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Title: Neural correlates of morphological processing and its development from pre-school to the first grade in children with and without familial risk for dyslexia

Year: 2022

Version: Published version

Please cite the original version:

Louleli, N., Hämäläinen, J. A., Nieminen, L., Parviainen, T., & Leppänen, P. H. (2022). Neural correlates of morphological processing and its development from pre-school to the first grade in children with and without familial risk for dyslexia. Journal of Neurolinguistics, 61, Article 101037. https://doi.org/10.1016/j.jneuroling.2021.101037

Journal of Neurolinguistics 61 (2022) 101037

Contents lists available at ScienceDirect

Journal of Neurolinguistics

journal homepage: www.elsevier.com/locate/jneuroling

Neural correlates of morphological processing and its development from pre-school to the first grade in children with and without familial risk for dyslexia

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ARTICLE INFO

Keywords:
Derivational morphology
Reading acquisition
Pre-school children
First grade children
Longitudinal
At-risk for dyslexia
MEG

ABSTRACT

Previous studies have shown that the development of morphological awareness and reading skills are interlinked. However, most have focused on phonological awareness as a risk factor for dyslexia, although there is considerable diversity in the underlying causes of this reading difficulty. Specifically, the relationship between phonology, derivational morphology, and dyslexia in the Finnish language remains unclear. In the present study, we used magnetoencephalography (MEG) to measure the brain responses to correctly and incorrectly derived Finnish nouns in 34 first grade Finnish children (21 typically developing and 13 with familial risk for dyslexia). In addition, we compared longitudinally the morphological information processing of 27 children (16 typically developing and 11 at-risk for dyslexia) first at pre-school age and then at first grade age. The task consisted of 108 pairs of sentences, including a verb and its root with the derivational suffix/-jA/. Correctly and incorrectly derived forms were presented both as real words and pseudowords. The incorrectly derived nouns contained a morpho-phonological violation in the last vowel of the noun before the derivational suffix. The brain activation of the typically developing children in response to morphological information processing showed sensitivity to the morphologically correct vs. incorrect contrast only in the cases of the real words. Children at-risk for dyslexia showed sensitivity to the morphological information processing both for real words and pseudowords. However, no significant differences between the groups emerged either for the correct vs. incorrect morphological contrast or for the correctly and incorrectly derived forms separately. Interestingly, in our previous study, cluster-based permutation tests showed significant developmental behavioral and brain differences between the children at pre-school age and at first-grade age in the morphological information processing of real words and pseudowords. Our results indicate the important role of derivational morphology in the early phases of learning to read.

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https://doi.org/10.1016/j.jneuroling.2021.101037
Received 6 August 2020; Received in revised form 14 September 2021; Accepted 18 October 2021
Available online 29 October 2021

1. Introduction

Reading is fundamentally a complex cognitive and linguistic process. Developing functional/typical reading skills is essentially interlinked with morphological awareness (Carlisle, 2003; Kuo & Anderson, 2006; McBride-Chang et al., 2013). More specifically, reading development requires converting orthographic forms into phonological units (phonological awareness) and is supported by the ability to efficiently manipulate the smallest, meaningful units of language, morphemes (morphological awareness) (Carlisle, 2003; Kuo & Anderson, 2006). For some children, learning to read poses a challenge, and this can be due to the complex nature of the reading process. Reading problems, or dyslexia, is defined as persistent and specific difficulty in typical reading acquisition and development (Ramus et al., 2003; Vellutino et al., 2004), has a strong genetic inheritance rate within families (Byrne et al., 2006; van Bergen et al., 2011; Olson and Keenan, 2015). Our study aims to explore whether morphological information processing in first graders differs between children with and without familial risk for dyslexia. Further, we examined whether processing morphological information in the brain changes from kindergarten (Louleli et al., 2020) to first grade in children with and without familial risk for dyslexia.

Several studies have established the important role of phonological processing in reading acquisition. Specific aspects of phonological processing—phonological awareness, phonological short-term memory, and rapid automatized naming (RAN)—have been found to be predictors of reading acquisition in several languages, for example Finnish (Puolakanaho et al., 2008; Ziegler et al., 2010) and Greek (Georgiou et al., 2008, 2012; Papadopoulos et al., 2009). From another point of view, intervention studies show that training of phonological skills in children with dyslexia can improve their reading performance (Goodwin & Ahn, 2010; Galuschka et al., 2014).

Before formal reading instruction, young children also develop morphological awareness by constructing the morpho-phonological representations of their language, which are used as a rule-based mechanism in language-related functions, i.e., the ability to identify correctly and incorrectly derived words (Louleli et al., 2020) or the ability to inflect words (Lyytinen & Lyytinen, 2004; Jessen et al., 2017). However, the automaticity of morphological information processing depends upon a longer developmental process from kindergarten to adulthood (Casalis & Louis-Alexandre, 2000).

Morphological awareness has been found to be a predictor for later reading skills in children (Kirby, Deacon et al., 2012) and to be strongly correlated with vocabulary across different grades (Nagy et al., 2006) and reading comprehension (Müller & Brady, 2001; Kirby, Deacon et al., 2012). Morphological awareness is associated with reading development across many languages, independently of the type of writing system—alphabetic, syllabic, or logographic—such as English (Kirby et al., 2012), French (Casalis & Louis-Alexandre, 2000), Dutch (Rispens et al., 2008), Greek (Diamanti et al., 2017), Japanese (Muroya et al., 2017), and Arabic (Tibi & Kirby, 2017).

All words across languages are composed of morphemes: free and bound. Free morphemes can stand alone (e.g., “house” or “car”), and bound morphemes are attached to a stem (prefixes in the beginning, infixes in the middle, and suffixes at the end of the word); combining a stem and a bound morpheme might involve phonological changes. For example, in Finnish the last vowel of a stem changes when the word is inflected (kivi—kive + n is “stone,” genitive) (Kiefer & Laakso, 2014). The Finnish language has a rich morphological system with rich inflectional morphology but also varying derivational morphology and compounding of words. Inflection changes the grammatical aspects of a word (tense, number, spatial, and temporal relations). Derivation generates new words, in which the meanings of the stem and the derived new word are somehow connected (like the case of drive–driver). There are approximately 140 Finnish derivational suffixes (Kiefer & Laakso, 2014). The suffix/-jA/, used in our morphological task, is highly productive, and it is used to derive new words based on verbs only: the suffix/-jA/produces frequent words commonly used in everyday life (e.g., opetta-ja = teacher) (Kiefer & Laakso, 2014).

Awareness of derivational morphology supports fluent reading and competent functional reading skills (Carlisle, 2003). From a theoretical perspective, awareness of derivational morphology might require deeper knowledge about the morphemes and their meanings (e.g., the semantic underpinnings of the suffix/-er/in the word/sing-er/denotes agentivity) (Carlisle, 2003; Kuo & Anderson, 2006). Previous behavioral studies with children attending primary school have demonstrated that awareness of derivational morphology is related to successful word reading, especially in languages with transparent orthographies and rich morphological systems (i.e., Spanish: Ramirez et al., 2010; Greek: Diamanti et al., 2017 and Manolitsis et al., 2017; Italian: Burani et al., 2002). Ramirez et al. (2010) tested the awareness of derivational morphology with two behavioral measures (morphological structure and morphological production) in Spanish, a linguistic system with transparent orthography and rich morphology (Ramirez et al., 2010). They showed that for 4th- and 7th-grade native Spanish speakers, 11% of the variance for word reading in Spanish was explained by their performance in the morphological tests (Ramirez et al., 2010). Additionally, a study by Vernice and Pagliarini (2018) tested morphological awareness behaviorally with three tasks (nominal derivational morphology, morphological production with object–picture relations, and morphological production with sentences) in monolingual (Italian) and bilingual (Arabic-Italian) children between the ages of 6 and 11 years with low socio-economic backgrounds (Vernice & Pagliarini, 2018). They showed that morphological awareness, especially awareness of derivational morphology, predicted reading fluency outcomes in first and second graders (Vernice & Pagliarini, 2018).

In dyslexia, the neural basis of phonological and auditory-based dysfunctions (Vellutino et al., 2004; Ramus et al., 2003; Goswami, 2002) on the one hand and visual word perception (Valdois, Bosse, & Tainturier, 2004; Bosse, Tanturier & Valdois, 2007; Lallier & Valdois, 2012; Lobier et al., 2012) on the other hand have been studied as potential underlying factors for compromised reading development. However, less emphasis has been given to morphological processing. Previous behavioral studies testing morphological awareness and morphological processing skills in children have not found any differences comparing pre-school children with and without risk for dyslexia (Law et al., 2016) or school-aged children with and without dyslexia (Casalis, Cole, & Sopo, 2004; Egan & Price, 2004). In these studies, behavioral differences were not found between children who were matched for their reading skills;

differences emerged only when age-matched groups were compared. These results mainly suggest that any observed differences in morphological processing between typical readers and readers with dyslexia may be a result of their reading experience (Law et al., 2016). However, Cunningham and Carroll (2015) indicated in their behavioral study that morphological awareness skills of first-grade students were predicted by phonological processing measured at pre-school age (Cunningham & Carroll, 2015). Similarly, Law et al. (2017) found that pre-school children with familial risk for dyslexia already had both phonological and morphological awareness deficits. They suggested that phonological and morphological awareness are interlinked and that the pre-reading deficit in morphological awareness is a consequence of the deficit in phonological awareness (Law et al., 2017; Law & Ghesquière, 2017).

To our knowledge, no studies have examined the brain basis of morphological information processing in childhood and its link to reading acquisition. In our previous study (Louleli et al., 2020), we examined this link and demonstrated that awareness of derivational morphology was reflected in the brain responses of children attending kindergarten. Specifically, morphological information processing was measured in two groups of 6–7-year-old children (with and without risk for dyslexia). A morphological task utilizing correctly and incorrectly derived words and pseudowords was used during magnetoencephalography (MEG) recordings. The results showed that both groups were sensitive to correct and incorrect morphological constructs for real words and pseudowords. However, the at-risk group exhibited differences compared to the typically developing group in the temporal and spatial distribution of brain activation, presumably due to their familial risk for dyslexia.

Generally, studies in dyslexia have shown the plurality of deficits related to this learning difficulty. Although phonological deficits are most commonly associated with dyslexia, subgroups of people with dyslexia have demonstrated difficulties also in other domains, for example, in processing non-linguistic auditory information (Goswami, 2002) or general visual information and/or in visual attention span (Valdois et al., 2004; Bosse et al., 2007; Lallier & Valdois, 2012; Lobier et al., 2012) and in rapid automatized naming (de Jong & van der Leij, 2003; Puolakanaho et al., 2007; Torppa et al., 2007; Papadopoulos et al., 2016; Lohvansuu et al., 2018). Therefore, it is clear that dyslexia could be considered a multifactorial learning difficulty with multiple and sometimes overlapping dysfunctions (Pennington, 2006). Interestingly, our recent findings (Louleli et al., 2020) suggest that pre-school children with familial risk for developmental dyslexia have problems also in the morpho-phonological domain. This feature might be especially meaningful for individuals who acquire a multimorphemic language such as Finnish.

Language processing in the brain can be studied with event-related potentials (ERPs) and event-related fields (ERFs). Different ERP/F components have been identified to reflect the stages of phonological, morphological, semantic, and syntactic processes in adults and to some extent in children. The current study focused on derivational morphology. In the auditory domain, ERP studies in Finnish (Leminen et al., 2013) and German (Hanna & Pulvermüller, 2014) adults using the oddball paradigm have reported stronger brain activity for derived words than derived pseudowords (Leminen et al., 2013) and for congruent than incongruent derived words at around 130–170 ms (Hanna & Pulvermüller, 2014). In both studies, the stronger responses for the known stimuli (derived words and derived congruent words) indicated lexicality effects, and they were interpreted to represent whole-word lexical representations in the brain (Leminen et al., 2013; Hanna & Pulvermüller, 2014). Additionally, an ERP study testing the effects of morphological processing in Finnish adults (Leminen et al., 2010) demonstrated that brain responses at a late time window (274–314 ms) differed between illegally derived pseudowords and existing words in Finnish, although no difference was found between legal and illegal pseudowords or between real words and legal pseudowords (Leminen et al., 2010).

In the visual domain, studies on 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 (Janssen et al., 2006; Bölte et al., 2010). Similarly, stronger responses at the 400–550 ms time window were elicited during tasks focused on derivational morphology in Finnish when adults were detecting lexical anomalies (Leinonen et al., 2008). ERF studies have also tried to disentangle the time course of adults' brain responses during morphological processing. Earlier MEG studies in English, testing adults and using single words with different morphological complexity, have demonstrated that the early visual M170 response is sensitive to the morphological structure of words (Zweig & Pylkkänen, 2009; Solomyak and Marantz, 2009). Furthermore, ERF responses during visual processing of derivational word forms in comparison to non-derived words in French adults have revealed brain activity differences at 350 ms (Cavalli et al., 2016). The same pattern has been found for English stimuli (Solomyak and Marantz, 2009).

In summary, morphological manipulation of both spoken and written words has elicited differential brain responses at both early time windows starting at 130 ms and late time windows of around 400 ms. Thus, the brain responses can provide information on how the processing stages of morphological information develop during childhood and how these stages are affected by reading acquisition.

1.1. Goal of the study

This study examines the brain basis of morphological processing in early readers (first-grade) with and without risk for dyslexia during processing of correctly and incorrectly derived real words and pseudowords in the Finnish language. We specifically investigate whether typically developing first-grade children differentiate correctly and incorrectly derived words and pseudowords and how this is reflected in their brain responses. We also test whether and how children at-risk for dyslexia differ from typically developing children in processing morphological information. Finally, we determine if the neural correlates of morphological information processing change over time from kindergarten to first grade in children with and without familial risk for dyslexia.

2. Methods

2.1. Participants

A sample of native Finnish-speaking first graders from central Finland, previously tested at 6.5–7 years old (Louleli et al., 2020), participated again in our study at the age of 7.5–8 years old. Data included in the behavioral and MEG analysis (morphological task) were from 34 participants (21 typically developing and 13 at-risk for dyslexia) for real words and 29 participants (20 typically developing and 9 at-risk for dyslexia) for pseudowords (Table 1). Initially, 40 children participated at 7.5–8 years (26 without familial risk for dyslexia and 14 with familial risk for dyslexia). Of these, 6 children (5 typically developing and 1 at-risk for dyslexia) were excluded from the analysis of the morphological task for real words and 11 children (6 typically developing and 5 at-risk for dyslexia) from the analysis of the morphological task for pseudowords. The exclusion was based on excessive movement artifacts or the bad signal quality of the MEG data.

For the longitudinal cluster-based permutation statistics, we compared 27 pre-school children from our previous study (Louleli et al., 2020) with 27 first grade children from the current study who participated in the MEG measurements (Table 2). Both groups included 16 children without familial risk for dyslexia and 11 children with familial risk for dyslexia.

None of the participants had hearing or neurological problems or head injuries or were using medication affecting the central nervous system. All participants included in the analyses had normal or corrected-to-normal vision (using special goggles for MEG measurements). The participants at-risk for dyslexia were defined as having at least one parent and/or sibling with a diagnosis of dyslexia and/or a parent with self-reported reading problems based on a questionnaire completed by the parents.

Ethical approval for this study was provided by the Ethical Committee of the University of Jyväskylä in accordance with the Declaration of Helsinki. Before the measurements, participants and their parents were fully informed about the goals and methods of the study. Both the participants and their parents gave their written informed consent to participate in the study. For the brain activity measurements with MEG, all participants received movie tickets as compensation for participating in the study.

2.2. Cognitive characteristics of the sample

As with the pre-school children (Louleli et al., 2020), the first grade children's cognitive skills were assessed on a separate visit before the MEG measurement (Table 3). The behavioral assessments included the Wechsler Intelligence Scale for Children Fourth Edition (WISC IV: Wechsler, 2003). Block design for visuospatial reasoning, vocabulary for expressive vocabulary, and digit span (forward and backward) for working memory were administered. In the block design test, the children were shown how to arrange blocks to build a design, and they had to form the same design. The task had escalating levels of difficulty: in harder sections, they were shown a design via a figure, and they had to form it. In the vocabulary test, the children heard a word and had to describe its meaning. In the digit span test, a series of numbers was said to the children, and they had to repeat the same series of numbers either in forward or backward order.

Phonological processing, which measures phonemic/phonological awareness, was assessed with two phonological processing tasks from the Developmental Neuropsychological test battery (NEPSY II): word segment recognition, in which the children were first asked to repeat a word segment by segment and phonological manipulation, in which the children were first asked to repeat a word and then to repeat the same word by leaving out a phoneme or a syllable or by changing one phoneme with another phoneme (Korkman et al., 2007). Finally, RAN (Denckla & Rudel, 1976) was measured separately for objects and letters: first, the children had to name as quickly and accurately as possible pictures of five common objects or letters. The performance of the participants was scored as total time in seconds. The objects and letters were arranged in five rows each containing 10 materials per row.

2.3. Stimuli

In this study, we used the same morphological awareness task as in our previous study (Louleli et al., 2020). The stimuli were 216 pairs of words consisting of a verb and its derived noun with the derivational suffix/–jA/(/-ja/−/–jä/) (Fig. 1). The Finnish suffix/-jA/is broadly used to produce a noun from a verb, for example, johtaa (verb, "to lead") and johta**ja** (noun with the agentive

Table 1
Demographic information of the first grade children included in the MEG data analyses.

	Demographic information of the first grade children			
Morphological task	Real words		Pseudowords	
Participants per task	Typically developing first grade children	At-risk for dyslexia first grade children	Typically developing first grade children	At-risk for dyslexia first grade children
Number of Participants	21	13	20	9
Age (average)	7 years and 7 months (SD = 0.36)	7 years and 8 months (SD = 0.46)	7 years and 6 months (SD = 0.32)	7 years and 8 months (SD = 0.49)
Gender	11 girls and 10 boys	5 girls and 8 boys	9 girls and 11 boys	3 girls and 6 boys
Handedness	20 right-handed	12 right-handed	20 right-handed	9 right-handed

Table 2

Demographic information of the participants included in the longitudinal data analyses (pre-school and first grade children).

Demographic information of the longitudinal group								
Morphological task	Real words				Pseudowords			
Participants per task	Typically developing children		At-risk for dyslexia children		Typically developing children		At-risk for dyslexia children	
	Pre-school	**First grade**	**Pre-school**	**First grade**	**Pre-school**	**First grade**	**Pre-school**	**First grade**
N of participants	16	16	11	11	14	14	9	9
Age (average)	6 years and 7 months (SD = 0.36)	7 years and 7 months (SD = 0.36)	6 years and 8 months (SD = 0.44)	7 years and 8 months (SD = 0.44)	6 years and 8 months (SD = 0.37)	7 years and 8 months (SD = 0.37)	6 years and 8 months (SD = 0.49)	7 years and 8 months (SD = 0.49)
Gender	9 girls and 7 boys	9 girls and 7 boys	4 girls and 7 boys	4 girls and 7 boys	8 girls and 6 boys	8 girls and 6 boys	3 girls and 6 boys	3 girls and 6 boys
Handedness	15 right-handed	15 right-handed	11 right-handed	11 right-handed	13 right-handed	13 right-handed	9 right-handed	9 right-handed

Table 3
Descriptive statistics of the participants' cognitive skill measures.

Behavioral assessments	Typically developing first grade children				At-risk for dyslexia first grade children				
	Mean (max.)	SD	Range	N participants	Mean (max.)	SD	Range	N participants	t-values p-values
Block design	31.95 (68)	11.72	10–52	21	28.38 (68)	11.31	14–53	13	t(32) = 0.874, p = .884
Vocabulary	25.47 (66)	8.80	10–46	21	23.07 (66)	6.43	13–37	13	t(32) = 0.850, p = .206
Digit span	12.04 (32)	1.88	9–16	21	11.61 (32)	2.46	8–15	13	t(32) = 0.577, p = .051
Phonological processing	41.33 (53)	6.02	24–53	21	38.46 (53)	6.18	29–50	13	t(32) = 1.337, p = .789
RAN (Objects)	64.50	18.01	39.71–119.39	21	63.46	10.75	46.49–85.96	13	t(32) = 0.188, p = .161
RAN (Letters)	42.74	11.54	28.39–78.08	21	43.30	10.35	30.11–60	13	t(32) = −0.145, p = .938

Note: The descriptive statistics of the pre-school children's cognitive skill measures have already been published in Louleli et al., 2020. Max. means the maximum value of the cognitive measure.

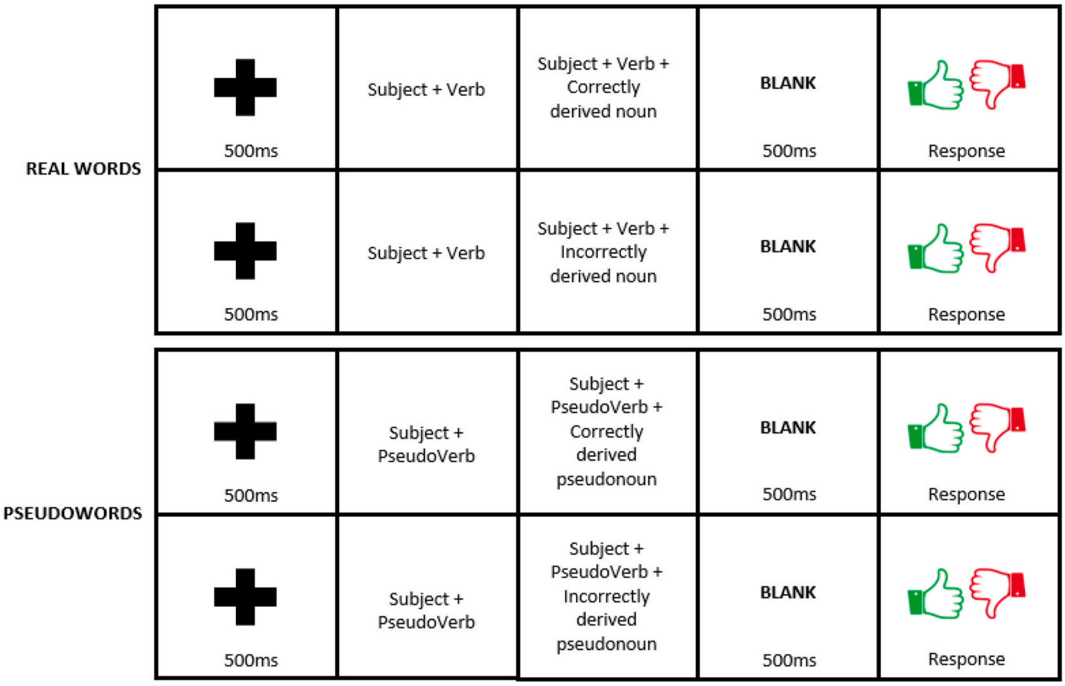

Fig. 1. Morphological awareness task. Each trial started with a 500 ms fixation cross, followed by a pair of sentences, followed by a 500 ms blank screen, followed by a thumbs up/down picture where participants had to respond.

marker, "lead**er**"). The word pairs were created under two conditions: real words and pseudowords. Real words were selected from a corpus of word frequencies in Finnish newspapers (2010) (https://github.com/GrammaticalFramework/GF/blob/master/lib/src/finnish/frequency/src/suomen-sanomalehtikielen-taajuussanasto-utf8.txt). This corpus was chosen as the source for the real words because it consists of the most common Finnish lemmas taken from newspapers. The newspapers' language represents frequently used words in everyday Finnish written language. The pseudowords were created based on the real words. They carry no semantic meaning, but they were created according to the phonological, morphological, grammatical, and syntactic rules of the Finnish language (Louleli et al., 2020).

The derivational nouns were further split into correctly and incorrectly derived forms, with 54 nouns in each subcategory (Fig. 1). Both the correct and the incorrect forms were nouns derived from the verbs, but the incorrectly derived forms were formed with an incorrect morpho-phonological change in the last vowel before the derivational suffix/-jA/(e.g., joht**i**ja) (for more details, see Louleli et al., 2020).

For each verb of the incorrectly derived forms, the last vowel was always replaced with another vowel. Diphthongs were completely avoided. The changing of the vowels in our stimuli did not violate Finnish vowel harmony rules. For the replacements, the most distant vowels, based on the place and manner of articulation, were chosen to replace the existing ones to avoid unnecessary confusion or inability to hear the vowel changes in the context of testing small children. For example, the vowel/a/was replaced by/i/(johtaja - johtija), the vowel/o/was replaced by/a/(velkoja - velkaja), and so on. Two vowels were not used in the morpho-phonological changes: 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 word forms, e.g., maksaa ("to pay") + jA = maksaja "payer"), and vowel replacement can also create real word forms, e.g. maksoja (maksa ("liver") + plural partitive = maksoja "livers"). The vowels were replaced identically in real words and pseudowords.

All stimuli were recorded in a recording studio at the University of Jyväskylä by a female Finnish speaker (44 kHz sampling frequency, 32-bit quantization recorded in stereo channels). The recorded sound files were edited with Sound Forge Pro 11.0 and Praat (Boersma & Weenink, 2018) (5 ms were added in each sound file at the beginning and end of each sentence). The morphological awareness task was programed with Presentation software (Neurobehavioral Systems, Inc., Albany, CA, United States) running on a Microsoft Windows computer.

2.4. MEG experiment

MEG data were collected by a 306-channel (204 gradiometers and 102 magnetometers) whole-head Elekta Neuromag TRIUX system (Elekta AB, Stockholm, Sweden) in a magnetically shielded and soundproof room at the Center for Interdisciplinary Brain Research (CIBR) at the University of Jyväskylä. In all the recordings, the MEG system was in a 68° upright gantry position. The head position was continuously monitored with five head position indicator coils (HPI coils) attached to the scalp (three on the participant's forehead and one on each ear). Two pairs of electro-oculograms (EOGs) were used to capture eye blinks and eye movements; one pair was placed lateral to each eye and the other pair was placed above and below the left eye. An additional EOG was used as ground reference, and it was placed on the participant's right collarbone. To compensate for head movements, additional digitized points (~120) were also collected over the scalp for each subject using the Polhemus Isotrak digitizer (Polhemus, Colchester, VT, USA).

During the brain activity measurements, participants were sitting 1 m from a projecting screen with a projector using a refresh rate of 60 Hz. Detailed instructions were given through inserted headphones at 60 dB (SPL) as small stories for the children. For the real words, a girl had to pass a language exam for school, and the participant had to advise her which word pairs she had learned accurately and which not. To do so, the participants could judge the pairs of sentences and give their responses through pressing a button: a right button press for the correct pairs and a left button press for the incorrect pairs of sentences. For the pseudowords, another story was used: a girl tried to create a new language to contact her friends in secret, and again the participant through button presses was asked to help her find out which word pairs could be considered accurate Finnish words and which could not. Knowing the correct forms is based on learned representations built during language development, and this procedure starts before school age (Louleli et al., 2020). After the instructions, there was a practice task with six trials.

The main task had a black fixation cross present on the screen for 500 ms, then the participants were auditorily presented with the pairs of sentences (e.g.,/Hän johtaa. Hän on johtaja/) (= "He leads." "He is a leader."), followed by a blank screen for 500 ms, and finally they had to respond through button presses. After each block of trials (54 pairs of sentences per block), 1-min animated videos were used as attention-getters to help the participants stay focused on the task. In each measurement session, the first two blocks included real words, and the next two blocks included pseudowords. All the pairs of stimuli within a category were randomly intermixed, but the pairs themselves were always presented together (yoked/joined stimuli). All the stimuli were presented only once. 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). Together with the MEG data, accuracy and reaction times were recorded. Overall, the task lasted approximately 40 minutes.

2.5. MEG data analysis

After the MEG recordings, head movements were corrected and external noise sources were attenuated using the temporal extension of the signal-space separation method (tSSS) (Taulu & Kajola, 2005; Taulu & Simola, 2006) of the Maxfilter 2.2 program (Elekta AB, Stockholm, Sweden). The head position was transformed to that of the first MEG recording block for each child. Bad channels observed during the measurement were manually marked and then reconstructed in Maxfilter 2.2. After the initial head movement correction, the data were analyzed with BESA 6.1 (BESA GmbH, Munich, Germany). Independent Component Analysis (ICA; infomax algorithm) was used separately for the magnetometers and gradiometers to correct for eye blinks and eye movements; it was applied in a representative 60 s time window. The MEG signal was low-pass filtered at 30 Hz (zero phase, 24db/oct) and high-pass filtered at 0.5 Hz (zero phase, 12db/oct). Thereafter, the MEG signal was segmented into trial-based windows from −200 to 1100 ms with respect to the onset of the derivational suffix/-jA/(100 ms pre-stimulus baseline) and averaged separately for the correctly and incorrectly derived real words and pseudowords. Segments with over 1200 fT/cm rejection level for gradiometers and 4000 fT for magnetometers were rejected. The two orthogonal gradiometer channel pairs were combined in Matlab R2015b using the vector sum.

2.6. Statistical analyses

For the first grade children, accuracy and reaction times in the morphological awareness task were examined using independent samples t-tests for the between-subjects contrast of the groups: 34 participants (21 typically developing and 13 at-risk for dyslexia) for real words and 29 participants (20 typically developing and 9 at-risk for dyslexia) for pseudowords (see section 3.1).

For the ERFs, sensor-level statistical analysis was performed with cluster-based permutation tests (Maris & Oostenveld, 2007) in BESA Statistics 2.0 (BESA GmbH, Munich, Germany) for the within- and between-group comparisons on the combined gradiometers (based on two-tailed paired or independent t-tests). The within-group analysis included the ERF responses to the correctly vs. incorrectly derived pairs of sentences, separately for the control and the at-risk group and separately for the real words and the pseudowords (see sections 3.2, 3.3, 3.4 and 3.5). The correctness of the morphological ending in the stimuli can be detected at ~100 ms before the beginning of the suffix/-jA/from the last vowel of the derived noun, but the suffix/-jA/was nevertheless used as the trigger point (zero point in the timeline) as a clear acoustic point to set as the baseline. The number of permutations was 3000, the cluster alpha was 0.05, and the distance between the sensors was set at 4 cm. Based on our previous study (Louleli et al., 2020), the responses to the correct vs. incorrect contrast were examined in three time windows of interest: 0–300, 300–700, and 700–1100 ms. For all the comparisons within and between the groups, we corrected the p-values of the cluster-based permutation tests by applying a false discovery rate (FDR) correction of q = 0.05 (Benjamini & Hochberg, 1995). It was applied separately for the within- and between-group comparisons.

For the longitudinal data, the behavioral performance in the morphological task during MEG recordings of the pre-school children (Louleli et al., 2020) was compared with that of the first grade children. Specifically, for the within-subjects contrast of age (kindergarten, first grade) and the between-subjects contrast of group (at-risk, control), accuracy and reaction times in the morphological awareness task were examined with 2 x 2 repeated measures ANOVAs in IBM SPSS (see section 3.6). Finally, we compared with cluster-based permutation tests the developmental brain differences within the typically developing group (difference waveform between 16 pre-school typically developing children vs. 16 first grade typically developing children) with each morphological contrast for both real words and pseudowords. The same developmental comparisons were examined within the group at-risk for dyslexia (see section 3.7).

3. Results

3.1. *Behavioral performance in the morphological task during MEG—first-grade children*

The accuracy and reaction times for real words and pseudowords during the morphological (MEG) task are presented in Table 4 for the control and at-risk groups. There were no significant differences in any of the conditions between the groups.

3.2. *Within-group MEG results for real words in the first grade typically developing children*

The strength of the averaged ERFs of the typically developing children (N = 21) differed between the correctly and incorrectly derived real words in all three time windows: 0–300, 300–700, and 700–1100 ms. Table 5 and Fig. 2 show the averaged ERF waveforms.

3.3. *Within-group MEG results for real words in the first grade children at-risk for dyslexia*

The averaged ERFs of the children at-risk for dyslexia (N = 13) differed between the correct and incorrect real words for two time

Table 4

Accuracy and reaction time (RT) results of first grade children (standard deviation [SD] and (% of correct responses) in the morphological awareness task during MEG for correctly and incorrectly derived real words and pseudowords for controls and at-risk children as well as for correctly and incorrectly derived pseudowords for controls and at-risk children.

Real Words			
Accuracy per Group	Typically developing (N = 21)	At-risk (N = 13)	t-values p-values
Correct responses for correctly derived nouns (max. 54)	51 (SD = 2.58) (94.44%)	49.30 (SD = 4.80) (91.31%)	ns
Correct responses for incorrectly derived nouns (max. 54)	51.4 (SD = 2.69) (95.32%)	50.1 (SD = 3.91) (92.87%)	ns
RT per Group	**Typically developing (N = 21)**	**At-risk (N = 13)**	**t-values** **p-values**
RT for correctly derived nouns (ms)	1273.24 (SD = 779.82)	1138.42 (SD = 621.75)	ns
RT for incorrectly derived nouns (ms)	1059.30 (SD = 478.96)	1009.54 (SD = 497.35)	ns
Pseudowords			
Accuracy per Group	**Typically developing (N = 20)**	**At-risk (N = 9)**	**t-values** **p-values**
Correct responses for correctly derived nouns (max. 54)	38.2 (SD = 12.57) (70.74%)	39.66 (SD = 10.55) (73.45%)	ns
Correct responses for incorrectly derived nouns (max. 54)	38 (SD = 9.70) (70.37%)	27.22 (SD = 13.33) (50.41%)	ns
RT per Group	**Typically developing (N = 20)**	**At-risk (N = 9)**	**t-values, p-values**
RT for correctly derived nouns (ms)	1893.25.07 (SD = 1249.99)	1804.87 (SD = 883.10)	ns
RT for incorrectly derived nouns (ms)	1892.33 (SD = 1174.77)	1755.40 (SD = 532.39)	ns

Table 5

Summary of the channel level (combined gradiometers) cluster-based permutation statistics for the typically developing group (N = 21): the time window for each cluster-based permutation test analysis, the cluster range in time and the cluster's time point of maximum difference, the p-value for the cluster, and the direction of the response (>indicating stronger field strength). The cluster location was based on the sensor's location. Correct = Correctly derived stimuli; Incorrect = Incorrectly derived stimuli; Max. = Maximum.

Time window for analysis	Time window for cluster, cluster range	cluster p-value	Direction	Cluster's location
0–300 ms	14–141 ms (max. 76 ms)	0.000***	Incorrect > Correct	right fronto-temporal region
	51–106 ms (max. 87 ms)	0.001**	Incorrect > Correct	left temporal region
	266–300 ms (max. 281 ms)	0.03*	Incorrect > Correct	left occipito-temporal region
300–700 ms	381–406 ms (max. 392 ms)	0.0003***	Incorrect > Correct	left temporo-parietal region
	472–555 ms (max. 520 ms)	0.0006**	Incorrect > Correct	left frontal and right parietal region
	451–622 ms (max. 573 ms)	0.000***	Incorrect > Correct	left temporal region
	633–687 ms (max. 657 ms)	0.010*	Incorrect > Correct	right occipital region
700–1100 ms	781–816 ms (max. 795 ms)	0.016*	Incorrect > Correct	left frontoparietal region

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

windows (0–300 and 300–700). Table 6 and Fig. 3 show the averaged ERF waveforms for each time window.

3.4. Within group MEG results for pseudowords separately for typically developing and at-risk for dyslexia children at the first grade

The averaged ERFs of the typically developing children (N = 20) did not significantly differ between the correct and the incorrect pseudowords during any time windows of the analyses after the FDR correction.

The averaged ERFs of the children at-risk (N = 9) differed between the correctly and the incorrectly derived pseudowords in the 300–700 time window. Table 7 and Fig. 4 show the averaged ERF waveforms for each time window.

3.5. Between-group statistical MEG results for real words and pseudowords

For the real words, the ERFs for the correctly and incorrectly derived real words and for the correct vs. incorrect contrast did not differ between the typically developing children and the children at-risk for dyslexia in any time window. Similarly, for the pseudowords, no significant differences between the groups were found.

3.6. Longitudinal statistical behavioral results during MEG recordings

The behavioral performance in the cover task during MEG recordings of the pre-school children (Louleli et al., 2020) was compared with the behavioral performance of the first grade children (27 pre-school and 27 first grade children) (Table 8). The comparisons for the main effect of age (pre-school vs. first grade) showed significant differences in the accuracy of incorrectly derived real words and in the accuracy of correctly derived pseudowords after the FDR correction; in both cases, the first grade children were more accurate than the pre-school children. No significant differences in the participants' accuracy and reaction times were observed in any other condition.

3.7. Longitudinal statistical brain results during MEG recordings

The brain activity responses during MEG recordings of the pre-school children (Louleli et al., 2020) were compared with the brain responses of the first grade children for the difference between correctly vs. incorrectly derived real words and pseudowords. For real words, the brain responses for correct vs. incorrect morphological contrast were significantly different between pre-school and first grade children at 470–611 ms (max. 508 ms, p = .005), in which the pre-school's brain responses were larger than the first grade's responses after FDR correction. No significant differences were observed in any other condition tested (correctly derived real words, incorrectly derived real words, correctly vs. incorrectly derived pseudowords, correctly derived pseudowords and incorrectly derived pseudowords).

4. Discussion

Our study investigated the morphological information processing of children with and without risk for dyslexia while they were attending first grade at school. We measured their brain responses with MEG, while they were performing a morphological awareness task. This is the first study to examine morphological information processing, specifically derivational morphology, in first grade children with MEG (Fig. 5A). Moreover, we tested whether and how morphological information processing changes developmentally by comparing the brain responses of typically developing pre-school children (Louleli et al., 2020) with typically developing first grade children and the brain responses of children at-risk for dyslexia at pre-school (Louleli et al., 2020) with at-risk first grade children.

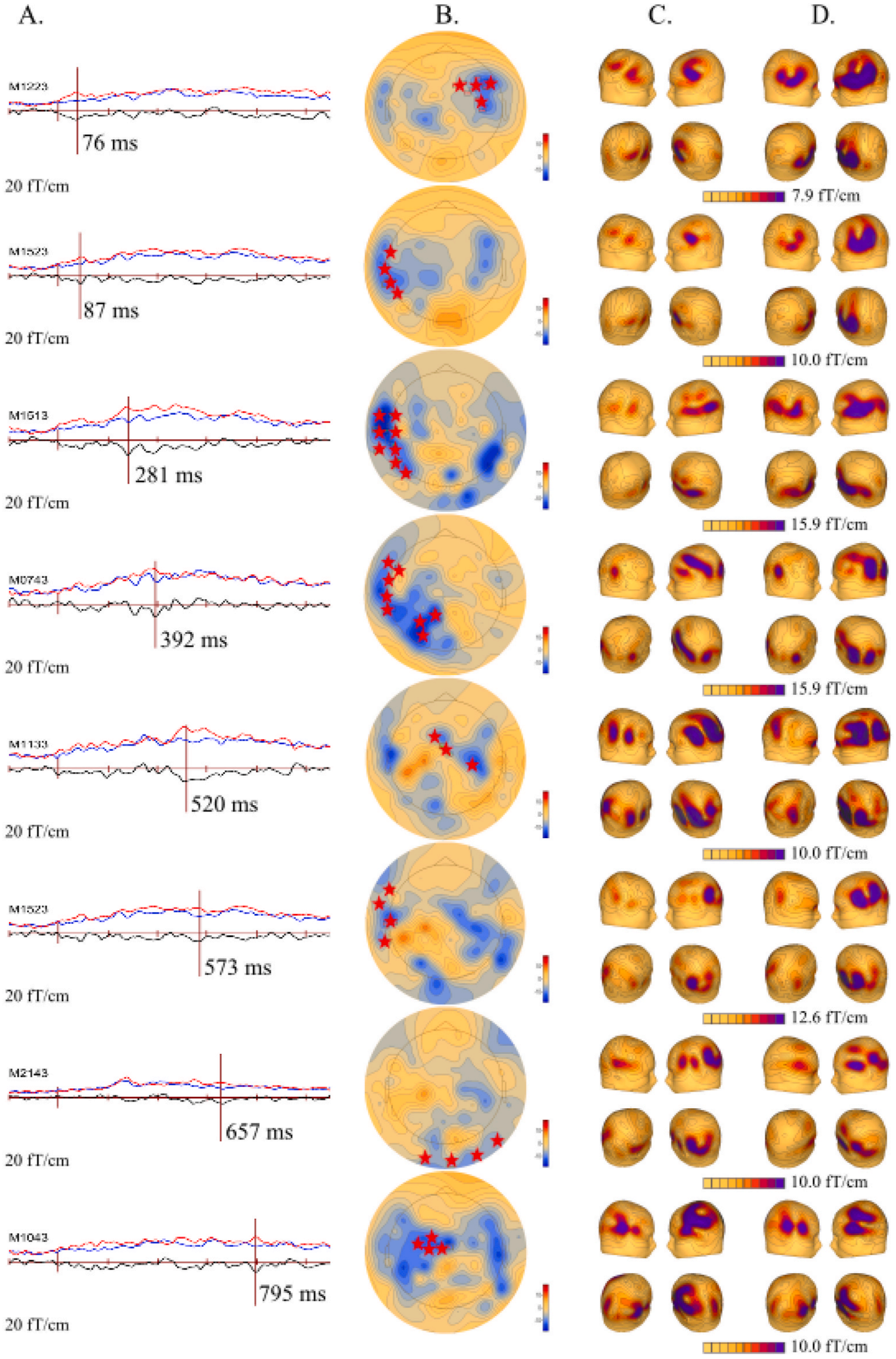

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Fig. 2. Control group (N = 21) **A.** Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns, and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **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 labelled with stars. Blue and red colours indicate the direction of the ERF difference for contrast (negative or positive flux amplitude, −10 fT/cm to 10 fT/cm). **C.** Topography of the distribution of gradient fields for the correctly derived nouns and **D.** for the incorrectly derived nouns represented during the time-points of maximal significant difference in the cluster-based permutation statistics between the responses to the correctly vs. incorrectly derived nouns, indicated by the vertical line.

Table 6
Summary of the channel level (combined gradiometers) cluster-based permutation statistics for the typically developing group (N = 21): the time window for each cluster-based permutation test analysis, the cluster range in time and the cluster's time point of maximum difference, the p-value for the cluster, and the direction of the response (>indicating stronger field strength). The cluster's location was based on the sensor's location. Correct = Correctly derived stimuli; Incorrect = Incorrectly derived stimuli; Max. = Maximum.

Time window for analysis	Time window for cluster, cluster range	cluster p-value	Direction	Cluster's location
0–300 ms	56–86 ms (max. 78 ms)	0.001**	Incorrect > Correct	left fronto-temporal and right frontal region
	160–269 ms (max. 247 ms)	0.008*	Incorrect > Correct	left occipito-temporal region
300–700 ms	372–424 ms (max. 399 ms)	0.0003***	Incorrect > Correct	left frontal, parietal, and temporal region

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

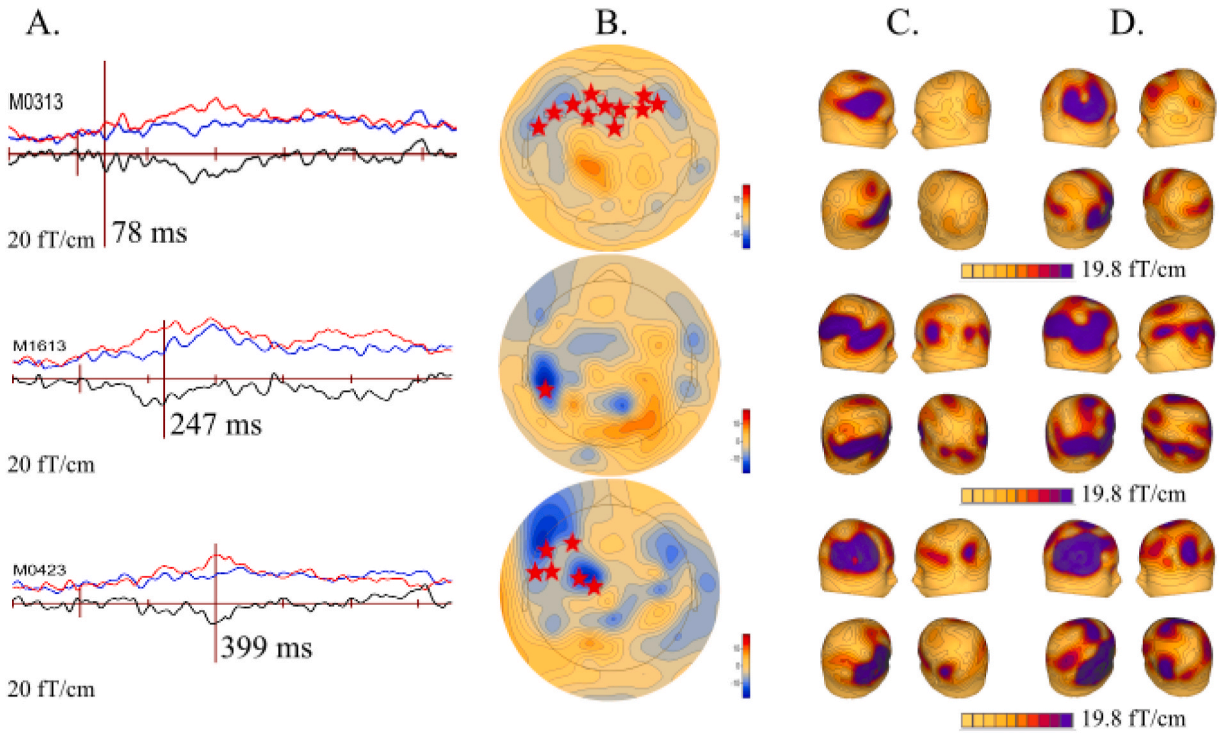

Fig. 3. At-risk group (N = 13) **A.** Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns, and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labelled with stars. Blue and red colours indicate the direction of the ERF difference for contrast (negative or positive flux amplitude, −10 fT/cm to 10 fT/cm). **C.** Topography of the distribution of gradient fields for the correctly derived nouns and **D.** for the incorrectly derived nouns represented during the time-points of maximal significant difference in the cluster-based permutation statistics between the responses to the correctly vs. incorrectly derived nouns, indicated by the vertical line.

4.1. Behavioral results of the morphological task during MEG - first grade children

Our first goal was to investigate whether first grade typically developing children were sensitive to the morphological information for real words and pseudowords. The behavioral results for accuracy and reaction time (RT) performance in the morphological

Table 7
Summary of the channel level (combined gradiometers) cluster-based permutation statistics for the at-risk for dyslexia group (N = 9): the time window for each cluster-based permutation test analysis, the cluster range in time and the cluster's time point of maximum difference, the p-value for the cluster, and the direction of the response (>indicating stronger field strength). The cluster's location was based on the sensor's location. Correct = Correctly derived stimuli; Incorrect = Incorrectly derived stimuli; Max. = Maximum.

Time window for analysis	Time window for cluster, cluster range	cluster p-value	Direction	Cluster's location
300–700 ms	303–355 ms (max. 314 ms)	0.005*	Correct > Incorrect	left parietal, temporal and occipital regions
	542–677 ms (max. 631 ms)	0.017*	Incorrect > Correct	left temporal region

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

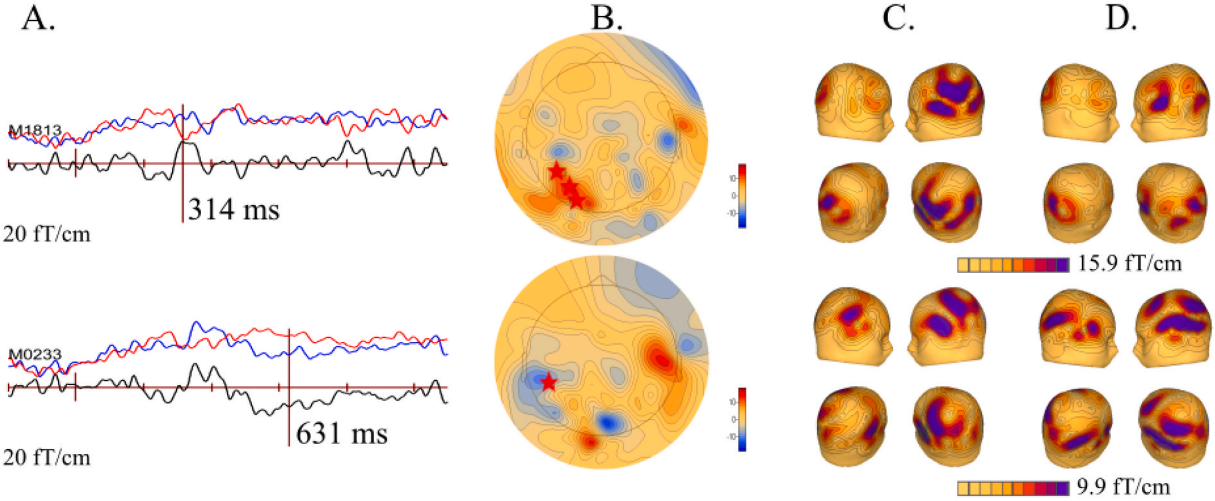

Fig. 4. At-risk group (N = 9) **A.** Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns, and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs for the correct vs. incorrect contrast shown at the time point marked in A. Significant clusters are labelled with stars. Blue and red colours indicate the direction of the ERF difference for contrast (negative or positive flux amplitude, −10 fT/cm to 10 fT/cm). **C.** Topography of the distribution of gradient fields for the correctly derived nouns and **D.** for the incorrectly derived nouns represented during the time-points of maximal significant difference in the cluster-based permutation statistics between the responses to the correctly vs. incorrectly derived nouns, indicated by the vertical line.

awareness task during the MEG recordings for the correctly and the incorrectly derived real words and pseudowords demonstrated no significant differences between the groups for the real words or the pseudowords. These findings are similar to the pre-school findings, where in all the conditions (except the correctly derived words), the groups did not differ (Louleli et al., 2020).

Even though the between-group comparisons (typically developing vs. at-risk for dyslexia children) did not reach significance in most of the conditions in first grade children, there were between-age differences for typically developing first grade and pre-school children for real words; the percentage of correct responses for correctly derived real words changed 3.87%, while for incorrectly derived real words there was a change of 10.39% between pre-school and first grade age (Louleli et al., 2020). The same pattern of different percentages in responses occurred between the first grade and pre-school children at-risk for dyslexia; the percentage of correct responses for correctly derived real words had a 10.55% of change, while for incorrectly derived real words the percentage of change reached a 15.2% (Louleli et al., 2020).

As far as the pseudowords are concerned, there were differences between the typically developing first grade and pre-school children: the percentage of correct responses for correctly derived pseudowords changed over 34.24% between pre-school and first grade (Louleli et al., 2020). Similarly, there was a slight change of 0.77% change in the percentages for the correct responses for incorrectly derived pseudowords (Louleli et al., 2020). These trends in the response patterns led us to explicitly examine longitudinally the differences in the behavioral and brain development between pre-school children and first grade children and specifically to determine how these differences in morphological information processing progress year by year of development (see section 3.6 and 3.7).

4.2. Brain responses of typically developing first grade children for the correctly vs. incorrectly derived real words' contrast

Moreover, our aim was to investigate whether the brain processes of first grade typically developing children showed sensitivity to the morphological information for real words. The neural processing of typically developing first grade children was sensitive to the

Table 8
One-way ANOVA of the participants' behavioral performance in the cover task during MEG recordings for the between-subjects contrasts (N = 27 pre-school children with and without risk vs. 27 first-grade children with and without risk).

	27 pre-school children			27 first grade children			Between groups
Behavioral assessments in MEG	N (participants)	Mean (SD)	Range	N (participants)	Mean (SD)	Range	F(df) values, p values
Accuracy for correctly derived real words	27	87.16 (10.25)	53.70–100	27	92.44 (7.33)	66.66–100	F(1) = 4.734 p = .034
Accuracy for incorrectly derived real words	27	81.47 (25.09)	0–98.14	27	94.78 (5.38)	81.48–100	**F(1) = 7.255 p = .009***
Reaction times for correctly derived real words	27	1532.60 (1517.29)	557.55–8847.85	27	1198.90 (726.69)	548.33–4049.53	F(1) = 1.062 p = .307
Reaction times for incorrectly derived real words	27	1148.92 (496.60)	456.66–3038.25	27	988.36 (393.08)	472.33–2374.07	F(1) = 1.735 p = .194
Accuracy for correctly derived pseudowords	24	44.90 (26.89)	0–87.03	24	70.90 (18.59)	38.88–98.14	**F(1) = 15.177 p = .000***
Accuracy for incorrectly derived pseudowords	24	71.29 (22.26)	20.37–100	27	63.23 (20.13)	25.92–94.44	F(1) = 1.844 p = .181
Reaction times for correctly derived pseudowords	24	1384.95 (657.74)	505.12–2895.85	25	1872.45 (1214.46)	61.11–5660.44	F(1) = 3.016 p = .089
Reaction times for incorrectly derived pseudowords	24	1337.96 (689.38)	411.96–2663.40	27	1802.72 (985.28)	482.79–5163.75	F(1) = 3.718 p = .060

Note: Accuracy performance is presented in percentages and Reaction time performance is presented in milliseconds.

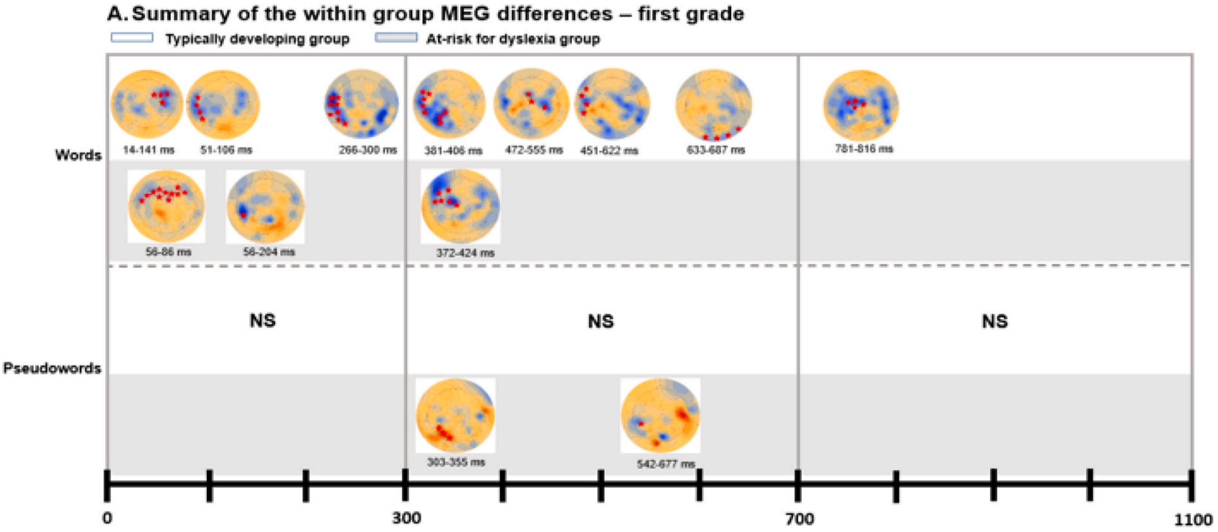

Fig. 5. Summary of the within-group differences of the cluster-based permutation statistics for the correct vs. incorrect morphological derivation per group (In white: typically developing children and in gray: at-risk for dyslexia children) per time-window (0–300, 300–700, and 700–1,100 ms) separately for reals words and pseudowords.

morphological information processing in all the time windows of the analyses; they showed significant differences between the correctly and the incorrectly derived real words in the first analysis time window (0–300 ms) at ca. 10–150 ms and at 250–300 ms, in the middle time window (300–700 ms) at ca. 400 ms and around ca. 600 ms, and in the late time window (700–1100 ms) at ca. 780–820 ms. The correctness of the morphological ending was defined with an approximately 100-ms delay, as the suffix/-jA/was used as the trigger point as a clearly identifiable syllable that is the same for each stimulus. In our results, this affected the timing of the effects of interest.

We speculate that the early brain responses (before 300 ms, ca 400 ms from detectable difference in stimuli) operate as an outcome of top-down processes in the brain emerging for the real words, building on the long-term phonetic/phonological representations that have already been formulated in the young brain (Kuhl, 2004; Werker & Yeung, 2005). A significant difference between the correctly vs. the incorrectly derived words emerged in the first time window at ca. 280 ms in the left occipito-temporal region. The difference found in the current study for first grade children, was previously observed in pre-school children; both pre-school and first grade children had stronger ERFs for the incorrectly derived real words, similar timing of activation, but different topography; in pre-school children the differences emerged in the left-occipitotemporal region, while in first grade children the difference was seen in the left fronto-temporal region. This difference reflects morpho-syntactic processes in the brain, as the children had to judge whether the auditorily presented pair of sentences were correctly derived or not. Furthermore, Leminen et al. (2010) showed activation at a similar time window when testing the brain responses of Finnish adults on a lexical decision task with correctly derived and incorrectly derived words. These early brain responses indicate that the morphological information processes are already present at pre-school age and remain similar in terms of timing at first grade and possibly even adulthood. Interestingly, the shift in location from the occipito-temporal to the fronto-temporal areas between pre-school and first grade may indicate developmental changes in the specific neurocognitive mechanisms that are utilized for morphological decisions.

Significant differences for the correctly vs. incorrectly derived morphological contrast also occurred in the 300–700 ms time window of the analyses; in all the cases, the responses were larger for the incorrectly derived words than correctly derived words. This time window is clearly in line with the classical N400 response, previously found at ca. 250–500 ms (Kutas & Federmeier, 2011). The classical N400 response has been found to emerge with semantically incongruent endings, mainly due to the difficulty in integrating the meaning of an anomalous word (i.e., incorrectly derived) in accordance with the context of a sentence (Kutas & Federmeier, 2011). The enhanced activation in this time window (300–700 ms) 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) or during the visual detection of lexical inconsistencies (Leinonen et al., 2008; Morris et al., 2011, 2013; Lavric et al., 2007; Smolka et al., 2015). It is noteworthy that the processing of semantic information has been found to take place around the same time in early-school-aged children as in adults (Nora et al., 2017), even though the brain responses of pre-school children deviate from those in adult brain activation in temporal distribution and for auditory information (Parviainen et al., 2011, 2019; Ponton et al., 2000). In general, this time window seems to relate to the processing of lexico-semantic information in children (cf. Friederici, 2005), and our novel findings reveal the neuronal time course of processing more specific linguistic information (Finnish derivational morphology) in first-grade children. In the current study as well as in our previous study we showed that this time window is sensitive to derivational morphology both in first grade children and pre-school children (Louleli et al., 2020).

Enhanced brain activation for incorrectly derived words also emerged at ca. 520 ms, at ca. 570 ms, and at ca. 650 ms, which was in accordance with the previously identified P600 response, which challenged syntactic processing (Friederici, 2002; Friederici & Weissenborn, 2007). The P600 response has been found to emerge earlier in timing, at ~500–750 ms, when syntactic integration is difficult (Kaan et al., 2000) and later at ~750–1000 ms, when the subject engages in reanalysis/repair processes (Friederici et al., 2002; Molinaro et al., 2008, 2011). Interestingly, first grade children showed significant effects in brain activation, not only in the time window depicting the early P600 response (ca. 520, at ca. 570, and at ca. 650 ms) but also in the later time window, at ca. 800 ms, depicting the late P600 response. Therefore, the typically developing first grade children were found to engage in both early and late P600 processes. This observation possibly means that first-grade children not only evidence (the expected) challenges with syntactic integration processes but are also capable of engaging themselves in the reanalysis/repair process of the anomalous stimuli. These results show developmental brain differences; the first grade children seem to have developed more automatic linguistic processes compared to the pre-school children, who might have slower and less automatic linguistic processes due to their young age and lack of formal training. Overall, the current findings demonstrate at the brain level that 7.5–8-year-old typically developing first grade children showed sensitivity to the morphological information about the correctly vs. incorrectly derived words of their language, which were somewhat more advanced and automatic compared to their pre-school age performance.

4.3. Brain responses of first grade children with familial risk for dyslexia for the correctly vs. incorrectly derived real words' contrast

Our second goal was to investigate the brain responses of first grade children with familial risk for dyslexia in morphological information processing for real words. The ERFs of first grade children at risk for dyslexia showed comparable time windows with the control group of children for the sensitivity to morphological information, evidenced at ca. 60–90 ms, at ca. 160–270 ms, and at ca. 400 ms. The significant differences for the correctly vs. incorrectly derived contrast were observed in the first time window at ca. 60–90 ms in the left fronto-temporal and right frontal region and at ca. 160–270 ms in the left occipito-temporal region. Differences were found in the typically developing children at a similar time window but a bit earlier in time. Moreover, differences in the first time window were also observed in our previous study (Louleli et al., 2020) having similar timing and topography of activation. In general, the brain differences found in pre-school and in first grade children could indicate the existence of well-structured/well-developed phonological representations in the brain for native real words (Kuhl, 2004; Werker & Yeung, 2005). However, it should be noted that cluster-based permutation tests have limitations in estimating time points and cluster topographies precisely (Sassenhagen & Draschkow, 2019), so the small temporal and spectral differences between groups cannot be determined with certainty.

Additionally, a significant brain difference for the correct vs. incorrect morphological contrast was observed in the middle time window at ca. 400 ms in a quite wide region, including the left frontal, parietal, and temporal regions, being larger for the incorrectly derived nouns. The differences at ca. 400 ms (in fact, at ca. 500 ms, where the correctness of the morphological ending takes place starting from the preceding vowel and the beginning of the suffix/-jA/) seemed to happen across a similar time window with those of the typically developing group. This time window most likely reflects the lexico-semantic N400 type of process (Kutas & Federmeier, 2011), which was also found in the typically developing children. The findings for typically developing children and children at risk for dyslexia were similar in terms of the timing of activation but not in topography. In typically developing children, the differences emerged in the left temporo-parietal region, with larger responses for the incorrectly derived nouns, while in children at-risk for dyslexia the difference was seen in the left frontal, parietal, and temporal regions, also with larger responses for the incorrectly derived nouns. These results suggest that both groups exhibited somewhat different response patterns to the morphological contrast for the real words, even though these between-group differences did not manifest themselves when directly comparing the two groups (see section 3.5).

4.4. Brain responses of first grade children for the correctly vs. incorrectly derived pseudowords' contrast

Our third aim was to examine the morphological information processing in first grade children with and without risk for dyslexia by testing the correctly vs. incorrectly morphological contrast in pseudowords. The first grade children with typical development were able to recognize and differentiate the correctly and the incorrectly derived pseudowords when tested behaviorally. However, after testing the brain responses for the difference between the correctly vs. the incorrectly derived pseudowords with cluster-based permutation statistics, this difference (previously seen behaviorally) did not survive the FDR correction for typically developing children. This suggests that 7.5–8-year-old children with typical development have acquired the ability to differentiate the correct vs. incorrect contrast for derivations, but we were unable to indicate the corresponding sensitivity in the brain. This may be due to the fairly small number of participants and therefore lack of power in detecting the brain-level effect in ERFs, but it could also be that a different neural process, such as a change in connectivity pattern, underlies the behavioral effect.

Differences between the correctly vs. the incorrectly derived pseudowords were also tested for the first grade children with familial risk for dyslexia. Interestingly, for children with familial risk for dyslexia, the brain responses were sensitive to the difference between the correctly and the incorrectly derived pseudowords. Specifically, their brain responses were sensitive to the difference of the morphological pseudo-nouns only in the 300–700 ms time window of the analyses at ca. 300–350 ms in a wide network of the left hemisphere, including the left parietal, temporal, and occipital regions, with larger responses for the correctly derived stimuli and at 540–680 ms in the left temporal region, with more enhanced responses for the incorrectly derived stimuli. The early effect at ca. 300–350 ms could result from an attempt at lexical access and lexical processing when the brain has to process potential words, in our case the pseudowords that were created in accordance with the rules of Finnish language, which is why the responses were more enhanced for the correctly derived pseudowords. It is somewhat surprising that only the at-risk children showed sensitivity in the brain for the morphological contrast of the correctly vs. the incorrectly derived pseudowords. However, this might reflect the relatively limited vocabulary evident in children with less efficient reading skills. Therefore, for readers with familial risk for dyslexia, pseudowords could engage a fairly similar chain of processes in the brain in comparison to real words, as hinted by the above result on lexical access, whereas in fluent readers the processing of real words is more efficiently separated from pseudowords, and the specific task in the present study does not require the entire lexical processing pathway. In other words, the specific linguistic elements (such as derivational morphology) are better distinguishable as separate skills within language in fluent readers. The at-risk children might need to activate the entire lexical ("like pseudowords would be real words") regime for performing the task.

4.5. Between group differences during the first grade

Furthermore, we aimed to investigate whether the group with familial risk for developmental dyslexia showed differential processing of morphological information compared to the typically developing group during the first year of literacy education. Similar to the pre-school children with and without familial risk for dyslexia (Louleli et al., 2020), no significant brain differences were found when directly comparing the two groups (typically developing vs. children at-risk for dyslexia) for the contrast of the correctly vs. the incorrectly derived words or pseudowords. Furthermore, no differences between the groups were found when testing the ERFs separately for the correct and incorrect derivations, neither for real words nor for pseudowords. This might be due to the small number of participants, especially in the at-risk group, and consequently a lack of power in detecting the brain-level differences in ERFs. It is noteworthy that some differences existed in the brain responses in the within-group analyses, but this pattern needs to be confirmed with bigger samples.

Interestingly, a study by Ramus and Szenkovits (2008) testing phonological representations of dyslexic individuals found out that dyslexics' phonological grammar was intact; then, they proposed that dyslexic individuals could have impairments in their ability to consciously manipulate phonological representations, which is a crucial mechanism for typical reading acquisition by assigning relationships between symbols and sounds (Ramus & Szenkovits, 2008). In light of this work, differences between groups in the morphological task were not found, either because of the nature of the task (measures judgements about the correctness of morphophonology) or because the cluster-based permutation tests are rather conservative and fail to be sensitive to small differences. At any rate, brain level differences of morphological processing between the groups are at best weak.

4.6. Longitudinal behavioral differences between pre-school and first grade children

Additionally, our aim was to determine if the relationship between morphological information processing changed over time from kindergarten to first grade in children with and without familial risk for dyslexia. First, we tested this by comparing longitudinally the behavioral performance in the MEG cover task in the same children between pre-school measurement (Louleli et al., 2020) and first grade measurement after one year of literacy education (see section 3.6). Second, we tested this by comparing the brain changes across these time points via cluster-based permutation statistics for the between-group differences (see section 3.7). For the behavioral performance, the children at first grade were able to identify and differentiate more accurately the incorrectly derived real words and the correctly derived pseudowords compared to the pre-school children.

4.7. Longitudinal brain differences between pre-school and first grade children

Our final goal was to examine whether morphological information processing changes from the pre-school and pre-reading stage to the first grade in children with and without familial risk for dyslexia. We tested this by comparing longitudinally the brain responses of children tested at pre-school age (Louleli et al., 2020) and then at first grade age after one year of literacy education (section 3.7).

For the developmental brain comparisons, we compared the brain responses of pre-school and first grade children for the correctly derived real words and pseudowords, the incorrectly derived real words and pseudowords and the difference of the correct vs. incorrect morphological contrast for real words and pseudowords. A significant difference was found between pre-school and first grade children at 508 ms in the right temporal, frontal and parietal region; pre-school brain responses were larger than the first grade responses after FDR correction. There were no other significant differences in any other of the conditions tested (correctly derived real words, incorrectly derived real words, correctly vs. incorrectly derived pseudowords, correctly derived pseudowords and incorrectly derived pseudowords). These results clearly indicate developmental brain differences: the children at first grade age seem to have developed more automatic morphological information processing compared to their pre-school age, when they were younger, had less linguistic experience, and had had no literacy education (Louleli et al., 2020).

4.8. Limitations

Overall, our study brings new insights about morphological information processing, specifically of first grade children and developmentally between pre-school and early readers, yet it has some limitations. First, the morphological awareness task used naturally produced stimuli that are closer to reality during speech perception processing, but they could be slightly different in their acoustic features in each sentence, producing less clear ERF responses compared to, for example, sinusoidal tones, although the sentences were carefully counterbalanced to reduce such effects. Second, due to the slight variability in length and the acoustic features per stimuli, the suffix/-jA/was nevertheless used as the trigger point it is a clearly identifiable syllable that was the same for each stimulus, even though the correctness of the morphological ending was defined from the vowel before the suffix/-jA/. This affected the timing of the effects of interest with an approximately 100 ms delay compared to earlier studies. Third, similar to our previous study (Louleli et al., 2020), all the participants' responses (correct and incorrect) during the MEG morphological task were included for the ERF analysis because of the low number of stimuli per condition; however, the use of all the responses gave the ERF analyses a better signal-to-noise ratio for the examination of brain responses reflecting the automatic processing of derivational morphology. Moreover, the small number of participants is not ideal, especially for developmental group comparisons, but future studies could use our results as a basis for the examination of brain activity reflecting the processing of derivational morphology.

5. Summary and conclusions

In summary, our results suggest that early readers with low risk for developmental dyslexia and early readers with high risk for developmental dyslexia are both capable of identifying correctly and incorrectly derived words and pseudowords of their language and thus seem to have acquired an awareness of derivational morphology. No significant differences were observed between the groups at the behavioral level. For the brain responses, the direct group comparison did not reveal any significant between-group differences. The longitudinal within-group comparison showed important developmental changes in the processing of derivational morphology from pre-school to school age both on the behavioral and the brain levels. It seems that the pre-school age is a period where morphological information processing is still immature and under progress, whereas the first grade age seems to have developed further in identifying the anomalous/incongruent lexico-semantic manipulations in real words, even in children at-risk for dyslexia. Our study demonstrates that it is feasible to approach the neural underpinnings of specific neurolinguistic aspects of language development, namely derivational morphology, already in the early school years, using both longitudinal within-group settings and between-group comparisons. Studies with larger sample sizes in these challenging age ranges are needed to disentangle the significance of morphological information processing, especially for young children with and without familial risk for developmental dyslexia.

Funding

This research study was supported by the EU project PredictAble for "Understanding and predicting developmental language abilities and disorders in multilingual Europe" (Horizon2020 Marie-Sklodowska-Curie Actions (MSCA) Innovative Training Network (ITN) - European Training Network (ETN) (grant agreement, no. 641858) and the Department of Psychology, University of Jyväskylä.

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Declaration of competing interest

None.

Acknowledgments

The authors would like to thank Annastiina Kettunen for her help with creating and recording the stimuli and Katja Koskialho, Ainomaija Laitinen, Sonja Tiri, and Maria Vesterinen for assisting with the data collection.

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