICCs for 50 ms ISI tone-pairs at the initial testing was a significant predictor of nonword repetition two years later. They suggested that rapid temporal processing abilities contribute to auditory decoding in subsequent years, consistent with the idea that early auditory temporal processing likely facilitates the ability to discriminate phonological units (Poeppel, 2003).