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**Author(s):** Louleli, Natalia; Hämäläinen, Jarmo A.; Nieminen, Lea; Parviainen, Tiina; Leppänen, Paavo H.T.

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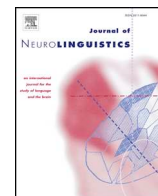
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# Dynamics of morphological processing in pre-school children with and without familial risk for dyslexia



Natalia Louleli<sup>a,b,\*</sup>, Jarmo A. Hämäläinen<sup>a,b</sup>, Lea Nieminen<sup>c</sup>, Tiina Parviainen<sup>a,b</sup>,  
Paavo H.T. Leppänen<sup>a,b</sup>

<sup>a</sup> Department of Psychology, University of Jyväskylä, Finland

<sup>b</sup> Centre for Interdisciplinary Brain Research, University of Jyväskylä, Finland

<sup>c</sup> Centre for Applied Language Studies, University of Jyväskylä, Finland

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## ABSTRACT

Difficulties in phonological processing and speech perception are associated with developmental dyslexia, but there is considerable diversity across people with developmental dyslexia (e.g., dyslexics with and without phonological difficulties). Phonological and morphological awareness are both known to play an important role in reading acquisition. Problems in morpho-phonological information processing could arguably be associated with developmental dyslexia, especially for Finnish, which is a rich morphologically language. We used MEG to study the connection between morpho-phonology in the Finnish language and familial risk for developmental dyslexia. We measured event-related fields (ERFs) of 22 pre-school children without risk and 18 children with familial risk for developmental dyslexia during a morphological task. Pairs of sentences consisting of a verb and its derived noun with the derivational suffix *-jA* and pairs of sentences consisting of a pseudo-verb and its pseudo-noun ending with the same suffix were presented to the participants. The derived nouns were also divided into correctly and incorrectly derived forms. Incorrectly derived forms contained an incorrect morpho-phonological change in the last vowel before the derivational suffix *-jA*. Both typically developing children and children at-risk for developmental dyslexia were sensitive to the morphological information, both in the case of real words and pseudowords, as shown by the sensor level analysis and cluster-based permutation tests for the responses to the morphologically correct vs. incorrect contrast. The groups showed somewhat different response patterns to this contrast. However, no significant differences were found in the between-group differences. No significant differences emerged between typically developing children and children at-risk for developmental dyslexia neither for real words nor for pseudowords. Overall, these findings suggest that pre-school children with and without risk for developmental dyslexia are already sensitive to the processing of morpho-phonological information before entering school.

## 1. Introduction

Language acquisition requires complex cognitive skills. The ability to connect written language successfully with spoken language results in typical reading acquisition (Carlisle, 2003). Development of fluent reading skills requires the ability to map written forms into phonological units (phonological awareness) as well as the ability to efficiently manipulate small units of language with

\* Corresponding author. Department of Psychology, University of Jyväskylä, Finland.

E-mail address: [natalia.n.louleli@jyu.fi](mailto:natalia.n.louleli@jyu.fi) (N. Louleli).

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meaning, the morphemes (morphological awareness) (Carlisle, 2003; Kuo & Anderson, 2006). Difficulties in the acquisition of typical reading skills are addressed as developmental dyslexia (Ramus et al., 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Developmental dyslexia has a genetic basis (Byrne et al., 2006; van Bergen et al., 2011; Olson & Keenan, 2015), and thus children with a family history of developmental dyslexia have a higher risk of developing developmental dyslexia than children without such a history (Pennington & Lefly, 2001; Puolakanaho et al., 2007, 2008). The goal of the current study is to investigate brain processes measured using magnetoencephalography (MEG) while Finnish pre-school children with and without familial risk for developmental dyslexia identify correct and incorrect morphological constructs in real words and pseudowords. Brain responses measured with MEG can reveal different processing stages of morphological information, while behavioral measures are limited to reflecting the outcome of the whole chain of processing stages.

Morphological awareness is acquired well before formal reading instruction, but it follows progressive development similar to that of reading fluency; children's performance in morphological tasks increases from kindergarten to the first and second grades (Casalis & Louis-Alexandre, 2000). Moreover, a previous study tested awareness of derivational morphology behaviorally with two behavioral measures (morphological structure and morphological production) in Spanish, a language that has a consistent (shallow) orthography with a rich morphological system (Ramirez, Chen, Geva, & Kiefer, 2010). The participants were children, native speakers of Spanish, attending fourth and seventh grades. It was found that participants' performance in the morphological tests explained 11% of the variance for word reading in Spanish language (Ramirez et al., 2010). In Finnish language, it was found that children start acquiring morphological production skills, including the ability to inflect words, between the ages of 2–4 years old (Lyytinen & Lyytinen, 2004). Further, morphological awareness has been found to be a predictor of later reading skills in children (Kirby et al., 2012), strongly correlated with vocabulary across different grades (Nagy, Berninger, & Abbott, 2006), word reading (Wang, Yang, & Cheng, 2009), and reading comprehension (Müller & Brady, 2001; Kirby et al., 2012; Wang et al., 2009).

In this study, the language of interest is Finnish. Finnish has a very rich morphological system. Almost all nouns, pronouns, adjectives, and numerals have 2200 and every verb has as many as 12,000 inflectional forms (Karlsson, 1982). In addition to this, a large body of Finnish vocabulary consists of words created through either derivational processes, such as suffixation or prefixation, or compounding. Finnish has a transparent and consistent orthography with an almost one-to-one correspondence between sounds and letters.

Awareness of derivational morphology has been studied with event-related potentials (ERPs) (Bölte, Schulz, & Dobel, 2010; Janssen, Wiese, & Schlesewsky, 2006; Leinonen, Brattico, Järvenpää, & Krause, 2008; Leminen et al., 2010, 2013) and event-related fields (ERFs) (Solomyak & Marantz, 2009; Zweig & Pykkänen, 2009). Use of ERP/Fs is particularly beneficial when studying small children whose behavioral measures can be partly unreliable. Also, ERP/Fs can reveal different processing stages for morphological information, while behavioral measures always reflect the outcome of the whole chain of processing stages.

Earlier studies on derived word processing based on adults' ERPs reported effects at the 130–170 ms time-window to be larger for derived words than for derived pseudowords (Leminen et al., 2013). The stimuli were presented auditorily in an oddball paradigm design performed by Finnish participants. Enhanced brain activation for derived words rather than for derived pseudowords showed lexicality effects, and the derived words were interpreted as whole-word memory traces in the brain (Leminen et al., 2013). Similar results were found in an oddball paradigm with derived congruent and incongruent words performed by German adults (Hanna & Pulvermüller, 2014). Enhanced brain activation emerged at the 135–175 time-window after stimulus onset, and it was larger for congruent derived words compared to incongruent derived words (Hanna & Pulvermüller, 2014). Similarly, the larger activation for derived words was interpreted as whole-form storage for German derived words in the brain (Hanna & Pulvermüller, 2014). Also, very early brain activation emerged at 170 ms (M170) in visual tasks for English single words using MEG (Solomyak & Marantz, 2009; Zweig & Pykkänen, 2009). This M170 activity, which was previously associated with letter strings and face perception, was suggested to be considered as a component for morphological processing (Zweig & Pykkänen, 2009). Effect of morphological manipulation in the ERPs of Finnish adults was significant at the 274–314 time-window while the participants were comparing illegal derived pseudowords with existing words in Finnish (Leminen et al., 2010). However, there were no significant effects between legal and illegal pseudowords either between real words or legal pseudowords (Leminen et al., 2010). Furthermore, adults' ERFs showed higher responses at 350 ms during visual processing of derivational word forms in comparison to non-derived words for French (Cavalli et al., 2016) and for English stimuli (Solomyak & Marantz, 2009). Moreover, studies on visually derived word processing with ERPs in adults reported activation in the 300–500 ms time-window with a peak at 400 ms for violations in derivations for German stimuli (Bölte et al., 2010a; Janssen et al., 2006). Similarly, stronger responses at the 400–550 ms time-window were elicited during tasks focused on derivational morphology with Finnish visually presented stimuli when adults were detecting lexical anomalies (Leinonen et al., 2008).

In general, based on the above studies on derivational processing in adults, it is shown that responses in the early time-window (0–300 ms) were exhibited when adults had to distinguish real derivational forms when compared to pseudowords or pseudo-derivational forms. Brain responses in the middle time window (300–700 ms) emerged after the detection of lexical violations. Regarding source localization studies, MEG studies showed stronger left temporal cortex activation by 380–590 ms in adults when processing incorrectly vs. correctly derived stimuli (Bölte et al., 2010). Moreover, fMRI studies on adults' derivational morphology showed that derived words elicited stronger activity than simple words in the left inferior frontal areas (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Meinzer, Lahiri, Flaisch, Hannemann, & Eulitz, 2009), in the left/right occipital and temporal areas (Gold & Rastle, 2007), and bilaterally in occipito-temporal areas (Meinzer et al., 2009) as well as in the right parietal areas (Meinzer et al., 2009).

Developmental dyslexia is a language difficulty that causes problems in the acquisition of typical reading and writing skills and occurs despite normal intelligence, appropriate schooling, and normal environmental and cognitive factors (Vellutino et al., 2004).

Individuals with developmental dyslexia have difficulties in acquiring typical phonological skills, and they are found to exhibit lower performance in measures of phonological awareness, phonological short-term memory, and speech perception compared to controls (Ramus et al., 2003; Shaywitz & Shaywitz, 2005; Ziegler & Goswami, 2005; Hamalainen, Salminen, & Leppanen, 2013). Although a phonological deficit is considered to be a cause of developmental dyslexia, there is considerable diversity across people with developmental dyslexia in their cognitive skill profiles (Joanisse, Manis, Keating, & Seidenberg, 2000). In fact, there are several types of deficits regarding developmental dyslexia. Subgroups of people with developmental dyslexia have difficulties, for example, in processing auditory stimuli (Goswami, 2002), in rapid automatized naming (RAN) (de Jong & van der Leij, 2003; Lohvansuu, Hämäläinen, Ervast, Lyytinen, & Leppänen, 2018; Papadopoulos, Spanoudis, & Georgiou, 2016; Puolakanaho et al., 2007; Torppa et al., 2007), and in visual attention span (Bosse, Tainturier, & Valdois, 2007; Lallier & Valdois, 2012; Lobier, Zoubinetsky, & Valdois, 2012; Valdois, Bosse, & Tainturier, 2004). In the past, most of the focus has been largely on phonological processing, while there is a debate on the actual role of the deficit—whether people with developmental dyslexia have impaired phonological representations or whether individuals with developmental dyslexia cannot successfully access the phonological representations in their brain (Boets et al., 2013).

Morphological awareness is found to be a cognitive predictor for later reading skills in children (Kirby et al., 2012), strongly correlated with reading vocabulary across different grades (Nagy et al., 2006) and reading comprehension (Kirby et al., 2012; Müller & Brady, 2001), so a subgroup of dyslexics, although demonstrating problems in phonological processing, might have morpho-phonological deficits as well. Therefore, it is evident that developmental dyslexia does not manifest itself with a specific type of difficulty but with multiple deficits per individual (Pennington, 2006).

Derivational morphology is an important aspect for the acquisition of normal reading skills (Carlisle, 2003). Studies on dyslexic adults across different languages have shown contradictory results. On one hand, previous studies have reported lower performance in behavioral morphological tasks, including derivational morphology (for example, in French; Casalis, Cole, & Sopo, 2004). In line with this observation, morphosyntactic processing tested in dyslexic adults elicited delayed brain responses at 600 ms (mentioned as P600 responses) in Dutch, German, and Italian speakers (Cantiani, Lorusso, Perego, Molteni, & Guasti, 2013; Cantiani, Lorusso, Guasti, Sabisch, & Männel, 2013b; Rispens, Been, & Zwarts, 2006), showing the existence of morphological difficulties in dyslexia. Similarly, a study investigating the morphosyntactic processing of 8- to 13-year-old Italian children diagnosed with dyslexia also revealed difficulties in the production of derivational and inflectional morphology (Cantiani, Lorusso, Perego, Molteni, & Guasti, 2015). Additionally, Chinese dyslexic readers from 1st to 4th grades who participated in morphological awareness tasks, including morpheme discrimination and morpheme production, performed less well compared to same-age typical readers (Chung, Ho, Chan, Tsang, & Lee, 2010). On the other hand, previous studies have also reported intact morphological awareness and morphological processing skills in children with and without dyslexia (Egan & Price, 2004; Casalis, Cole, & Sopo, 2004) and in pre-school children with and without risk for dyslexia (Law, Wouters, & Ghesquière, 2016), or differences between groups were only found when comparing groups that were matching in age but not in reading skills. These results mainly suggest that any observed differences between typical readers and readers with dyslexia may be a result of the reading experience (Law et al., 2016).

The majority of studies on morphological processing has mainly been conducted in adults with typical reading skills or, in some cases, in dyslexic adults, adolescents, and partly children. However, studying pre-school children could reveal whether a deficit in morphological awareness could be a risk factor and predictor of later reading development or if reading acquisition actually affects morphological awareness, and that is why people with developmental dyslexia deal with deficits in morphological information processing. Studies have demonstrated that developing dyslexia is inheritable within family members as developmental dyslexia is partially caused by genetic factors (Byrne et al., 2006; Olson & Keenan, 2015; van Bergen et al., 2011), which means that children with a dyslexic parent have a higher risk of developing dyslexia themselves (Pennington & Lefly, 2001; Fisher & Defries, 2002; Puolakanaho et al., 2007, 2008).

Longitudinal studies (Jyväskylä Longitudinal study [JLD] and Dutch Dyslexia Programme [DDP]) have conducted measurements in infants and children with and without risk for developmental dyslexia before formal literacy education to investigate early auditory processing and reading-related functions and mechanisms from birth to adulthood (Lyytinen et al., 2004, 2001; Snowling & Melby-Lervag, 2016; van Bergen et al., 2011; van der Leij, Lyytinen, & Zwarts, 2001). Studies have demonstrated that the brain ERPs of newborns at-risk for developmental dyslexia showed deficits in change detection of acoustic features of speech compared to newborns without risk (Guttorm et al., 2005, 2010; Leppänen et al., 2010; Richardson, Leppänen, Leiwo, & Lyytinen, 2010). Additionally, the brain activity of 6-month-old Finnish infants at-risk for developmental dyslexia can predict reading speed in 14-year-old Finnish children (Lohvansuu et al., 2018), and the brain activity of 6-month-old Italian infants can predict expressive language in 20-month-old babies with and without risk for developmental dyslexia (Cantiani et al., 2016, 2019). Moreover, ERP responses of 17-month-old babies with and without risk for developmental dyslexia were correlated with language comprehension at 4–4.5 years with reading fluency for words and pseudowords in second grade (van Zuijen et al., 2012). It seems that genetic risk factor is one of the main causes of developing dyslexia (Pennington & Lefly, 2001; Byrne et al., 2006; Puolakanaho et al., 2008, 2007; van Bergen et al., 2011; Olson & Keenan, 2015), which means that children with a dyslexic parent have higher risk of developing dyslexia later on in life. The aforementioned studies clearly indicate predictive effects from early childhood to school age.

Previous studies testing behaviorally phonological and morphological skills of pre-school children with and without risk for dyslexia have demonstrated that the pre-reading measures of phonological and morphological awareness are interlinked (Casalis & Louis-Alexandre, 2000). Specifically, a behavioral study by Cunningham and Carroll (2015) demonstrated that the phonological processing of pre-school children predicted skills in morphological awareness in first-grade students (Cunningham & Carroll, 2015). Similarly, Law, Wouters, and Ghesquière (2017) found that children with familial risk already had both phonological and morphological awareness deficits before reading instruction. They suggested that the observed pre-reading deficit in morphological

awareness was a consequence of the deficit in phonological awareness (Law et al., 2017; Law & Ghesquiere, 2017).

1.1. Goal of the study

The goal of the current study is to investigate brain processes with ERFs related to correct vs. incorrect morphological constructs in real words and pseudowords in Finnish pre-school children with and without familial risk for developmental dyslexia. Studies on derivational processing in children with and without risk for developmental dyslexia have not been conducted previously, and, to our knowledge, this is the first study to investigate derivational morphology with ERFs in children at pre-school age. In this study, we are interested in morphological awareness and representations of pre-school children during MEG recordings before they receive formal literacy education. Specifically, we ask whether typically developed pre-school children differentiate correct and incorrect derivative words and pseudowords and how this is reflected in their ERF brain responses. Further, we explore whether and how children at-risk for developmental dyslexia have a differential pattern of brain responses compared with typically developed children. We studied these questions in the morphologically rich Finnish language using the MEG technique.

2. Methods

2.1. Participants

Initially, 45 pre-school children aged 6.5–7 years took part in the study. The final sample consisted of 40 and 34 participants in the real word and pseudoword conditions, respectively. All were native Finnish speakers attending kindergarten. In Finland, formal reading instruction starts in the first grade, when the children are about 7 years old. We recruited families from the area of Central Finland, and, based on the familial risk for developmental dyslexia, we divided them into a control group (N = 25) and an at-risk group (N = 20). The familial risk of the participating children was evaluated using questionnaires completed by their parents. Specifically, this questionnaire included questions about whether or not the parent had or still has reading or writing difficulties and whether or not the parent had been diagnosed with a language delay or specific language impairment or attention deficit or epilepsy or any other neurological disease. Also, each parent was asked whether or not he/she had a close relative (i.e., parents, siblings, nieces/nephews) with reading or writing problems. The at-risk group participants were required to have at least one parent and/or sibling with a diagnosis of developmental dyslexia and/or one parent with self-perceived reading difficulties. For the MEG analyses during the morphological task for real words, three participants from the control group and two participants from the at-risk group were excluded due to movement artifacts. Similarly, in the pseudoword condition, nine control participants and three children at-risk for developmental dyslexia were excluded from the MEG analyses due to movement artifacts. The final number of participants for the real word condition was 22 typical children and 18 with familial risk for developmental dyslexia, and the final number for the pseudoword condition was 17 typical children and 17 at-risk for developmental dyslexia (Table 1).

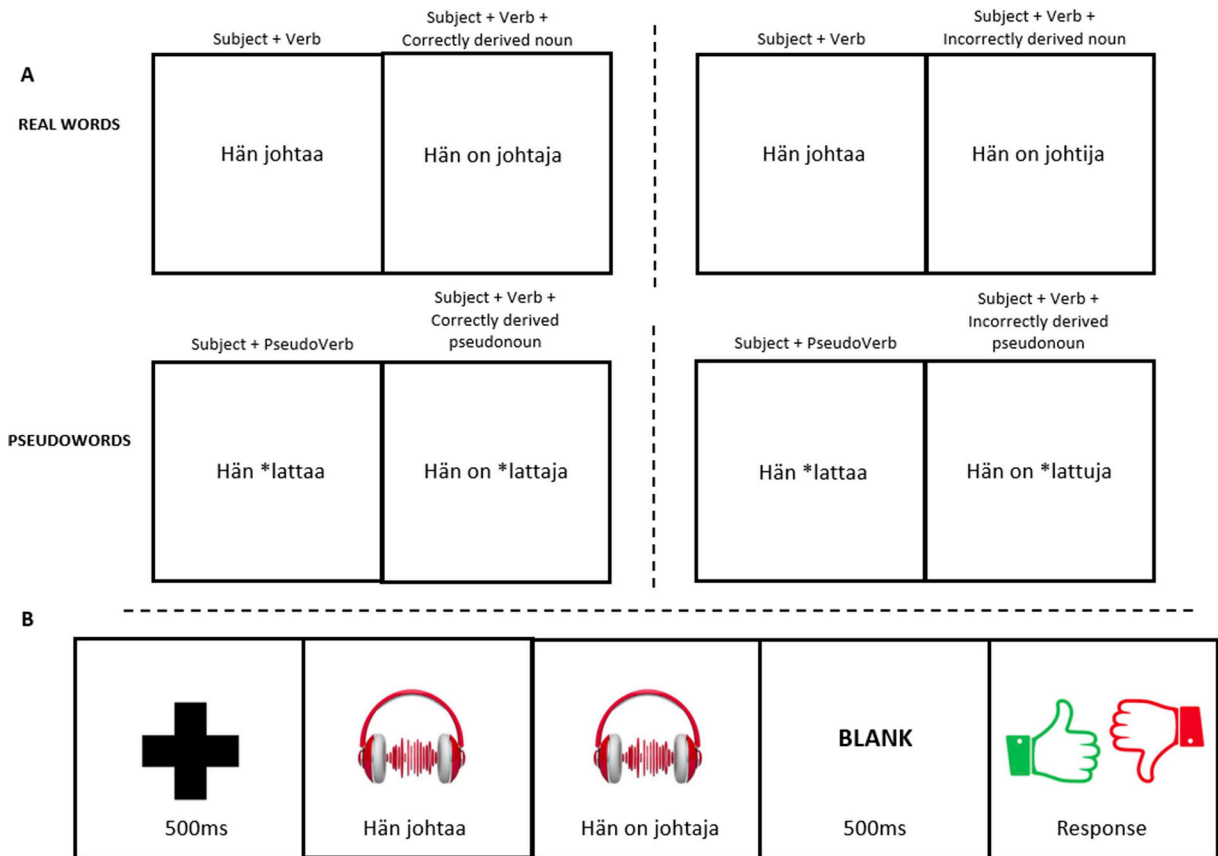
All the children were healthy with normal hearing and normal or corrected-to-normal vision. Prior to participation, all parents and children gave their written consent after being fully informed about the purpose and the methods of the study. The study was approved by the Ethical Committee of the University of Jyväskylä, following the Declaration of Helsinki.

2.2. Stimuli and procedure

For the MEG recordings, a morphological awareness task was created (Fig.1). We created 216 pairs of words consisting of a verb and a noun derived from the verb with the derivational suffix -ja (/ -ja/ - / -jä/), which is broadly used to form a noun from a verb in Finnish, for example, johtaa (verb, “to lead”) - johtaja (noun with the agentive marker, “leader”). The word pairs were created in two categories: real words and pseudowords. The real words were commonly used words of the Finnish language selected from a Finnish

**Table 1**  
Demographic information of participants included in the data analyses.

Participants per task	Control group (real words/pseudowords)	At-risk group (real words/pseudowords)
<b>Number of Participants</b>	22/17	18/17
<b>Age (average)</b>	6 y and 8 m (SD = 0.44–0.45)	6 y and 9 m (SD = 0.43–0.47)
<b>Gender</b>	12 girls and 10 boys/9 girls and 8 boys	7 girls and 11 boys/7 girls and 10 boys
<b>Handedness</b>	21/16 right-handed	18/17 right-handed
<b>Parental Educational Level</b>	<b>Control group (real words/pseudowords)</b>	<b>At-risk group (real words/pseudowords)</b>
<b>PhD/Master's Degree</b>	14 mothers and 6 fathers/11 mothers and 3 fathers	4 mothers and 2 fathers/4 mothers and 2 fathers
<b>Bachelor's Degree</b>	6 mothers and 11 fathers/5 mothers and 9 fathers	6 mothers and 5 fathers/6 mothers and 5 fathers
<b>Vocational School and Comprehensive/Higher Secondary School</b>	1 mother and 2 fathers/1 mother and 2 fathers	5 mothers and 8 fathers/4 mothers and 7 fathers
<b>Total</b>	21 mothers and 19 fathers/17 mothers and 14 fathers	15 mothers and 15 fathers/14 mothers and 14 fathers



**Fig. 1.** Morphological awareness task. **A.** Stimuli consisted of real words with a correct or incorrect morpho-phonological change and pseudowords with a correct or incorrect morpho-phonological change. **B.** Procedure of the morphological awareness task. Each trial started with a 500 ms fixation cross, followed by a pair of sentences, followed by a 500 ms blank screen, followed by a thumbs up/down picture where participants had to respond.

corpus of words (2010) that includes the 9996 most common Finnish lemma taken from newspapers that can be found in official dictionaries. This corpus was chosen as the source because the language of the newspapers represents the most commonly used words in everyday Finnish (<https://github.com/GrammaticalFramework/GF/blob/master/lib/src/finnish/frequency/src/suomen-sanomalehtikielen-taajuussanasto-utf8.txt>). Pseudowords were created to follow the phonological, morphological, grammatical, and syntactic rules of the Finnish language but not to carry any meaning.

Both categories consisted of 108 pairs of words including the verb and its derivational noun with the suffix /-jA/. The pseudowords were matched with the real words in the number of syllables and letters and derivational ending. All the derivational words were trisyllabic, including 11 words with 6 letters, 24 words with 7 letters, and 19 words with 8 letters. According to Finnish vowel-harmony rules, 42 derivational forms end with /-ja/, and 12 derivational forms end with /-jä/.

The categories of the derivational nouns were further divided into two subcategories of correctly and incorrectly derived forms, with 54 items in each subcategory. Correctly derived forms were the aforementioned word forms, and incorrectly derived forms contained an incorrect morpho-phonological change in the last vowel before the derivational suffix /-jA/ (e.g., johtija). In the legally derived nouns, this last vowel before the suffix is often the same as the final vowel of the verb (e.g., johtaa – johtaja), but it can also be different (e.g., tekee – tekijä). Knowing the correct forms is thus based on learned representations built during language development. The incorrectly derived forms were created by replacing the last vowel of the derived noun with a vowel different from that in the verb. The vowels of the derived nouns were selected based on the vowel harmony for both the incorrectly derived forms and the pseudowords. For the phonological changes, the most distant vowels, in terms of the place and the manner of articulation, were chosen to replace the correct vowels to avoid unnecessary confusion or the inability to hear the vowel changes while testing small children. For example, the front vowels replaced the back vowels and vice versa, and the closed replaced the open ones. Two vowels were not used in the morpho-phonological derivations—the vowel /-e/ because in Finnish this vowel never appears before the derivational form /-jA/ and the vowel /-o/ because this vowel with the suffix /-jA/ can create real words (i.e., maksaja [real noun, “payer”]—maksoja [real derivation, but also a real noun, “livers”]; huoltaja [real noun, “custodian”]—huoltoja [real noun, “maintenances”]). The morpho-phonological changes were identical between the real words and pseudowords. Diftongs were not used.

The participants performed the morphological awareness task during MEG recording (Fig. 1). The instructions were presented through insert-headphones at 60 dB (SPL) as small stories for the children—for the real words, a little girl performs a language test for

school, and the participant was asked to help by telling the little girl which pairs of sentences she has learned properly and which words she still has to practice. For the pseudowords, a little girl tries to invent new Finnish words to communicate secretly with her friends, and the participant was asked to help her identify which pairs of sentences could be Finnish words and which ones could not. After hearing the instructions, participants completed a six-trial practice task. During the main task, for each trial, a fixation cross was presented on the screen for 500 ms, then the aforementioned pairs of sentences (e.g.,/Hän johtaa. Hän on johtaja/) (= He leads. He is a leader.) were auditorily presented to the participants one after another followed by a blank screen for 500 ms, and finally the participants were to give their responses through a button press, the right button for the correct pairs and the left for the incorrect pairs of sentences. After each block of trials, small animated videos were presented to help the participants to maintain attention (1 min).

Each block consisted of 54 pairs of sentences. The first and second presented blocks included real words, while the third and fourth blocks included pseudowords. All the stimulus pairs within a category were presented randomly intermixed, but the pairs themselves were always presented together (yoked/joined stimuli). In total, the participants were presented with 216 trials, 54 pairs of sentences for each of the four categories (real words with a correct or incorrect morpho-phonological change and pseudowords with a correct or incorrect morpho-phonological change). All the stimuli were presented only once.

The sentences were recorded by a female native Finnish speaker in a recording studio at the University of Jyväskylä using a 44 kHz sampling frequency, 32-bit quantization recorded in stereo channels. The resulting sound files were edited using Sound Forge Pro 11.0 and Praat (5 ms were added as a baseline in each sound file before the onset and offset of each sentence to avoid clicking sounds). The task lasted in total approximately 40 min. In addition to MEG data, the accuracy and reaction times of the responses were recorded. The stimuli were presented via headphones at 60 dB (SPL). Participants were sitting 100 cm away from the projection screen with the projector (refresh rate of 60 Hz), which was located outside the magnetically shielded room. The task was presented with Presentation software (Neurobehavioral Systems, Inc., Albany, CA, United States) running on a Microsoft Windows computer.

### 2.3. MEG acquisition

The experiments were conducted in a child-friendly environment in the Centre for Interdisciplinary Brain Research (CIBR) at the University of Jyväskylä. Continuous MEG data were recorded in a magnetically shielded room using a 306-channel Elekta Neuromag TRIUX system (Elekta AB, Stockholm, Sweden), which measures the magnetic field over the scalp using a sensor triplet (two planar gradiometers and one magnetometer) at each location. The head position inside the helmet was monitored with five head position indicator coils (HPI coils), which were attached to the scalp—three coils were attached to the forehead, and one coil was attached behind each ear. The HPI coils' location was determined with respect to the anatomical fiducials (nasion, right and left pre-auricular points) with the Polhemus Isotrak digitizer (Polhemus, Colchester, VT, United States). Additional digitized points (~120) were also taken over the scalp for each subject. This procedure is critical for head movement compensation after the recording session. The data were collected with a sampling rate of 1000 Hz and band-pass filter of 0.1–330 Hz. The MEG system was in a 68° upright gantry position during the recordings. Eye movements and eye blinks were recorded with two pairs of electro-oculogram (EOG) electrodes; one pair was placed horizontally (HEOG) and the other vertically (VEOG) to the participants' eyes. An additional electrode was used as a ground reference placed on the participant's right collarbone.

### 2.4. MEG data analysis

The data were pre-processed with Maxfilter 2.2 (Elekta AB, Stockholm, Sweden) to estimate the position of the head, to correct for head movements, and to remove external magnetic disturbance and noise during the MEG recording by the signal space separation method. The separate recording blocks were first transformed to the same coordinate system within each individual child by using the first block as the reference across the recording session. The temporal extension of the signal-space separation (tSSS) with movement compensation was used for movement corrections (Taulu & Kajola, 2005; Taulu & Simola, 2006). The bad channels observed during the measurement were manually marked and then reconstructed in Maxfilter 2.2. The pre-processed data were analyzed with BESA 6.1 (BESA GmbH, Munich, Germany). First, independent component analysis (ICA) was applied in a 60-s time-window to create an IC model for the removal of the following artifacts from the whole dataset—eye blinks, horizontal and vertical eye movements, and cardiac artifacts, separately for magnetometers and gradiometers. Then, continuous MEG data were high-pass filtered at 0.5 Hz (zero phase, 12db/oct) and low-pass filtered at 30 Hz (zero phase, 24db/oct). Thereafter, the MEG data were epoched into –200 to 1100 ms epochs relative to the onset of the derivational suffix/-jA/with 100 ms pre-stimulus baseline and averaged separately for the correctly and incorrectly derived real words and pseudowords. Remaining artifacts were removed by automatically excluding epochs exceeding 1200 fT/cm rejection level for gradiometers and 4000 fT/cm for magnetometers. All the participants had more than 70% accepted trials (38 trials accepted for the further analyses out of 54 trials) except for three participants (1 control and 2 at risk), who had 50% accepted trials (28/54). Based on the visual inspection, the data for these individuals did not differ from those of the other participants. To focus in more detail on the brain processes related to morphological violations, additional triggers were created and inserted in Matlab R2015b with the Fieldtrip toolbox (Oostenveld et al, 2011) for the onset of correctly and incorrectly derived real words and pseudowords (johtaja-johtija, \*lattaja-\*lattuja) and for the onset of the suffix/-jA/for real words and pseudowords. These triggers were used to create averaged ERFs with a –200 to 1100 ms time-window for the conditions mentioned above. The signals from the two orthogonal gradiometer channel pairs were combined using the vector sum implemented in Matlab R2015b with the Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). The combined gradiometer signal was chosen for the further analyses because it was less sensitive to external noise than the magnetometers. It has been shown, though, that using either

gradiometers or magnetometers does not change the MEG results (Carcés, López-Sanz, Maestú, & Pereda, 2017). Here, the results for the topography of the magnetometers are shown in the Supplement.

Sensor-level statistical analysis on the combined gradiometers was conducted using cluster-based permutations tests (Maris & Oostenveld, 2007) (based on two-tailed paired or independent t-tests) within and between groups, respectively, with BESA Statistics 2.0 (BESA GmbH, Munich, Germany). Cluster  $\alpha$  was set at 0.05, the number of permutations was set at 3,000, and the neighbor distance between sensors was set at 4 cm. The within-group analyses were calculated for the correct vs. incorrect suffix of the noun /-jA/ for the real words and for the pseudowords separately for the control and the at-risk group. The p-values of the cluster-based permutation tests were corrected by applying a false discovery rate (FDR) correction with  $p = 0.05$  (Benjamini & Hochberg, 1995) for each research question. The correctness of the morphological ending does in fact take place starting from the preceding vowel, and the beginning of the suffix /-jA/ was nevertheless used as the trigger point because of it being clear, whereas the vowel might be slightly varied in the length (~100 ms). Based on previous literature, the difference was examined in three time-windows of interest: at 0–300, 300–700, and 700–1100 ms. Brain activation in the first of these time windows has been shown to be related to early visual responses to morphological processes (M170) in adults (Solomyak & Marantz, 2009; Zweig & Pylkkänen, 2009) as well as in 7 to 8-year-old children (Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006). The middle time-window focused on the M350 (N400-like) responses previously found in adults (Cavalli et al., 2016; Solomyak & Marantz, 2009), which are mainly responsible for lexico-semantic manipulations (Helenius et al., 2002). The brain response at this time window is also associated with difficulty in integrating the meaning of an incongruent word with the context of the sentence (Kutas & Federmeier, 2011). The late time-window tested possible effects in the P600 response, which has been previously reported to emerge for syntactic and morpho-syntactic violations to sentence structures (Friederici, 2005).

### 2.5. Behavioral assessments

The children's cognitive skills were assessed prior to the MEG measurement on a separate visit to the Department of Psychology at the University of Jyväskylä (Table 2) The cognitive assessments included the following three subtests from the Wechsler Intelligence Scale for Children Fourth Edition (WISC IV): block design, which measures visuospatial reasoning; vocabulary, for expressive vocabulary; and digit span (forward and backward), for working memory. In the block design test, the children were shown how to form a design based on arranged blocks, after which they had to build the same design with escalating levels of difficulty. In the vocabulary test, the children heard a word, and they had to describe its meaning. In the digit span test, a series of numbers were said to the children, who had to repeat them in forward or backward order.

Moreover, a subtest from the Developmental Neuropsychological test battery (NEPSY II) (Korkman, Kirk, & Kemp, 2007) was used in the behavioral assessments: the phonological processing task, which is designed to assess phonemic/phonological awareness. In the phonological processing subtest, there were two phonological processing tasks: word segment recognition, where the children had to identify words from segments, and phonological elision, in which the children were first asked to repeat a word and then to repeat another word by omitting a phoneme or a syllable. Also, Rapid Automatized Naming (RAN) (Denckla & Rudel, 1976) was assessed; for this task the participants had to name as quickly and accurately as possible five objects. The objects were frequent, everyday life objects arranged in five rows with 10 objects per row. The task was recorded, and the performance of the participants was scored as the total time in seconds. Finally, letter knowledge was also assessed by presenting 29 letters one by one. The sum of correct answers (max. 29) was used as a measure.

## 3. Results

### 3.1. Real words

#### 3.1.1. Behavioral performance during MEG morphological awareness task

The participants' behavioral performance, accuracy and reaction time, in the morphological task for real words during MEG

**Table 2**

Descriptive statistics of the participants' cognitive skill measures (N = 22 pre-school typically developing children, N = 17 pre-school children at risk for dyslexia).

Behavioral assessments	Typically developing children				At-risk children				t-values, p-values
	Mean (max.)	SD	Range	N (participants)	Mean (max.)	SD	Range	N (participants)	
<b>Block design</b>	24.27 (68)	8.45	10–44	22	20.35 (68)	8.37	10–42	17	t(37) = 1.141, p = 0.158
<b>Vocabulary</b>	18.45 (66)	7.58	4–34	22	14.05 (66)	8.64	3–40	17	t(37) = 1.689, p = 0.100
<b>Digit span</b>	10.71 (32)	1.55	8–14	22	9.82 (32)	2.32	4–14	17	t(37) = 1.411, p = 0.167
<b>Phonological processing</b>	33.81 (53)	6.65	23–45	22	30.64 (53)	6.99	23–50	17	t(37) = 1.444, p = 0.157
<b>RAN (objects)</b>	69.21	15.94	47.34–103.75	22	75.81	16.94	49.20–121	17	t(37) = -1.248, p = 0.220
<b>Letter knowledge</b>	25.61 (29)	3.52	17–29	13	22.26 (29)	5.86	10–29	15	t(26) = 1.795, p = 0.084



**Table 3**

Accuracy and reaction time results (group means, standard deviations [SD], and percentages of correct responses of the individually averaged responses) in the morphological awareness task performed during MEG recording for correctly and incorrectly derived real words for the control and at-risk groups.

Accuracy per Group	Controls (N = 22)	At-risk (N = 18)	t-values, p-values
<b>Correct responses for correctly derived nouns (max. 54)</b>	48.9 (SD = 3.97) (90.57%)	43.6 (SD = 7.41) (80.76%)	t(38) = 2.888, p = 0.006
<b>Correct responses for incorrectly derived nouns (max. 54)</b>	43.8 (SD = 12.5) (84.93%)	41.9 (SD = 15.6) (77.67%)	ns
RT per Group	Controls (N = 21*)	At-risk (N = 18)	t-values, p-values
<b>RT for correctly derived nouns (ms)</b>	1170.30 (SD: 456.80)	1221.35 (SD = 386.88)	ns
<b>RT for incorrectly derived nouns (ms)</b>	1097.52 (SD = 557.76)	1057.63 (SD = 353.01)	ns

Note: \* = participants that were removed due to continuously pressing the same button throughout the experiment.

recording are presented in Table 3 for both groups. The total number of responses per category was 54. There was a significant group difference in the accuracy for the correctly derived words between the control group and the at-risk group; the control group was more accurate than the at-risk group. No significant differences in the accuracy for the incorrectly derived words were found between the control and the at-risk group. There were no significant group differences for reaction time neither for correctly derived words nor for incorrectly derived words between groups.

### 3.1.2. Within-group MEG results for real words in control participants

The averaged ERFs of the typical children (N = 22) differed between the correctly and incorrectly derived real words as tested at the early (0–300 ms), middle (300–700 ms), and late (700–1100 ms) time-windows.

The correct vs. incorrect contrast showed a significant difference ( $p < 0.05$ ) in the first time-window at the 15–56 ms time-window in the left occipito-temporal region. The responses to the incorrectly derived nouns were larger than those to the correctly derived nouns. The same contrast showed significant difference in the middle time-window at the 300–312 ms time-window in the left fronto-temporal region, with larger responses to the incorrectly derived than to the correctly derived nouns and at the 469–494 ms time-window in the right frontal region, with larger responses for the correctly derived nouns as well as at the 467–547 ms time-window in the right occipito-temporal region, with larger responses for the incorrectly derived nouns. In addition, in the late time-window, the correct vs. incorrect contrast showed significant difference at the 1000–1071 ms time-window in the right fronto-temporal region, with larger responses to the correctly derived than to the incorrectly derived nouns. Table 4 and Fig. 2 show the averaged ERF waveforms for each of the significant time points.

### 3.1.3. Within-group MEG results for real words in at-risk participants

The averaged ERFs of the children at-risk for developmental dyslexia (N = 18) differed between the correct and incorrect real words for all the analyzed time-windows (0–300 ms, 300–700 ms, 700–1100 ms). For the real words, the responses to the correctly vs. incorrectly derived words showed significant difference ( $p < 0.05$ ) for the first time-window at 58–120 ms in the left occipito-temporal region, at the 56–204 ms time-window in the right and left parietal regions as well as at the 269–300 ms time-window in the right parietal, occipital, and temporal regions, with larger amplitude for the incorrect derived stimuli than for the correct derived stimuli in all cases. The same contrast revealed significant difference in the middle time-window at 358–372 ms in the left frontal region and at the 504–533 ms time-window in the left frontal region, with larger responses for the correctly derived stimuli as well as at the 587–626 ms time-window in the right occipital region and at the 542–583 ms time-window in the left parieto-occipital region, with larger responses for the incorrectly derived stimuli. In addition, in the late time-window, the correct vs. incorrect contrast showed significant difference at 1004–1057 ms in the right fronto-parietal region; larger responses for the incorrectly derived stimuli were identified. Table 5 and Fig. 3 show the averaged ERF waveforms for each time window.

## 3.2. Pseudowords

### 3.2.1. Behavioral performance

The participants' behavioral performance, accuracy and reaction time, in the morphological task for pseudowords during MEG recording are presented in Table 6 for both groups. The total number of responses per category was 54. No significant differences in the accuracy for correctly and incorrectly derived pseudo-nouns were found between the control and the at-risk group. There were no significant differences for the reaction time neither for correctly nor for incorrectly derived pseudowords found between groups.

### 3.2.2. Within-group MEG results for pseudowords in control participants

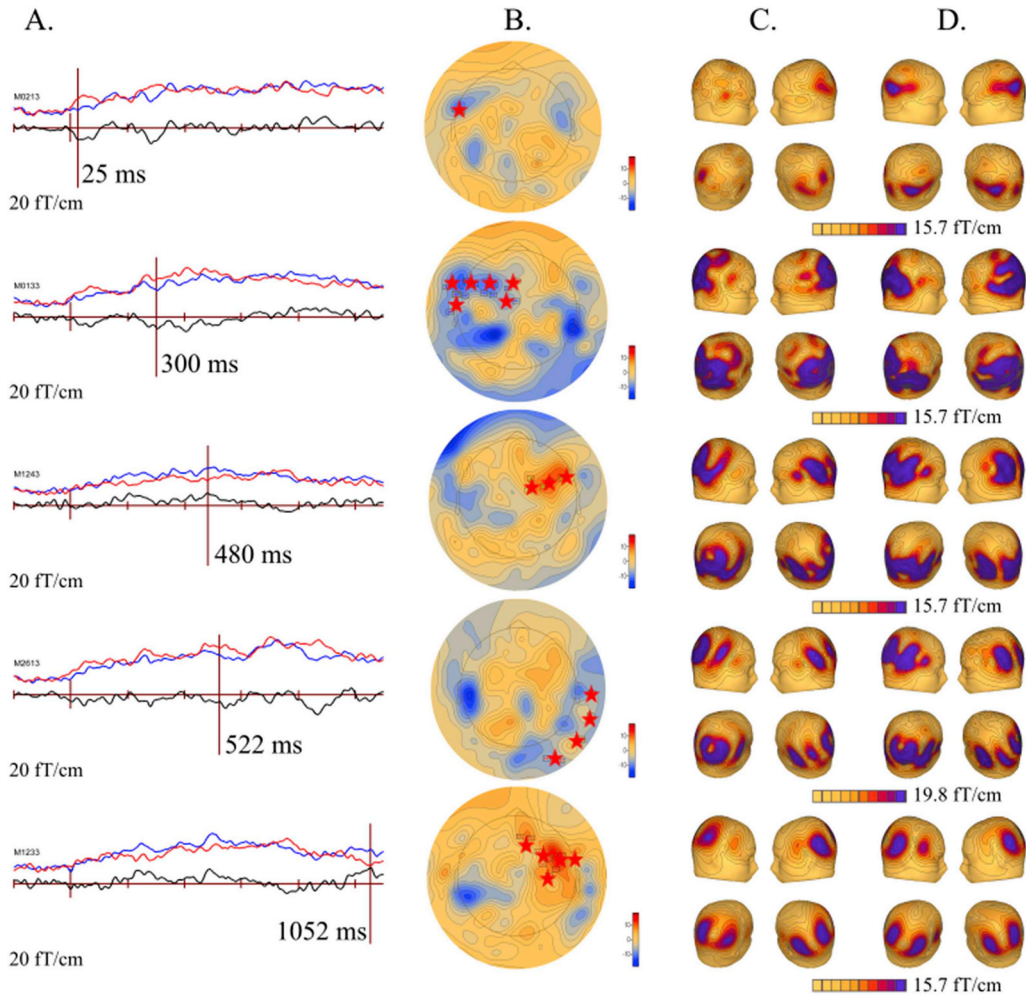
The averaged ERFs of the typical children (N = 17) differed between the correct and incorrect pseudowords for two time-windows of the analyses (0–300 and 300–700 ms) similar to the real words but did not differ at the late time-window (700–1100 ms). For the pseudowords, the correct vs. incorrect contrast showed significant cluster in the first time-window at 247–267 ms in the left temporo-parietal region, with larger responses for the correctly derived stimuli compared to the incorrectly derived stimuli. The same contrast showed a significant cluster in the middle time-window at 562–602 ms in the right fronto-temporal region, with larger

**Table 4**

Summary of the channel-level (combined gradiometers), cluster-based permutation statistics for the typically developing group (N = 22): the time window for each cluster-based permutation test analysis; the significant cluster range and the cluster's time point of maximum difference; the p-value for the cluster's maximum point; the direction of the response: Correct = Correctly derived stimuli and Incorrect = Incorrectly derived stimuli; and the cluster's location based on the sensors location (max. = maximum).

Time-window for analysis	Time-window for cluster, cluster range (cluster's time point of maximum difference)	Cluster p-value	Direction	Cluster's location
<b>0–300 ms</b>	15–56 ms (max. 25 ms)	0.005*	Incorrect > Correct	left occipito-temporal region
<b>300–700 ms</b>	300–312 ms (max. 300 ms)	0.004**	Incorrect > Correct	left fronto-temporal region
	469–494 ms (max. 480 ms)	0.013*	Correct > Incorrect	right frontal region
	467–547 ms (max. 522 ms)	0.001**	Incorrect > Correct	right occipito-temporal region
<b>700–1100 ms</b>	1000–1071 ms (max. 1052 ms)	0.001**	Correct > Incorrect	right fronto-temporal region

Note: The correctness of the morphological ending takes place starting from the preceding vowel, and the beginning of the suffix /-jA/ was nevertheless used as the trigger point because of it being clear, whereas the preceding vowel might be slightly varied in length (~100 ms).



**Fig. 2.** A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns, and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). B. Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labeled with stars within the rectangles (p-values < 0.05). Blue and red indicate the direction of the ERF difference for contrast (negative or positive flux amplitude,  $-10 \mu\text{V}$ – $10 \mu\text{V}$ ). Blue indicates magnetic flux directed into the brain (negative flux), and red shows flux directed out of the brain (positive flux). C. Topography of the distribution of gradient fields for the correctly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. D. Topography of the distribution of gradient fields for the incorrectly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

responses for the incorrectly derived stimuli than for the correctly derived stimuli. Table 7 and Fig. 4 show the averaged ERF waveforms for each time window.

### 3.2.3. Within-group MEG results for pseudowords in at-risk participants

The averaged ERFs of the children at-risk (N = 17) differed between the correctly and incorrectly derived pseudowords for two time-windows (0–300 and 700–1100 ms) but did not differ at the middle time-window (300–700 ms). For the pseudowords, the correctly vs. incorrectly derived contrast showed significant difference in the first time-window at 69–100 ms in the left and right parietal region, with larger responses for the incorrectly derived stimuli. The same contrast showed significant difference in the late time-window at 1032–1076 ms in the left occipital region, being larger for the incorrectly derived stimuli. Table 8 and Fig. 5 show the averaged ERF waveforms for each time window .

### 3.3. Between-group statistical results for real words and pseudowords

For the real words as well as for the pseudowords, the magnetic fields for correct vs. incorrect contrast did not differ between

**Table 5**

Summary of the channel-level (combined gradiometers), cluster-based permutation statistics for the at-risk group (N = 18): the time-window for each cluster-based permutation test analysis; the significant cluster range and the cluster's time point of maximum difference; the p-value for the cluster's maximum point; the direction of the response: Correct = Correctly derived stimuli and Incorrect = Incorrectly derived stimuli; and the cluster's location based on the sensor's location (max. = maximum).

Time-window for analysis	Time-window for cluster, cluster range (cluster's time point of maximum difference)	Cluster p-value	Direction	Cluster's location
0–300 ms	58–120 ms (max. 72 ms)	0.005*	Incorrect > Correct	left occipito-temporal region
	56–204 ms (max. 191 ms)	0.000***	Incorrect > Correct	right and left parietal region
	269–300 ms (max. 285 ms)	0.01*	Incorrect > Correct	right parietal, occipital and temporal region
300–700 ms	358–372 ms (max. 363 ms)	0.0003***	Correct > Incorrect	left frontal region
	504–533 ms (max. 513 ms)	0.000***	Correct > Incorrect	left frontal region
	542–583 ms (max. 551 ms)	0.007*	Incorrect > Correct	left parieto-occipital region
	587–626 ms (max. 607 ms)	0.000***	Incorrect > Correct	right occipital region
700–1100 ms	1004–1057 ms (max. 1039 ms)	0.033**	Incorrect > Correct	right fronto-parietal region

Note: The correctness of the morphological ending takes place starting from the preceding vowel, and the beginning of the suffix/-jA/was nevertheless used as the trigger point because of it being clear, whereas the preceding vowel might be slightly varied in length (~100 ms).

typically developing children and children at risk for developmental dyslexia in any of the time-windows tested (0–300 ms, 300–700 ms, 700–1100 ms). Similarly, cluster-based permutation tests separately for the correctly and incorrectly derived words and pseudowords did not differ between typically developing children and children at risk for developmental dyslexia after the FDR correction.

#### 4. Discussion

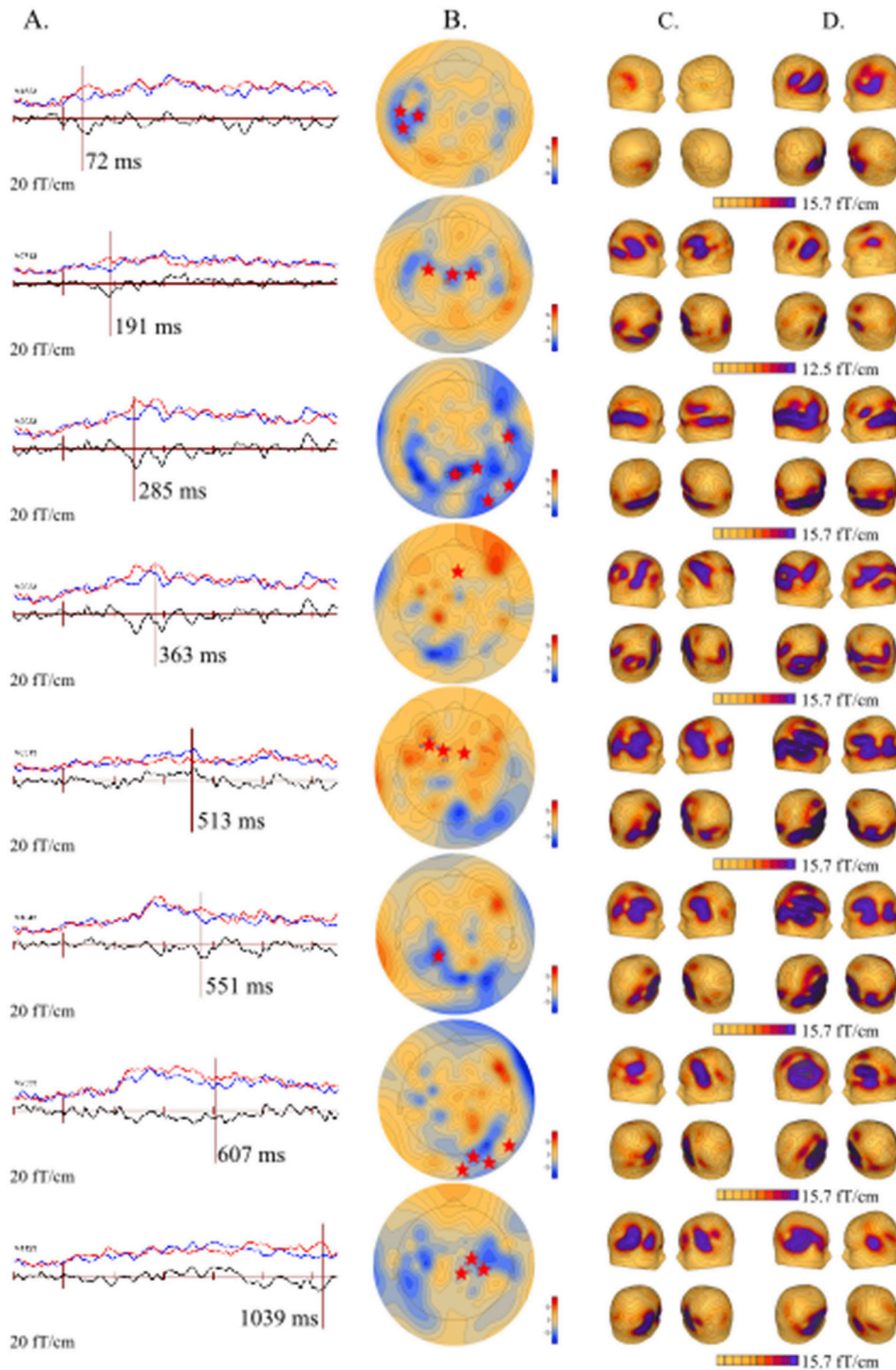
The aim of the present study was twofold; first, to examine whether pre-school children are sensitive to the correct morphological constructs in real words and in extracting the underlying rule for those constructs in pseudowords and second, to examine whether pre-school children at-risk for developmental dyslexia would show atypical development of morphological sensitivity (Fig. 6). To this end, we used a morphological awareness task based on Finnish derivational morphology during MEG recordings. To our knowledge, this is the first study to investigate derivational morphology with MEG in children of pre-school age. The main reason for using MEG brain recordings to study derivational morphology is that MEG has great temporal sensitivity and can be used to tease apart different phases of processing in time.

*Can typically developed pre-school children differentiate the correctly and incorrectly derived words, and how is this reflected in their ERF brain responses?*

First, we were interested in testing whether typically developed pre-school children can differentiate the correctly and incorrectly derived nouns and pseudo-nouns and how this is reflected in their ERF brain responses. Our behavioral results demonstrated that there was a significant difference between the typical group and the group at risk for developmental dyslexia in the accuracy of identifying correctly derived words. Specifically, the control group was more accurate than the at-risk group in identifying the correctly derived words. The accuracy for the incorrectly derived words and the reaction time data did not differ between groups.

For typically developing children, the brain activation was sensitive to the morphological information both in the case of real words and pseudowords. Brain responses differentiated between correctly and incorrectly derived words first at ca. 20–50 ms, in the middle time-window at ca. 300 ms and around 500 ms, and in the late time-window at ca. 1000–1070 ms. The stimuli were produced naturally, so the significant difference occurring in the first time-window clearly reflects top-down processes for the real words based on the long-term phonetic/phonological representations (Kuhl, 2004).

A significant difference also emerged close to 300 ms (in fact, ca. 400 ms from the time point from which the correctness of the derivation could be judged), which agrees with previous results for ERP studies with adults (Leminen et al., 2010). Importantly, in Leminen et al. (2010), they showed main effects at a similar time-window, being stronger for the illegally derived pseudowords than existing words when testing Finnish adults (Leminen et al., 2010). The aforementioned results and our results likely reflect lexico-semantic processes in the brain as the participants had to judge whether the presented word was correctly derived (Leminen et al., 2010). In the present study, this time-window also matches with the classical N400 response, which reflects lexico-semantic processing at the sentence level, and it occurs here as a response to the anomalous/incongruent sentence ending between the correctly and incorrectly derived words. The N400 responses usually emerge between 250 and 500 ms after stimulus onset, when sentences have semantically incongruent endings (Kutas & Federmeier, 2011; Silva-Pereyra et al., 2005). This finding is also in line with previous similar N400-like responses found in adults for visually presented words (morphologically congruent and incongruent nouns and adjectives) (Cavalli et al., 2016; Solomyak & Marantz, 2009). It has been suggested that the N400 activation could reflect two functionally distinct processing stages, where in the first 300 ms after the stimulus onset the word representations are activated and selected and then at around 400 ms of activation lexical integration happens (Vartiainen, Prviainen, & Salmelin, 2009). However, other studies have suggested that the N400 response would reflect lexical access (Lau, Phillips, & Poeppel, 2008). It has also been suggested that lexical access and lexical integration could already take place within 200 ms from the time point in which the listener



**Fig. 3.** A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). B. Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labeled with stars within the rectangles (p-values < 0.05). Blue and red indicate the direction of the ERF difference for contrast (negative or positive flux amplitude,  $-10 \mu\text{V}$ – $10 \mu\text{V}$ ). Blue indicates magnetic flux directed into the brain (negative flux), and red shows flux directed out of the brain (positive flux). C. Topography of the distribution of gradient fields for the correctly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. D. Topography of the distribution of gradient fields for the incorrectly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 6**

Accuracy and reaction time results (group means, standard deviations [SD], and percentages of correct responses of the individually averaged responses) in the morphological awareness task performed during MEG recording for correctly and incorrectly derived real words for the control and at-risk groups.

Accuracy per Group	Controls (N = 17)	At-risk (N = 17)	t-values, p-values
Correct responses for correctly derived pseudo-nouns (max. 54)	20.2 (SD = 15.58) (37.5%)	26.7 (SD = 14.90) (49.4%)	ns
Correct responses for incorrectly derived pseudo-nouns (max. 54)	37.6 (SD = 13.24) (69.6%)	39 (SD = 11.71) (72.22%)	ns
<b>RT per Group</b>	<b>Controls (N = 16*)</b>	<b>At-risk (N = 17)</b>	<b>t-values, p-values</b>
RT for correctly derived nouns (ms)	1219.48 (SD = 675.33)	1314 (SD = 589.15)	ns
RT for incorrectly derived nouns (ms)	1184.48 (SD = 750.90)	1255.39 (SD = 579.66)	ns

Note: \* = participants that were removed due to continuously pressing the same button throughout the experiment.

recognizes the word (Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Pulvermüller, Shtyrov, Ilmoniemi, & Marslen-Wilson, 2006). It should be noted that the processing of semantic information has been shown to emerge around the same time in early-school-aged children as in adults (Nora et al., 2017). Thus, we could expect reasonably well-matched time-windows for the processing of lexico-semantic information in children and adults. However, it is also evident that the brain responses of pre-school children deviate from those in adult brain activation in many respects, especially in timing and for auditory information (Parviainen, Helenius, & Salmelin, 2019, 2011; Ponton, Eggermont, Kwong, & Don, 2000). Nevertheless, very little is known about the neuronal time course of processing linguistic information (derivational morphology) in pre-school-aged children. Our study shows novel results in this regard since we found that the neuronal time course of processing derivational morphology in children of pre-school age has a similar pattern to that shown in previous studies with adults.

Moreover, significant differences for correctly vs. incorrectly derived words occurred in the time-window where the P600 response has been identified in earlier studies. The activation was enhanced in the ca. 470–550 ms time-window (ca. 570–650 ms from the onset of recognition of correct vs. incorrect derivation). Previous studies have proposed the existence of two functionally different processing stages, the early stage P600 (~500–750 ms) and the late stage P600 (~750–1000 ms), where the first could represent difficulties with syntactic integration processes (Kaan, Harris, Gibson, & Holcomb, 2000) and the latter reanalysis/repair processes (Friederici, 2002; Molinaro et al., 2008, 2011). We observed only the response corresponding most likely to the early P600 at ca. 470–550 ms time-window (see Fig. 2). This observation possibly means that young children had difficulties with syntactic integration processes, but they did not engage in the reanalysis/repair process of the incoming syntactic anomalies because they might have slower and less automatic language processes due to their young age. Moreover, a significant difference observed in the late time-window at 1000–1071 ms could be an anticipation of the motor response prior to the button press during the morphological awareness task (see section 2.2). The topography of the cluster (near the motor cortex at right fronto-temporal channels for real words) would also support this interpretation. Overall, these findings demonstrate at the brain level that 6.5- to 7-year-old typical pre-school children were sensitive to the morphological information about the correctly vs. incorrectly derived words of their language.

*Can children at-risk for developmental dyslexia differentiate the correctly and incorrectly derived words, and how is this reflected in their ERF brain responses?*

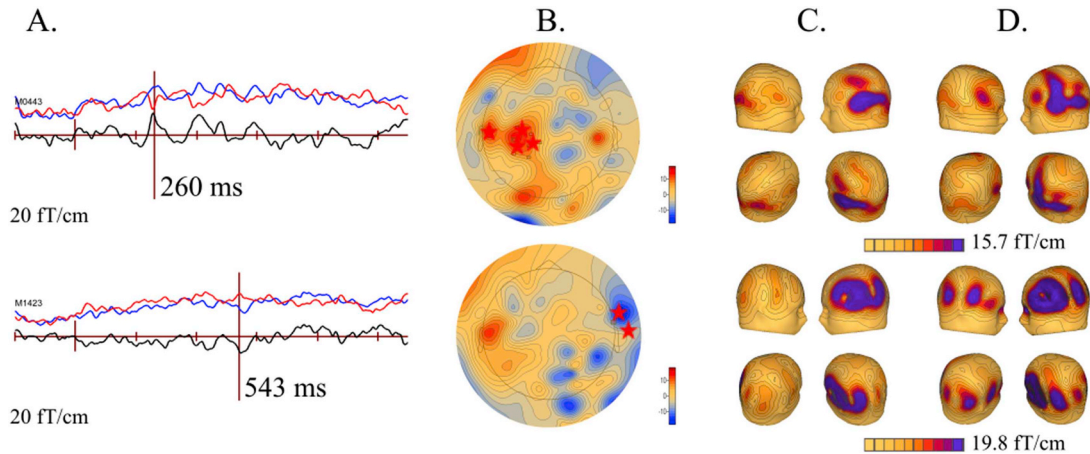
The children with familial risk for developmental dyslexia showed a pattern of findings similar to those of the children without familial risk for real words. The ERFs of children at risk for developmental dyslexia showed comparable time-windows for the sensitivity to morphological information, shown in the first time window at ca. 60–200 ms and at ca. 270–300 ms, in the middle time-window at ca. 360 ms and around 500–620 ms as well as in the late time-window at ca.1000–1050 ms. The significant difference observed in the first time-window at ca. 60–200 ms in the left occipito-temporal region and at ca. 50–200 ms in the right and left parietal region, previously found in the typically developing children somewhat earlier but at a similar time-window with a similar cluster's location, reflects long-term representations for native real words (Kuhl, 2004). Both clusters start at almost the same time but have their own distinct topographies, which suggests at least partly different, perhaps overlapping or closely linked top-down processes. However, due to the limitations of cluster-based permutation in estimating time points and topography very precisely (Sassenhagen & Draschkow, 2019), this finding cannot be determined with certainty.

Moreover, an additional cluster emerged in the first time window at ca. 270–300 ms, being larger for the incorrectly derived nouns. The differences at ca. 270–300 ms (in fact, at ca. 370–400 ms from the time point where the correctness of the derivation could be determined) seem to happen across a similar time-window with those of the typically developing group, being larger for the incorrectly derived words but with a very different cluster's topography; the significant cluster was found in the right parietal, temporal, and occipital regions (see Fig. 3). Furthermore, the group at-risk for developmental dyslexia had significant cluster differences at the ca. 360–370 ms and ca. 500–530 ms time-windows in the left frontal region, being larger for the correctly derived words. These differences emerged across the N400 time-window as a result of lexico-semantic processes for the correctly vs. incorrectly derived morphological contrast, similarly to the group without risk for developmental dyslexia. In general, it seemed as though the N400-like responses appeared a bit later in time compared to the typically developing group but with a very similar cluster topography in the left frontal region. However, unlike the typically developing group, the brain activation was stronger for the correctly derived words than incorrectly derived words.

**Table 7**  
 Summary of the channel-level (combined gradiometers), cluster-based permutation statistics for the typically developing group (N = 17): the time-window for each cluster-based permutation test analysis; the significant cluster range and the cluster's time point of maximum difference; the p-value for the cluster's maximum point; the direction of the response: Correct = Correctly derived stimuli and Incorrect = Incorrectly derived stimuli; and the cluster's location based on the sensors location. (max. = maximum).

Time-window for analysis	Time-window for cluster, cluster range (cluster's time point of maximum difference)	Cluster p-value	Direction	Cluster's location
0-300 ms	247-267 ms (max. 260 ms)	0.015*	Correct > Incorrect	left temporo-parietal region
300-700 ms	526-602 ms (max. 543 ms)	0.006*	Incorrect > Correct	right fronto-temporal region

Note: The correctness of the morphological ending takes place starting from the preceding vowel, and the beginning of the suffix /-jA/w/ was nevertheless used as the trigger point because of it being clear, whereas the preceding vowel might be slightly varied in length (~100 ms).



**Fig. 4.** A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). B. Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labeled with stars within the rectangles ( $p$ -values  $< 0.05$ ). Blue and red indicate the direction of the ERF difference for contrast (negative or positive flux amplitude,  $-10 \mu\text{V}$ – $10 \mu\text{V}$ ). Blue indicates magnetic flux directed into the brain (negative flux), and red shows flux directed out of the brain (positive flux). C. Topography of the distribution of gradient fields for the correctly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. D. Topography of the distribution of gradient fields for the incorrectly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Additionally, at-risk children showed significant differences for correctly vs. incorrectly derived words in the 300–700 ms time-window of the analyses. Specifically, the brain activations were larger for the incorrectly than correctly derived stimuli in the ca. 540–580 ms time-window and in the ca. 590–630 ms time-window in the left parieto-occipital and right occipital regions. As mentioned above, two functionally different processing stages have been suggested: the early and the late P600—although being negative for the at-risk group, where the first could demonstrate difficulties with processes of syntactic assimilation (Kaan et al., 2000), and the other represents reanalysis and reconstruction processes (Friederici, 2002; Molinaro et al., 2008, 2011). It seems that at-risk children are engaging in similar processing stages of the syntactic violation as the typically developing children; however, the clusters' topographies and time points are different. Lastly, significant differences appeared for the correctly vs. incorrectly derived words in the late time-window at 1000–1070 ms in the right fronto-parietal region, being larger for the incorrectly derived stimuli. Similar to the typically developing children, these very late differences could be a result of motor response or the preparation of the motor response to the button press.

These findings show for the first time that indeed pre-school children with familial risk for developmental dyslexia have also acquired sensitivity to derivational morphological processing as they seem to be capable of recognizing the correctly vs. incorrectly derived words of their language and involve several neural level-processes. Behaviorally, there were no significant differences, neither for the accuracy for correctly and incorrectly derived pseudo-nouns nor for the reaction time for correctly and incorrectly derived pseudowords between groups.

*Can typically developing children differentiate the correctly and incorrectly derived pseudowords, and how is this reflected in their ERF brain responses?*

Pre-school children's awareness of derivational morphology was also tested using correctly and incorrectly derived pseudowords. The brain responses of the children with typical development indicated that they were able to recognize and differentiate the correctly and incorrectly derived pseudowords. The pre-school children were sensitive to the difference between the morphologically derived pseudo-nouns in the first time-window at ca. 250–270 ms, having larger responses for correctly than incorrectly derived pseudowords in the left temporal and centro-parietal region, and in the middle time-window at ca. 530–600 ms, having larger responses for incorrectly than correctly derived pseudowords at the right fronto-temporal region, similar to the real words (see Fig. 4). This earlier effect at ca. 250–270 ms could relate to the processing of phonological information and an attempt for lexical access when engaged in the processing of potential words, the pseudowords. This interpretation is supported by previous findings in adults, shown in a review paper by Salmelin (2007), which demonstrates that when violation is observed (i.e., incorrectly derived pseudowords), this then seems to evoke additional activation in right fronto-temporal area at the ca. 530–600 ms time-window. It is not clear what this activation might be reflecting as fMRI studies have shown that children might have more bilateral language-related processing areas compared to adults (Brauer & Friederici, 2007). It is thus possible that the children might utilize a more widespread network of activation compared to adults (Gaillard et al., 2003; Holland et al., 2001). Nevertheless, the results show that pre-school children are able to represent the morphological rules in an abstract form, which can be implemented with meaningless pseudowords.

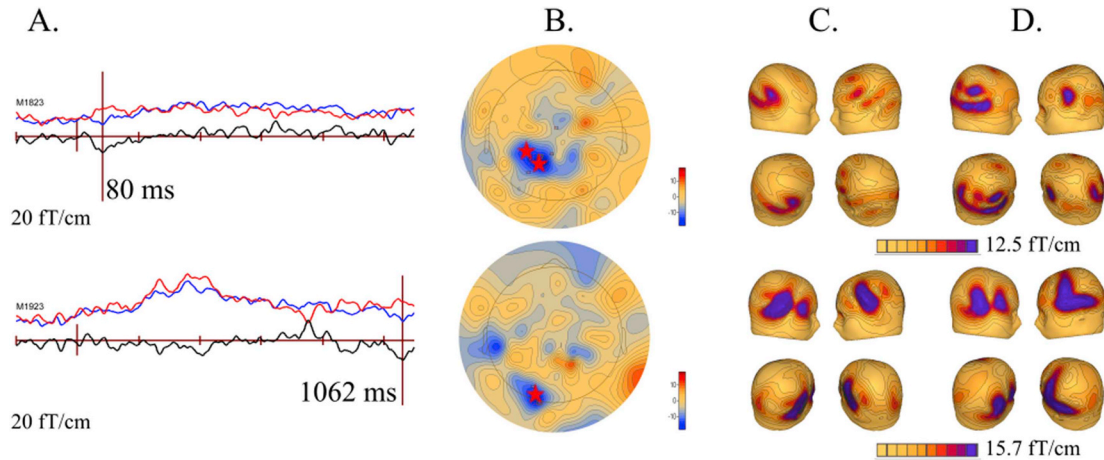


**Table 8**

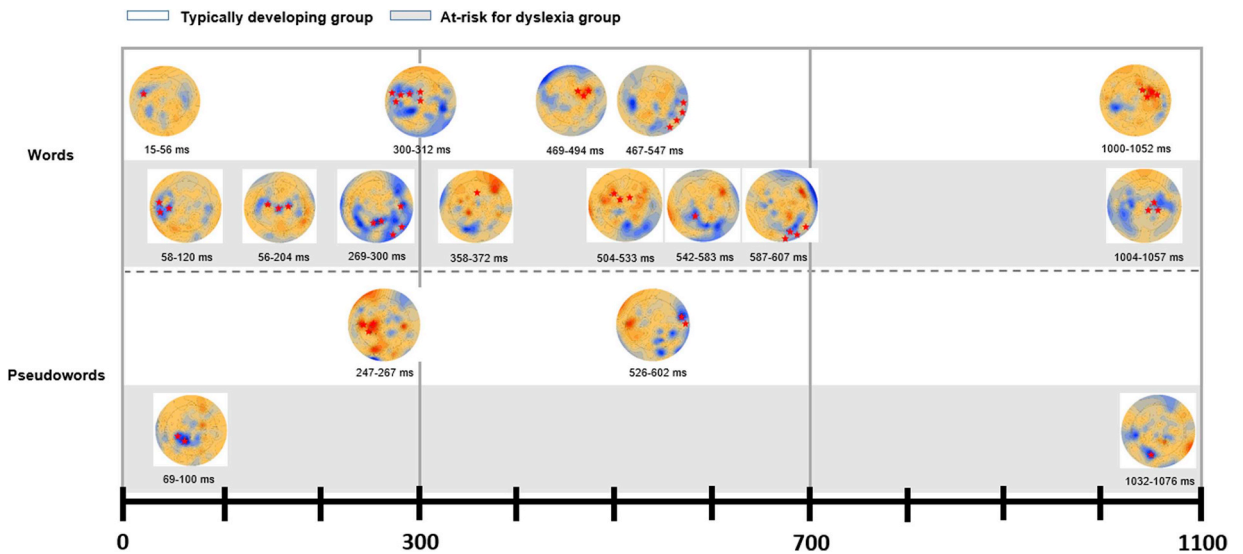
Summary of the channel-level (combined gradiometers), cluster-based permutation statistics for the at-risk group (N = 17): the time-window for each cluster-based permutation test analysis; the significant cluster range and the cluster's time point of maximum difference; the p-value for the cluster's maximum point; the direction of the response: Correct = Correctly derived stimuli and Incorrect = Incorrectly derived stimuli; and the cluster's location based on the sensors location. (max. = maximum).

Time-window for analysis	Time-window for cluster, cluster range (cluster's time point of maximum difference)	Cluster p-value	Direction	Cluster's location
0-300 ms	69-100 ms (max. 80 ms)	0.008*	Incorrect > Correct	left and right parietal region
700-1100 ms	1032-1076 ms (max. 1062 ms)	0.036*	Incorrect > Correct	left occipital region

Note: The correctness of the morphological ending takes place starting from the preceding vowel, and the beginning of the suffix /-jA/ was nevertheless used as the trigger point because of it being clear, whereas the preceding vowel might be slightly varied in length (~100 ms).



**Fig. 5.** A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). B. Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labeled with stars within the rectangles ( $p$ -values  $< 0.05$ ). Blue and red indicate the direction of the ERF difference for contrast (negative or positive flux amplitude,  $-10 \mu\text{V}$ – $10 \mu\text{V}$ ). Blue indicates magnetic flux directed into the brain (negative flux), and red shows flux directed out of the brain (positive flux). C. Topography of the distribution of gradient fields for the correctly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. D. Topography of the distribution of gradient fields for the incorrectly derived nouns depicted during the time points of maximal significant difference in the cluster-based permutations statistics between the responses to the correctly vs. incorrectly derived nouns. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 6.** Summary of the within-group differences of the cluster-based permutation statistics for the correct vs. incorrect morphological derivation per group (In white: typically developing children and in gray: at-risk for dyslexia children) per time-window (0–300, 300–700, and 700–1100 ms) separately for real words and pseudowords. Significant clusters are labeled with red stars within the rectangles ( $p$ -values  $< 0.05$ ). Blue and red indicate the direction of the ERF difference for contrast (negative or positive flux amplitude,  $-10 \mu\text{V}$ – $10 \mu\text{V}$ ). Blue indicates magnetic flux directed into the brain (negative flux), and red shows flux directed out of the brain (positive flux). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

*Can children at risk for developmental dyslexia differentiate the correctly and incorrectly derived pseudowords, and how is this reflected in their ERF brain responses?*

Processing differences between the correctly vs. incorrectly derived pseudowords were also tested for the pre-school children with familial risk for developmental dyslexia. The brain responses of the children with familial risk for developmental dyslexia indicated that they were able to recognize and differentiate the correctly and incorrectly derived pseudowords. The brain responses of the children at risk for developmental dyslexia were sensitive to the difference for the morphological pseudo-nouns in the first time-

window at 69–100 ms in the left and right parietal regions and in the late time-window at ca. 1030–1080 ms in the left occipital region. The significant difference observed in the first time-window at ca. 69–100 ms in the left and right parietal regions, similarly observed in the same group for the real words, likely reflects acoustic differences that exist in the pseudowords before the last syllable and is probably indicative of the correct/incorrect ending. Coarticulation is always present during speech production; therefore this early response could well reflect an anticipation mechanism due to the speaker's co-articulation, where the listener is able to predict an incorrect (vs. correct) suffix. The significant difference observed in the late time-window at ca. 1030–1080 ms in the left occipital region, being larger for the incorrectly derived stimuli, likely reflects motor response processes.

*Do children at-risk for developmental dyslexia have a differential pattern of brain responses, and how are they different from the typically developing group?*

Our second goal was to investigate whether or not the group with familial risk for developmental dyslexia showed differential processing of morphological (derivative) information compared to the typically developed group. No differences were found when directly comparing the contrast of correctly vs. incorrectly derived words or pseudowords between the groups. Similarly, no group differences emerged when examining the ERFs separately for the correct and incorrect derivations, neither for real words nor pseudowords. This suggests that children with and without risk for developmental dyslexia are capable of processing the incoming morphological information as early as at pre-school age; however, it is true that more research is needed to establish the significance of the process, especially in pre-school children.

Nonetheless, our behavioral results demonstrated that there was a significant difference between the typical group and the group at-risk for developmental dyslexia in the accuracy of identifying correctly derived words. Specifically, the control group was more accurate than the at-risk group in identifying the correctly derived words. These group differences are not observed for all stimuli and at the same time windows. These findings would rule out general differences in processing speech information and imply specific differences related to the stimulus material, that is, to syntactic manipulation.

Overall, our study has certain limitations. First, the stimuli for the morphological awareness task were produced naturally, which by default results in a slight variation in the length and other acoustic features of words per sentence. At the same time, the naturally produced stimuli are ecologically more valid than synthesized stimuli, but further studies should investigate how large an impact the acoustic features have in this task. Second, the correctness of the morphological ending was defined from the preceding vowel before the suffix/-jA/, but the beginning of the suffix/-jA/was nevertheless used as the trigger point because of it being a clearly identifiable syllable that was the same for each stimulus, whereas the preceding vowel depended on the word context and also might be slightly varied in length (~100 ms); thus the match of the noun with the verb or anomaly not matching with the verb can be detected at ca. 100 ms earlier than the trigger. Third, both the correct and incorrect responses during the morphological awareness task were included for the ERF analysis because the number of stimuli per condition would have been too small if half of the trials would have been rejected based on the behavioral responses. This could diminish the brain responses reflecting the conscious processing of syntactic violations; however, the use of both correct and incorrect responses for the ERF analyses gives a better signal-to-noise ratio for the examination of brain responses reflecting the automatic processing of derivational morphology.

In summary, the within-group differences suggest that preschool children with low risk for developmental dyslexia and children with high risk for developmental dyslexia were capable of identifying the correctly and incorrectly derived words and pseudowords of their language, and thus they seem to have acquired an awareness of derivational morphology. It is noteworthy that albeit significant within-group differences in both groups, which clearly indicates an ability of morpho-phonological processing, the groups had differences in within-group brain activation patterns and also in responses to correctly derived (behaviorally presented) real words and thus in brain responses to the morpho-phonological speech units for which representations have been built up over the years. Interestingly, the groups did not show any significant between-group differences, but they showed somewhat different response patterns to the morphological contrast both for real words and pseudowords. It is evident that more research is needed to establish the significance of morphological information processing, especially in pre-school children with and without familial risk for developmental dyslexia.

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## CRedit authorship contribution statement

**Natalia Louleli:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Jarmo A. Hämäläinen:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing - review & editing. **Lea Nieminen:** Conceptualization, Resources, Methodology, Writing - review & editing. **Tiina Parviainen:** Methodology, Resources, Validation, Writing - review & editing. **Paavo H.T. Leppänen:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing.

## Declaration of competing interest

None.

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