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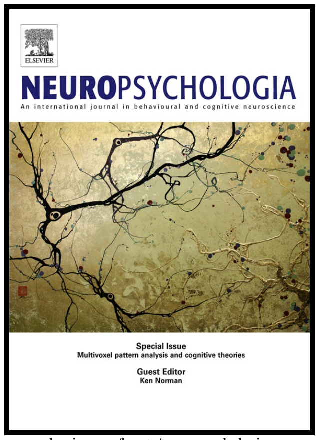

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Phoneme processing skills are reflected in children's MMN responses

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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 & 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 & 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; Putkinen et al., 2014b). It is shown to reach adult latencies of 100−250 ms in adolescence (Paquette et al. 2013; Shafer et al., 2000; Shafer et al., 2010). MMN has been recorded in children for changes in frequency (Maurer et al., 2003; Shafer et al., 2000), phonemes (Čeponienė et al., 2004; Datta et al., 2010; Kraus et al., 1999; Kushnerenko et al., 2002; Kuuluvainen et al., 2016; Lovio et al., 2009; Lovio et al., 2010), intensity (Lovio et al., 2009; Lovio et al., 2010; Partanen et al., 2013a) and duration (Lovio et al., 2009; Lovio et al., 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; Čeponienė 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 (Čeponienė 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; Čeponienė 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; Čeponienė 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; Korpilahti et al., 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 (Čeponienė 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 & 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; Lovio et al., 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 & Braff, 2005a, 2005b) or autistic patients (Weismüller 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, Table

1). 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 experiment protocol was approved by The Ethical Committee of the Humanities and Social and Behavioural sciences in the University of Helsinki, Finland.

2.2. Neurocognitive assessments

Children were tested with *Phoneme processing* subtest (NEPSY II, Korkman, Kirk & Kemp, 2008), *Auditory closure* subtest (ITPA, Kirk et al., 1972), along with *Block design* and *Matrix reasoning* subtests (WISC-IV, Wechsler, 2010). All the tests were rehearsed according to the test guidelines with children before the experiment, and they were well understood also by the bilingual children.

Phoneme processing (PP) subtest measures phonological awareness and auditory memory. In the first section, the child sees three pictures and hears names for each object in the pictures. The experimenter pronounces then a phoneme combination that is included in one of the object names and the child has to point to the object, which the syllable belongs to. In the next section the child is asked to remove a phoneme or combination of phonemes from the uttered word and say the resulting word out loud ("Say /tak:a/, 'fireplace'. Then say the same word without /t/". The right answer is /ak:a/, 'an old woman'). In the final section, (if it is reached) the child has to replace a phoneme or combination of phonemes with given phonemes ("Say /helmi/, 'pearl'. Now say the same word but replace /i/ with /a/". The right answer is /helma/, 'hem of skirt'). Testing is stopped after six consecutive wrong answers.

Auditory closure (AC) test probes if a child is able to produce a complete word out of an incomplete one. It is used regularly by speech therapists in Finland and other Scandinavian countries and has been found to differentiate children with specific language impairment (SLI) from typically developing children (Hannus et al., 2013). Because of its clinical relevance, we were interested to see if AC has a correspondence with neurophysiological measures. The procedure of the test goes as follows: experimenter says an utterance that is incomplete as a word. Participant then has to supplement it with phonemes to make it a proper word. More than one right answer is accepted (”What word do I mean with /avai/?” Right answer might be /avain/, ‘key’ or /avaimet/, ‘keys’).

Block design and *Matrix reasoning* are both subtests of The Perceptual Reasoning Index's section of WISC-IV. Block design (BD) measures visuospatial skills. Children form patterns with red-and-white blocks according to a displayed model, and this performance is timed. In Matrix reasoning (MR) test children are shown an array of pictures with one missing square, and have to select from five options the picture that fits the array. This test measures fluid reasoning skills. In our study, we combined BD and MR according to instructions in WISC-IV to form Perceptual Reasoning Index (PRI) as an indication of non-verbal intelligence.

2.3. The ERP paradigm

The stimuli were made with semisynthetic Speech Generation Method (for details, see Alku, Tiitinen & Näätänen, 1999) and were presented in a multifeature paradigm (Figure 1) (Näätänen et al., 2004). Unlike in traditional oddball paradigm where the deviant stimulus occurs typically 10-20% of the time, in multifeature paradigm every other stimulus is a standard and every other a deviant. In one paradigm there need to be several different deviant types that alternate so that every deviant type differs from the standard in only one feature (e.g. frequency or intensity). Thus, even though the deviants occur in 50% of the heard sounds, each deviant type appears only in e.g., 10%

of the stimuli. It has been shown that MMN responses of healthy adults in multifeature paradigm are similar to those elicited by traditional oddball paradigm (Pakarinen et al., 2009; Kujala, Lovio, Lepistö, Laasonen & Näätänen, 2006). In addition, in six-year-old children's responses to five different deviant types recorded in a multifeature paradigm were comparable to those recorded in an oddball paradigm (Lovio et al., 2009). The multifeature paradigm is a very efficient way to collect a large amount of data in short time, and thus it is very convenient method to measure children. In our study, one deviant type appeared approximately in 10% of the stimuli and the actual measurements took less than 20 minutes. Had we recorded the same amount of deviant trials in an oddball paradigm with 15% of the stimuli being deviants, it would have taken more than 50 minutes to measure one subject. For a child of 5–6 years of age it is a long time to sit still. Furthermore, as the previous literature is not coherent about the phoneme change types that might or might not be linked to test performance, we wanted to include different phoneme changes in our study.

***** Insert Figure 1 approximately here** ***

The standard stimuli STD (P = .50) were either /pi:/ or /te:/, presented in separate blocks (Table 1). The deviant stimuli were consonant change CON (P = .10), vowel change VOW (P = .10), vowel duration change DUR (P = .10), intensity change INT (louder P = .05 and softer P = .05) and frequency change FRE (higher P = .05, lower P = .05). The duration of the stimuli was 170 ms, excluding deviant DUR (100 ms). Onsets of the stimuli were 500 ms apart from each other. F0 was 101 Hz for all other stimuli expect for the FRE deviants which had the f0s of 93 Hz and 109 Hz. Intensity of the stimuli was ~70 dB (SPL) excluding the intensity deviants that were 63 dB and 77 dB. There were 465 stimuli in each of the four blocks and each block lasted for about 5 minutes. The order of the blocks was counterbalanced and the total EEG recording net time was 20 minutes.

The identical experiment paradigm has been used successfully in measuring MMN responses in both adults (Pakarinen et al., 2009) and children (Lovio et al., 2009).

Table 1 *The stimuli of the multifeature paradigm. Four blocks (two blocks for each standard stimuli) were played for the participant. The blocks were in randomized order.*

STD Standard	VOW Vowel deviant	CON Consonant deviant	DUR Vowel duration deviant	FRE Frequency deviant	INT Intensity deviant
/te:/	/ti:/	/pe:/	/te/	± 8 %	± 7 dB
/pi:/	/pe:/	/ti:/	/pi/	± 8 %	± 7 dB

2.4. The procedure

The EEG measurements and the neurocognitive tests were conducted in the kindergarten premises. The measurement rooms were as silent as possible, and only the participant and the experimenter(s) were present. EEG measurements and neurocognitive tests were conducted during the children's normal daily stay at kindergarten, on separate days. While preparing for and measuring EEG, the child watched an animated movie that was muted during measuring. The participants were asked to avoid unnecessary movement, to ignore the experimental stimuli, and to concentrate on the movie. The stimuli were presented via headphones (Sony Professional MDR-7506) with short breaks between blocks. Cookies and soft drink was offered during breaks. Preparation, measurement and removing the cap took approximately an hour, as did the neurocognitive testing.

2.5. Data recording and processing

The stimuli were presented with *Presentation 17.0* (Neurobehavioral Systems, Inc., CA, US) and the EEG was recorded with 32 Ag-AgCl scalp electrodes according to international 10-20 system (ActiCap; Brain Products, Germany). The EEG equipment was portable (Brainvision QuickAmp amplifier). The data were registered with sample rate of 500 Hz and recording reference was the average signal of all electrodes. Additional two active electrodes were placed on the mastoids behind both ears.

EEG was processed with BESA 5.3. software (MEGIS Software GmbH, Gräfelfing, Germany). Noisy electrodes were interpolated and eye blink artefacts were removed using semi-automatic Besa PCA method. Frequencies under 0.5 Hz and over 30 Hz were filtered out offline and the data were re-referenced to the mean of the mastoids. EEG was epoched from -100 ms before onset to 500 ms after the onset of the stimuli and the epochs including amplitudes exceeding ±120 μV were excluded from the analyses. The responses were averaged for each participant and the averaged responses were then exported to MATLAB R2012 (The MathWorks Inc., MA, US).

The response for intensity deviant was created by averaging the responses to both intensity changes (louder and softer). In the similar way, the response for frequency deviant was created by averaging the responses to increments and decrements of frequency. The difference signals were created for each deviant stimulus by subtracting the average standard response from the average deviant responses for each participant. The standard and deviant trials from all four blocks were combined according to the stimulus category. The electrodes F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 were chosen for further inspection. This is a typical choice in MMN paradigms, as it reveals front-back and left-right distribution of the brain responses. Mean amplitudes of MMN were calculated from the deviant-standard difference signal over 200−250 ms for CON, FRE, INT and VOW deviants and over 225−275 ms for DUR deviant. LDN mean amplitudes were calculated over 375−425 ms for all the deviants. The children’s MMN and LDN responses typically occur in these time windows and the visual inspection showed that all the inspected responses were prominent within these time ranges.

2.6. Statistical analyses

A three-way repeated measures ANOVA (5 deviants x 3 front-back electrode lines x 3 left-right electrode lines) was conducted with SPSS 24 (IBM Corporation, NY, USA) with three test scores (PP, AC and PRI) used as covariates and native language as between-subjects factor. Whenever sphericity could not be assumed in the analyses, Greenhouse-Geisser corrections were applied.

3. Results

3.1. Test performance

The average test results for the test scores (*PP, AC, PRI)* are outlined in Table 2.

Table 2 *Mean scores for all the tests.* N=70, mean age in months (SD) 69.30 (3.1).

Test	Mean scores (SD)	Minimum scores	Maximum scores
Phoneme processing (PP)	27.6 (3.6)	18	41
Auditory closure (AC)	14.0 (3.3)	5	20
Perceptual reasoning index (PRI)	29.4 (8.1)	12	48

3.2. Event-related potentials

Figure 2 shows the standard and deviant responses for the combined conditions for all participants. All the responses are larger on frontal and central than parietal lines. The inspected time windows are marked with white and grey blocks.

***** Insert Figure 2 approximately here *****

All deviants elicited MMN and LDN responses significantly differing from zero in the chosen time windows (Table 3).

Table 3 *Mean MMN (225–275ms for duration deviant, 200–250ms for all the other deviants) and LDN (375–425ms) amplitudes for all children at Fz. Standard deviations in brackets.*

Response	Deviant	Amplitude (μV)
MMN	Vowel	–2.7 (3.0)***
	Consonant	–1.1 (2.4)***
	Duration	–4.2 (3.0)***
	Intensity	–1.2 (2.2)***
	Frequency	–1.8 (2.9)***
LDN	Vowel	–5.1 (3.1)***
	Consonant	–3.4 (2.6)***
	Duration	–1.8 (2.7)***
	Intensity	–3.7 (2.8)***
	Frequency	–3.0 (2.5)***

The amplitudes significantly differing from the baseline are marked with asterisks.
*** $p<.001$

As hypothesized, the test scores in *Phoneme processing* had a significant main effect on the responses [F(1)= 4.315 ; *p*=.042] indicating that children with higher scores on the test showed a larger MMN amplitude relative to children with lower scores (for illustrational purposes, see Appendix, Figure 1 that depicts subtraction curves for higher and lower scoring children for all three tests). Main effects of *Auditory closure* [F(1)=.508 ; *p*=.479] or *Perceptual reasoning index* [F(1)= 1.700 ; *p*=.197] test scores on the responses were not significant, and neither was subjects' native language [F(1)= 056; *p*=.308].

For MMN, the only significant interaction was Left-Right x PRI [F(2, 130)=3.271; *p*=.041]. The post hoc comparisons were conducted by comparing the estimated mean amplitudes over the left, centre and right electrode lines when PRI scores were set at the first or the third quartile. These comparisons indicated that children with higher scores did not show any lateralization of responses [with higher quartile scores (35): Left: Mean = –2.1μV; Central: Mean= –2.0 μV; Right: Mean=–2.1 μV; significance of differences between Left-Right lines: Left vs. Central *p*=.596, Left vs. Right *p*=.962, Central vs. Right *p*=.581], whereas children with lower scores showed significant right-side dominance of the responses [with lower quartile scores (24): Left: Mean = –1.6μV; Central: Mean= –1.6 μV; Right: Mean= –1.9 μV; significance of differences between Left-Right lines: Left vs. Central *p*=.726, Left vs. Right *p*=.042, Central vs. Right *p*=.026]. No other significant main effects of interactions were found for the MMN. Furthermore, no significant main effects or interactions were found on LDN time window.

4. Discussion

4.1. Phoneme processing

As we hypothesized, children achieving higher scores in the *Phoneme Processing* subtest of NEPSY II showed larger MMN amplitudes than lower performers. In other words, the children's performance in the active behavioural test was reflected in the brain responses that were measured in a passive condition. Thus, it seems that automatic auditory change detection has a link, or that it even contributes, to phonological awareness. The mechanism behind this link is subject to speculation. It could be that the change detection reflects the accuracy of the memory trace, and the more accurate it is, the easier it is to make conscious inferences and manipulations of phonemes. More research is needed to find out if the differences in automatic change detection system are innate or a consequence of different auditory environments that children live in.

It is especially interesting that we were not comparing typically developing children to a clinical population, as most studies have done (e.g., Kujala, 2007; Lovio et al., 2010), but the difference was seen among typically developing children. Therefore, the salience or non-salience of responses is not dependent only on the possible diagnoses in children's linguistic development, but differentiates also typically developing children from each other. Since phonological awareness is a known index of later reading skills, brain responses connected to PA might also tell us early on how the reading skills of a child are likely to develop.

Contrary to what we hypothesized, the children's LDN responses did not show differences that might be linked to their performance in phoneme processing. Thus, we found no evidence that would link the LDN response to language processing skills. Further studies are needed to assess the significance of this response that is found in children and is likely to diminish with age (Bishop et al., 2011; Hommet et al., 2009; Liu et al., 2014).

4.2. Auditory closure

No differences linked to Auditory closure test emerged in the children's MMN or LDN responses. As we did find significant differences in responses based in subjects' scores of *Phoneme processing* test, it seems that AC is not as strongly linked to neural sound discrimination abilities as PP. Even though the manipulation of phoneme combinations is required also in this test, AC may be more closely associated with vocabulary size and linguistic memory than with phonological awareness.

4.3. Perceptual reasoning skills

Contrary to our second hypothesis, the higher performing children in *Perceptual Reasoning Index* test did not show larger MMN or LDN responses to phonemic stimuli than lower performing children. Thus, based on our study, it seems that perceptual measures of intelligence do not strongly correlate with discrimination of phonemic changes. Previous findings have not been very consistent as to which auditory change responses correlate with which intelligence test results; the studies have used different ERP paradigms and different tests. E.g., Light et al. (2007) found a correspondence between adults' MMN responses to duration change and overall level of functional status (Global Assessment of Functioning Scale, Hall, 1995). Both Partanen et al. (2013a) and Mikkola et al. (2007) found a link between verbal intelligence scores (WISC-IV, Wechsler, 2010; WPPSI-R, Wechsler, 1995) and responses for sound changes in children, Partanen et al. for intensity change and Mikkola et al. for frequency change. Nevertheless, the studied subjects were not comparable to each other or to the sample of the present study: Partanen et al. studied children representing very wide age distribution and Mikkola et al. compared children born preterm and full-term. As for us, we used non-verbal intelligence scores to measure children's intelligence, and phonemes as stimuli. Thus, it seems that the accuracy of auditory memory trace does not have a link to perceptual reasoning based on visual cues.

However, we found an interaction suggesting that whereas the responses of children with better perceptual reasoning skills are distributed evenly across the scalp, the responses of children not performing as well in these skills have a right side dominance. It might reflect differences in maturation – the brains of children with better perceptual reasoning skills are activated more evenly by auditory stimuli, while children with less strong performance in the same skills do show more lateralized activation. Yet, the reason for this rightward dominance is unclear. Bauer et al. (2009) found that when looking at area under the curve (AUC) of MMN, children with central auditory processing disorder (CAPD) who scored significantly lower in auditory memory span test than their peers, tended to have *left-hemisphere dominance* in their MMN. The control children's responses were evenly distributed. Partanen et al. (2013a) found that pre-schoolers had larger MMN responses on *left and central electrodes* to frequency deviant than school children, and according to Everts et al. (2009) *right-lateralization* of visuo-spatial processing *increases* by age, being more evenly distributed in young children than in older adolescents. As the literature of the correspondence between intelligence measures and lateralization of brain responses is scarce and very inconsistent, more research is needed to shed light on the associations between different measures of intelligence and neurophysiological indices.

4.3. Summary and conclusions

The current study investigated the associations between children's performance in linguistic and cognitive tests and their neural phoneme discrimination skills. We found that children's scores in *Phoneme processing* test were associated with their neural auditory discrimination abilities. The children scoring higher in the test had larger MMN amplitudes to phonemic changes. Furthermore, we found that children scoring lower in *Perceptual reasoning index* tests showed right-side dominance in their MMN responses. *Auditory closure* was not correlated with neural indices in this paradigm.

Taken together, based on ERP measurements and neuropsychological testing of seventy typically developing children, it seems that automatic auditory detection is linked to phonological awareness in preschool children. Further studies are needed to investigate whether this link is correlational or causal, and whether some day it will be possible to predict individual reading skills from auditory discrimination abilities. If so, it would enable one to tailor individual training programs to improve phonological awareness prior the child is supposed to learn to read. This approach would prevent or at least minimize also the problems often occurring in parallel with slow reading skill acquisition, namely low self-esteem and social disintegration.

Acknowledgements and conflict of interest

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Figure 1 − single column

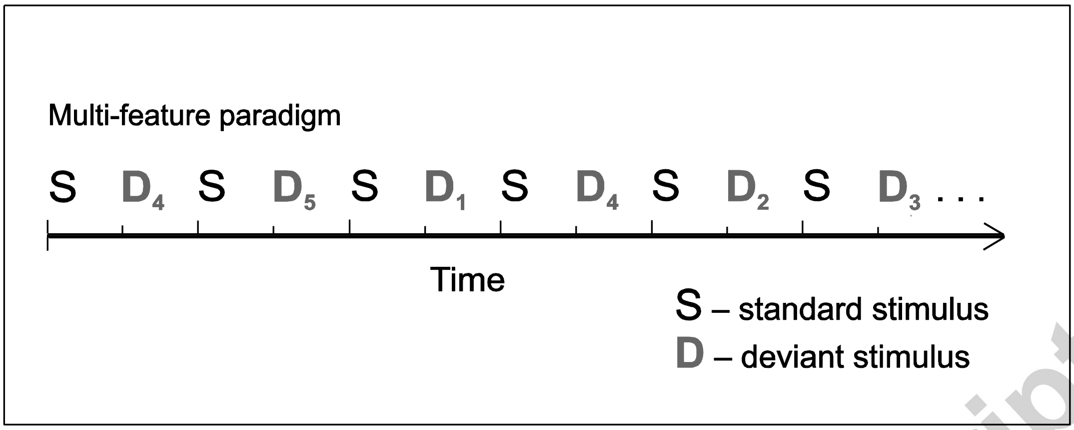

Figure 1 *Schematic illustration of the multifeature paradigm.* D_1-D_5 *stand for different deviant types used in the paradigm.*

Figure 2 – 2 columns, colour for both print and online

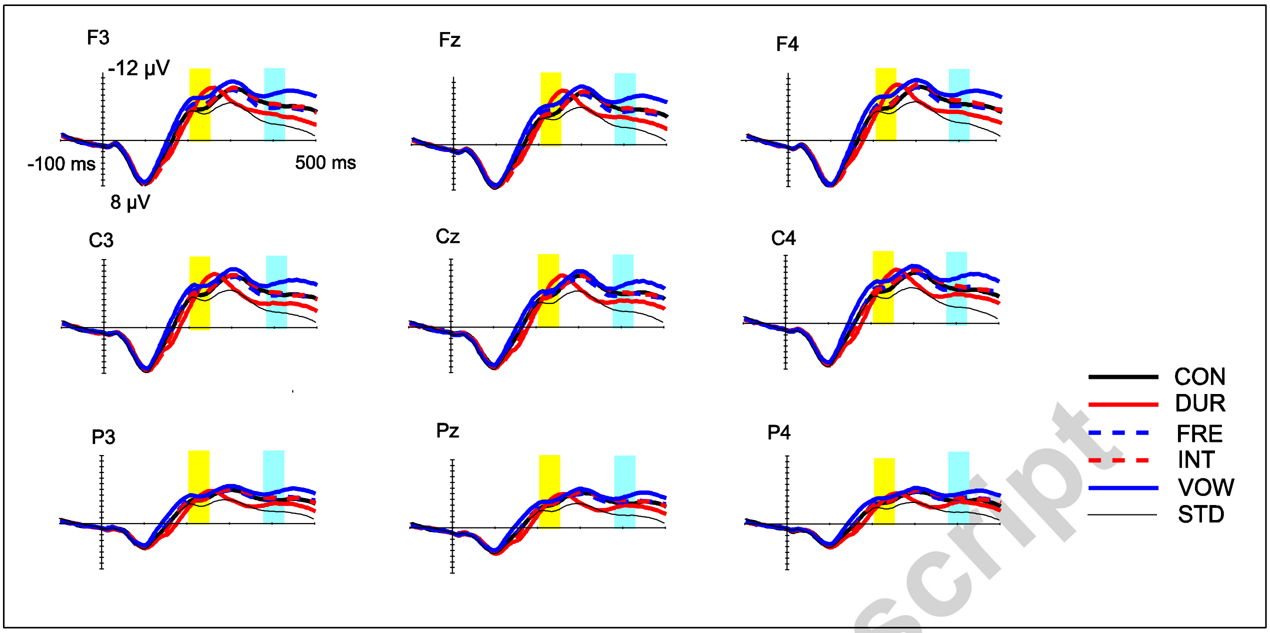

Figure 2 *Standard and deviant responses for combined conditions for all participants. Yellow blocks show the inspected MMN (200−250 ms) time window for Vowel, Intensity, Frequency and Consonant deviants (the MMN time window for Duration was chosen between 225−275ms). Blue blocks show the inspected LDN (375−425 ms) time windows for all deviants.*

Table 1 *Individual scores for all the tests. LP stands for children whose parents reported them having language problems or their close relatives having dyslexia and NLP for children whose parents did not report any problems.*

Subject		Scores		
		Phoneme Processing (Mean 27.6; SD 3.6)	*Auditory Closure* (Mean 14.0; SD 3.3)	*Perceptual Reasoning Index* (Mean 29.4; SD 8.1)
01	LP	24	16	22.5
05	LP	25	16	28.5
10	LP	25	13	27.0
12	LP	26	13	18.0
14	LP	32	14	19.5
17	LP	27	13	40.5
19	LP	33	13	45.0
25	LP	25	13	45.0

39	LP	28	14	28.5
42	LP	30	17	31.5
43	LP	32	11	48.0
57	LP	29	15	46.5
72	LP	27	7	21.0
03	NLP	24	19	30.0
04	NLP	32	20	22.5
06	NLP	29	17	36.0
07	NLP	25	11	12.0
09	NLP	33	18	34.5
11	NLP	34	15	39.0
13	NLP	26	13	22.5
15	NLP	24	15	34,5
16	NLP	27	14	33.0
18	NLP	29	17	25.5
21	NLP	27	18	21.0
22	NLP	31	17	27.0
23	NLP	30	19	37.5
24	NLP	25	14	12.0
27	NLP	24	13	33.0
28	NLP	26	12	33.0
30	NLP	26	19	39.0
32	NLP	29	18	36.0
33	NLP	26	14	22.5
34	NLP	27	13	30.0
35	NLP	30	15	30.0
36	NLP	25	16	28.5
37	NLP	25	14	21.0
38	NLP	26	18	39.0
40	NLP	28	19	36.0
41	NLP	29	14	36.0
44	NLP	24	13	28.5
48	NLP	26	11	27.0
49	NLP	30	8	22.5
50	NLP	28	15	27.0
52	NLP	26	12	24.0
54	NLP	41	14	27.0
55	NLP	28	14	27.0
56	NLP	22	14	24.0
58	NLP	26	6	36.0
59	NLP	25	13	25.5
60	NLP	29	15	30.0
61	NLP	28	17	25.5
62	NLP	39	19	46.5
63	NLP	30	12	30.0
64	NLP	27	18	24.0
65	NLP	27	16	24.0
66	NLP	25	14	21.0
67	NLP	33	17	30.0
68	NLP	28	12	28.5
70	NLP	26	14	28.5
71	NLP	26	7	33.0
73	NLP	26	11	22.5

74	NLP	26	5	24.0
75	NLP	30	12	21.0
76	NLP	29	15	16.5
78	NLP	30	13	30.0
80	NLP	23	9	16.5
81	NLP	24	7	45.0
82	NLP	28	14	37.5
83	NLP	18	10	30.0
84	NLP	26	14	30.0

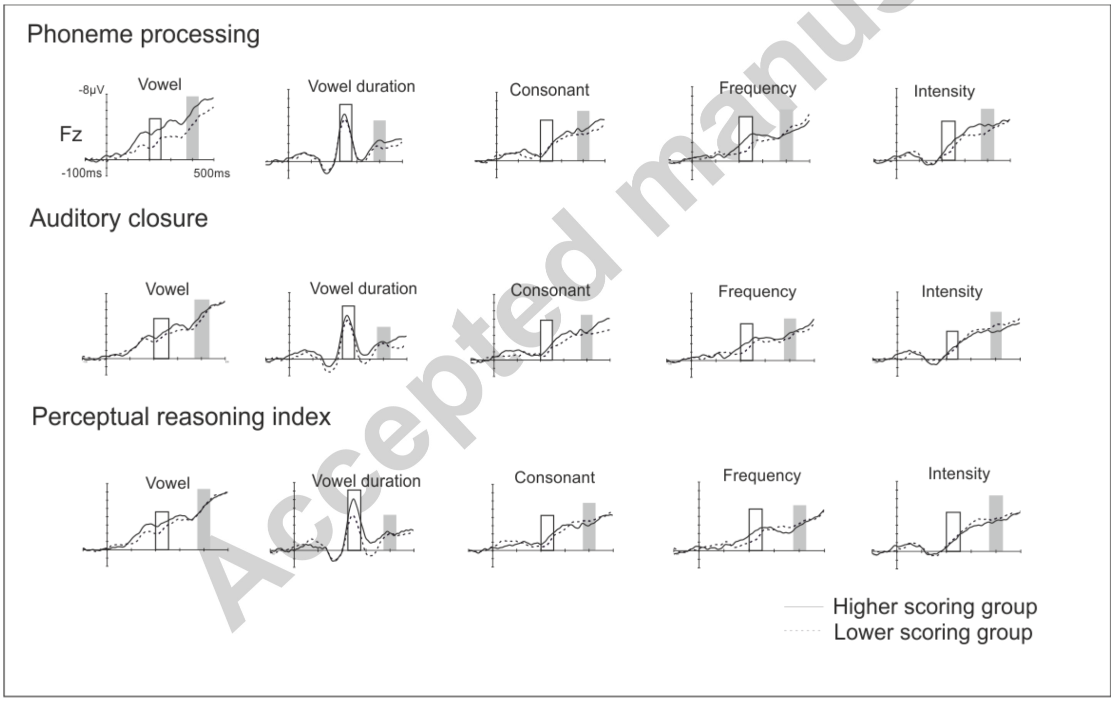

Figure 1 *Averaged subtraction waveforms at Fz electrode for higher and lower scoring groups in each test, for all deviants. The groups were divided based on median scores of the tests. Top: both Phoneme processing groups' responses at Fz electrode and the averaged distributions of responses during the MMN and LDN time windows for all deviants (N_{high}=31, N_{low}=39). Middle: both*

Auditory closure groups' responses at Fz electrode and the averaged distributions of responses during the MMN and LDN time windows for all deviants (N_{high}=28, N_{low}=42). Bottom: both Perceptual reasoning index groups' responses at Fz electrode and the averaged distributions of responses during the MMN and LDN time windows for all deviants (N_{high}=33, N_{low}=37). White blocks mark the inspected MMN and grey blocks the inspected LDN time windows.

Research highlights:

- Behavioural and ERP data were collected from 70 typically developing children.
- Better phoneme processing skills were associated with larger MMN responses.
- No correspondence between intelligence measures and MMN or LDN responses was found.