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Phoneme processing skills are reflected in children's MMN responses

Tanja Linnavalli[a,*], Vesa Putkinen[a,b], Minna Huotilainen[a,c,d], Mari Tervaniemi[a,d]

[a] Cognitive Brain Research Unit, Institute of Psychology and Logopedics, University of Helsinki, P.O.Box 9, FI-00014 Helsingin yliopisto, Finland
[b] Department of Music, University of Jyväskylä, Finland
[c] Swedish Collegium for Advanced study, Uppsala University, Uppsala, Sweden
[d] Cicero learning, Institute of Behavioural Sciences, University of Helsinki, Finland

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ABSTRACT

Phonological awareness (PA), the core contributor in phoneme processing abilities, has a link to later reading skills in children. However, the associations between PA and neural auditory discrimination are not clear. We used event-related potential (ERP) methodology and neuropsychological testing to monitor the neurocognitive basis of phonological awareness in typically developing children. We measured 5–6-year-old children's (N = 70) phoneme processing, word completion and perceptual reasoning skills and compared their test results to their brain responses to phonemic changes, separately for each test. We found that children performing better in *Phoneme processing* test showed larger mismatch negativity (MMN) responses than children scoring lower in the same test. In contrast, no correspondence between test scores and brain responses was found for *Auditory closure*. Thus, the results suggest that automatic auditory change detection is linked to phoneme awareness in preschool children.

1. Introduction

Literacy skills are among the most crucial abilities for successful functioning in our society. Achieving them early on helps a child to do well in school and succeed in later studies. In preschool children, phonological awareness (PA), the ability to perceive and manipulate sounds in spoken language, predicts later reading skills (Kirby et al., 2003; Silvén et al., 2004). Furthermore, the success in tests investigating PA in elementary school children seems to differentiate children with average and above average reading skills (Savage et al., 2005), although it is not clear if the relationship between PA and learning to read is causal or correlational (see e.g., Castles and Coltheart, 2004; Melby-Lervåg et al., 2012). Our knowledge of the correspondence between behavioural measures of pre-reading skills, such as phonological awareness, and neural prerequisites is still incomplete. There is much to learn about how success in neuropsychological tests manifests itself in the developing brain of children. Here we use well-established event-related potential (ERP) methodology to probe the neurocognitive basis of phonological awareness in typically developing children.

1.1. Mismatch negativity

Mismatch negativity (MMN) is a negative polarity component of ERPs that is thought to reflect the discrimination of change in a stream of repeating sounds (Näätänen, 1992; Winkler et al., 2009). According to the current theory, the brain predicts, i.e., forms a neural representation of the regular features in the auditory input and when a change is detected, an MMN response is elicited. MMN appears to originate from two areas: bilaterally supratemporal planes of the auditory cortices and prefrontal cortex (Näätänen and Escera, 2000; Rinne et al., 2000). MMN occurs even when the subject is not attending to the stimuli, and this makes it a practical tool to investigate young children that are easily distracted and sometimes unmotivated to participate experimental tasks (Näätänen et al., 2010; for a review, see e.g. Näätänen et al., 2007).

MMN can be recorded already in fetuses (Huotilainen et al., 2005) and newborns (Cheour et al., 2000; Kushnerenko et al., 2002; Partanen et al., 2013b; Trainor et al., 2001), and is well established in preschool (Lee et al., 2012; Lovio et al., 2009) and school-age children (Cheour et al., 2000; Datta et al., 2010; Kraus et al., 1999). With subtle deviants, MMN is small in amplitude during preschool and early school-age (Lovio et al., 2009; see e.g. Cheour et al., 2000), gradually increasing in amplitude (Bishop et al., 2011; Putkinen et al., 2014a, 2014b). It is shown to reach adult latencies of 100–250 ms in adolescence (Paquette et al., 2013; Shafer et al., 2000, 2010). MMN has been recorded in children for changes in frequency (Maurer et al., 2003; Shafer et al., 2000), phonemes (Čeponienè et al., 2004; Datta et al., 2010; Kraus et al., 1999; Kushnerenko et al., 2002; Kuuluvainen et al., 2016; Lovio

* Corresponding author.
E-mail address: tanja.linnavalli@helsinki.fi (T. Linnavalli).

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et al., 2009, 2010), intensity (Lovio et al., 2009, 2010; Partanen et al., 2013a) and duration (Lovio et al., 2009, 2010). It has also been found in children in response to more abstract features, such as changes in the direction of frequency change in sound pairs (Gumenyuk et al., 2003).

1.2. Late discriminative negativity

Korpilahti et al. (1995) first described the late discriminative negativity (LDN), a negative response occurring 350–550 ms after the stimulus onset. The response has been found predominately in children, both in preschool (Korpilahti et al., 2001; Korpilahti et al., 1995; Maurer et al., 2003) and school-age (Bishop et al., 2011; Čeponienè et al., 1998; Čeponienė et al., 2002; Datta et al., 2010; Hommet et al., 2009; Korpilahti et al., 1995; Liu et al., 2014; Shafer et al., 2005; for a review, see Cheour et al., 2001). LDN appears to diminish with age and is usually absent or nearly absent in adults (Bishop et al., 2011; Hommet et al., 2009; Liu et al., 2014), although some studies have reported finding it in adults (Alho, 1992; Trejo et al., 1995).

In comparison with MMN, LDN seems to have distinct neural generators (Čeponienè et al., 2004; Hommet et al., 2009), and thus should not be regarded as a late manifestation of the MMN. Furthermore, unlike MMN, LDN is larger for smaller deviants (Bishop et al., 2011; Čeponienè et al., 2004). Currently, LDN is thought to reflect additional cognitive processing of subtle changes in auditory stimuli, and not to be linked to attentive or sensory processes in the brain (Bishop et al., 2011; Čeponienè et al., 1998; Datta et al., 2010; Shafer et al., 2005).

Some studies have reported LDN to be more pronounced for speech than non-speech sounds (Bishop et al., 2011; Korpilahti et al., 2001, 1996; Kuuluvainen et al., 2016). Yet, the stimulus types in these studies have not always been acoustically comparable (Bishop et al., 2011; Korpilahti et al., 1996) and therefore the reason for differences in ERP amplitudes is not clear. There are also studies with matched stimuli that have not found any differences between linguistic and non-linguistic paradigms (Čeponienè et al., 2002; Davids et al., 2011). Overall, the functional significance of LDN response still needs clarification.

1.3. Links between neuropsychological measures and neurophysiological indices

Converging evidence shows that auditory ERPs and behavioural discrimination ability correspond in adults (Novitski et al., 2004; Winkler et al., 1999; for reviews, see Kujala and Näätänen, 2010; Kujala et al., 2007) and, according to some studies, in children (Kraus et al., 1996; Maurer et al., 2003). Additionally, association between children's neurophysiological measures and their skills in speech-related tests has come up in several studies (Kujala et al., 2001; Lovio et al., 2010, 2012;). For example, Lovio et al. (2010) found that 6-year-old children with familial risk for dyslexia both scored worse in phonological test and showed smaller MMNs elicited by speech sound changes than control children. Furthermore, some findings support the view that neurophysiological measures predict outcomes in speech-related tests (Hämäläinen et al., 2013; Jansson-Verkasalo et al., 2004; Kuhl et al., 2008; Maurer et al., 2009).

However, the association between ERPs and behavioural measures is not always straightforward and sometimes children do worse in tests than predicted from their brain responses (Bradlow et al., 1999). Thus, although it seems evident that there is a correspondence between ERP measures and linguistic test scores, the issue still needs clarification.

The relationships between intelligence measures and ERPs to auditory stimuli are largely understudied. Alternatively, the scarce literature may depend on the publication bias, since studies not finding any link between investigated measures tend not to be published. Most research seems to focus on schizophrenic (Kawakubo et al., 2006; Light and Braff, 2005a, 2005b) or autistic patients (Weissmüller et al., 2015). However, Light et al. (2007) found that the MMN response of healthy adults to *duration* change correlated with participants' overall level of functional status, as measured by Global Assessment of Functioning Scale (Hall, 1995). As for the children, Mikkola et al. (2007) found a correlation between MMN amplitudes to *frequency* changes and verbal IQ and verbal fluency test results when studying preterm and full-term children at the age of five years. In addition, when comparing children with speech disorders to typically developing children, Bauer et al. (2009) found that the amplitude of MMN correlated with the auditory memory span test results. Some studies have focused on typically developing children. Partanen et al. (2013a) discovered a connection between MMN amplitudes for *intensity* changes and verbal IQ tests in 4–12-year-old children. In addition, Liu et al. (2007) reported that the peak amplitudes of MMN and LDN responses of highly intelligent 11–12-year-old children for consonant change were larger and the LDN latency was shorter than those of their peers of average intelligence. As most of the studies show evidence for differences between healthy adults and groups of special features (e.g., schizophrenia patients), there is still much to be learned about associations between ERPs and intelligence measures within subject groups with no clinical background.

In our study we tested seventy typically developing children with three different tests, and thus aimed to find out whether subtle differences in neuropsychological test performance would be reflected in brain responses for phonemic stimuli. Finding such differences would suggest that there are fine-tuned links between neural substrates and testable linguistic or other cognitive abilities. Our hypothesis was that children with higher scores in linguistic tests would show larger MMN and LDN responses than the children with lower scores in the same tests. We also hypothesized that children having higher scores in tests for intelligence would show larger MMN amplitudes than their lower scoring peers. If our hypotheses prove right, it would mean that in typically developing children there is a direct link between phonological awareness and/or intelligence and hearing subtle details in linguistic sounds. Furthermore, if there are differences in how discriminating different phoneme change types differentiate children with higher and lower scores in each test, we will learn more about which sound features are more closely linked to phonological awareness, or intelligence, than others.

2. Materials and methods

2.1. Participants

All 75 participants were 5 – 6-year old kindergarten children (mean age 5 years 9 months). Due to less than 65% accepted stimulus trials in EEG data 5 participants were excluded, and data from 70 (44 female) participants were left for further analyses. The children attended 12 different municipal Finnish language kindergartens in Espoo region, and 57 of them were native Finnish speakers. The rest were bilingual, and spoke Russian (3), Estonian (2), Albanian (4), Somali (2), Swedish (1) and Armenian (1) as their native language. Bilingual children all spoke and understood Finnish at least relatively well. Among the children were thirteen whose parents reported their children either having language problems or having close relatives with dyslexia. However, there were no official diagnoses and these children's test results [*Phoneme Processing*: $t(68) = .327$, $p = .745$; *Auditory closure*: $t(68) = -.614$, $p = .542$; *Perceptual Reasoning Index*: $t(68) = 1.522$, $p = .133$] did not differ from those of the other children in the sample (for children's individual scores, see Appendix A, Table A1). Furthermore, we conducted two rANOVAs comparing the mean amplitudes of MMN and LDN responses of children with possible language problems and the other children on nine chosen electrodes for all deviants. As we found no differences [MMN: $F(1, 68) = 1.251$, $p = .283$; LDN: $F(1, 68) = .500$, $p = .482$], we included these children in the experiment.

The parents or guardians signed a written informed consent and the children gave their verbal assent before the experiment. The experi-