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Event-related brain potentials to change in the frequency and temporal structure of sounds in typically developing 5–6-year-old children

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ABSTRACT

The brain's ability to recognize different acoustic cues (e.g., frequency changes in rapid temporal succession) is important for speech perception and thus for successful language development. Here we report on distinct event-related potentials (ERPs) in 5–6-year-old children recorded in a passive oddball paradigm to repeated tone pair stimuli with a frequency change in the second tone in the pair, replicating earlier findings. An occasional insertion of a third tone within the tone pair generated a more merged pattern, which has not been reported previously in 5–6-year-old children. Both types of deviations elicited pre-attentive discriminative mismatch negativity (MMN) and late discriminative negativity (LDN) responses. Temporal principal component analysis (tPCA) showed a similar topographical pattern with fronto-central negativity for MMN and LDN. We also found a previously unreported discriminative response complex (P340–N440) at the temporal electrode sites at about 140 ms and 240 ms after the frequency deviance, which we suggest reflects a discriminative processing of frequency change. The P340 response was positive with a clear radial distribution preceding the fronto-central frequency MMN by about 30 ms.

The results indicate that 5–6-year-old children can detect frequency change and the occasional insertion of an additional tone in sound pairs as reflected by MMN and LDN, even with quite short within-stimulus intervals (150 ms and 50 ms). Furthermore, MMN for these changes is preceded by another response to deviancy, temporal P340, which seems to reflect a parallel but earlier discriminatory process.

1. Introduction

Speech perception depends largely on the ability to recognize frequency and temporal changes within short time windows. The processing of these auditory features has been suggested as one of the functional bases for speech perception and successful language development (Tsao et al., 2004). The development of auditory processing at the neurocognitive level is well characterized in infants, school-age children and adults, but surprisingly little is known about auditory processing in children at the age of 5–6 years. In this study, we describe the auditory processing stages of non-verbal tone pairs with frequency change and three-tone patterns involving a temporal structure change using event-related potentials (ERPs). To our knowledge, this is the first study to investigate 5–6-year-old children using stimuli involving changes in temporal tone patterns.

Our study focuses on both the obligatory and discriminatory processing of auditory features in children. Typically, obligatory and change detection ERPs are examined using the repetition of the same sounds and changes in sound features. The obligatory auditory ERP response pattern in children is dominated by the P1–N2-complex (P100–N250). The amplitudes and latencies of these responses decrease with age (Ponton et al., 2000, 2002; Čeponienė et al., 2002) and these changes are thought to be due to myelination and synaptic pruning (Ponton et al., 2000). The changes in ERPs coincide with the improvement of, e.g., frequency discrimination and gap detection (Fox et al., 2010; Hämäläinen et al., 2013; Wunderlich et al., 2006). However, in adults, frequently repeated sounds typically generate more complex obligatory

Abbreviations: ERPs, event-related potentials; EEG, electroencephalogram; ISI, interstimulus interval; WPI, within-pair interval; Hz, Hertz; Temporal PCA, temporal principal component analysis; Temporal PC, temporal principal component; TWI, temporal window of integration; MANOVA, multivariate analysis of variance.

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response series: P1, N1, P2 and N2 at the latencies of about 50 ms, 100 ms, 150 ms and 200 ms, respectively (Näätänen and Picton, 1987; Ponton et al., 2000).

Both P1 and N2 (in the context of children, the N2 response is from now on referred to as N250) have a fronto-central topography and are suggested to have their major sources in the secondary auditory cortices both in children and adults (Liégeois-Chauvel et al., 1994; Ponton et al., 2000; Čeponiené et al., 2002). In 5–6-year-old children, the P1 is found to peak at around 80–110 ms and is suggested to be associated with basic sensory sound detection (Ponton et al., 2000, 2002; Čeponiené et al., 2002). The N250 response to single tones in children peaks at 240–280 ms and it is largest between 4 and 10 years of age (Albrecht et al., 2000; Ponton et al., 2000; Wunderlich et al., 2006). The N250 response is suggested to represent the processing of acoustic stimulus parameters and complexity, building up on the neural representation or the sensory memory traces of repeated stimuli (Karhu et al., 1997; Khan et al., 2011; Parviainen et al., 2011; Čeponiené et al., 2002).

At the lateral temporal sites, an early maturing three-peaked series of responses (Na, Ta, Tb), the T-complex, was observed in response to tone bursts, clicks, and speech stimuli (Bruneau et al., 2015; Mahajan and McArthur, 2013; Shafer et al., 2011, 2015; Tonnquist-Uhlen et al., 2003; Wagner et al., 2013). It was suggested to be independent from the other obligatory ERPs (Bishop et al., 2011; Ponton et al., 2002; Shafer et al., 2011; Tonnquist-Uhlen et al., 2003). The T-complex is suggested to be associated with auditory sensory and language processing skills (Bruneau et al., 2003). In adults, the T-complex appears at 70–160 ms, while in children (5–12-year-olds) it appears at 100–190 ms and its amplitude decreases with age (Bruneau et al., 1997; Gomes et al., 2001; Pang and Taylor, 2000; Shafer et al., 2011; Tonnquist-Uhlen et al., 2003). The T-complex was found to represent activity in radially-oriented sources located on the lateral surface of the superior temporal gyrus near the auditory cortex in children and adults (Ponton et al., 2002).

The second focus of the present study is on pre-attentive change detection processes. The fronto-centrally dominant mismatch negativity (MMN) peaks at 130–350 ms and late discriminative negativity (LDN) peaks at 400–600 ms in children after the change onset in the stimuli (in adults at 100–200 ms and 400–500 ms, respectively) (Cheour et al., 2001; Datta et al., 2010; Korpilahti et al., 2001; Näätänen et al., 2007). Both MMN and LDN emerge as early as in infancy (Cheour et al., 2000; Hämäläinen et al., 2011; Leppänen et al., 1997, 2004) and are relatively mature by the age of 5–7 years (Cheour et al., 2000; Csepe, 1995; Čeponiené et al., 1998).

MMN is generated automatically, even without overt attention to the presented stimuli and it reflects the brain's preattentive ability to detect changes in a sound stream (Näätänen and Picton, 1987). It is elicited when an infrequent deviant stimulus occurs among the repetitive standard stimuli. The sources of the auditory MMN are located in the primary and secondary auditory cortices; the attention switch related subcomponent involves the frontal cortex (Deouell, 2007; Näätänen et al., 2007).

LDN is rarely reported in adults and its functional significance is still unclear (Alho et al., 1992; Escera et al., 2002; Čeponiené et al., 1998). It has been suggested that it reflects the further processing of sound deviance after the sensory detection and evaluation of the deviancy (Čeponiené et al., 2004).

The specific focus of this study is to describe the processing of tone pairs and multi-tone pattern stimuli 5–6-year-old children. The ERPs for these have been investigated in some studies with adults or in conjunction with clinical populations such as dyslexic children (Clunies-Ross et al., 2015; Hämäläinen et al., 2007, 2008; Kujala et al., 2000, 2001). Even though there are some studies using tone pairs and multi-tone patterns in children at 6–48 months and 9 years and older (Bishop and McArthur, 2004; Choudhury and Benasich, 2011; Fox et al., 2010) no studies using multi-tone patterns in 5–6-year-old children exist.

Tone pairs have been studied in 6–48-month-old children (Choudhury and Benasich, 2011; Hämäläinen et al., 2011), and also in older children (7–9 years) and 10–19-year-old adolescents (Bishop and McArthur, 2004). Short inter-stimulus intervals (ISIs) of less than 300 ms between tones in stimulus pairs result in merged fronto-central P1–N250 in 4-year-old children for both the standard and deviant stimuli, while over 200 ms ISIs are needed to elicit a distinct P1–N250 complex in 7–9-year-old children (Bishop and McArthur, 2004; Fox et al., 2010). However, even 50 ms within-pair interval (WPI) results in distinct obligatory ERP responses in 14–19-year olds (Bishop and McArthur, 2004). In contrast to the P1 and N250 responses, the T-complex is rarely reported in conditions where tone pair stimuli have been used. In one study, in 7–9-year-old children, the T-complex is clearly distinct with ISIs over 200 ms (Fox et al., 2010).

Frequency changes in tone pairs elicit MMN (for its correspondence with a positive polarity the term mismatch response (MMR) is used) and LDN responses in children between 6–48 months and 9 years and above (Choudhury and Benasich, 2011; Hämäläinen et al., 2008, 2011). However, the role of the T-complex in discriminative processing of sound features in children has been previously only hypothesized (Shafer et al., 2011). Shafer et al. (2011) did not find a strong relationship between the T-complex and MMN in speech-related experiments, suggesting at least partially independent processes for these components. They did not, however, directly examine the T-complex and MMN in the same study. In summary, there is very little knowledge of auditory processing of tone pairs and multi-tone patterns at the age of 5–6 years, particularly in relation to the T-complex.

In the present study, the processing of sound patterns containing (1) frequency and (2) rapid temporal changes, elements that are also present in speech, are explored by using brain responses in typically developing 5–6-year-old children. We will describe the fronto-central obligatory and change detection responses elicited by the tone pairs and multi-tone pattern. The role of the T-complex in the discriminative processing of sound features is of particular interest, as this has not been directly reported before. Based on the previous literature, as outlined above, the sound pairs were expected to elicit distinct obligatory P1–N250 responses to the standard and the deviant stimulus involving a large frequency change within a tone pair. On the other hand, we expected that for the temporal change (tone insertion), the obligatory and change detection responses would be merged and overlapping, involving P1, N250 and MMN components (Bishop and McArthur, 2004; Choudhury and Benasich, 2011; Hämäläinen et al., 2007, 2008; Sussman et al., 2008). We further assumed change detection responses, MMN and LDN, to reflect the differentiation between the standard and the deviant stimuli at around 200 ms and 450 ms, respectively, from the deviancy onset (Hämäläinen et al., 2008; Čeponiené et al., 1998, 2004). These change detection responses were expected to be quite similar for both frequency and temporal deviant stimuli. Finally, we assumed that we would find a T-complex in both stimulus types in the temporal scalp area reflecting obligatory auditory processing (Shafer et al., 2011; Tonnquist-Uhlen et al., 2003), and that the T-complex would show independent behavior as compared to the change detection responses MMN and LDN (Shafer et al., 2011; Tonnquist-Uhlen et al., 2003).

2. Methods

2.1. Participants

After the study received institutional approval from the City of Oulu's Daycare Services, twelve 5–6-year-old (range from 5 years and 1 month to 6 years and 1 month; 4 females, 8 males) typically developing children participating in preschool education were recruited for the study. Parents provided the written informed consent to the study. The study was carried out in accordance with the Declaration of Helsinki. All children had performance IQs of over 85 (mean 103; range 92–114;