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Natalia Louleli

Brain Responses to Morphological Processing at Pre-School and First Grade in Children with and without Familial Risk for Dyslexia

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF EDUCATION AND
PSYCHOLOGY

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ABSTRACT

Louleli Natalia
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Typical reading acquisition requires converting written forms (orthography) into a spoken language (phonology) and the ability to manipulate efficiently the smallest meaningful units of language, the morphemes. Dyslexia or difficulties in the acquisition of reading and writing skills, prevent typical reading acquisition and development. Dyslexia is heritable within families; thus, a history of dyslexia within a family could lead to higher chances of the progenies inheriting dyslexia themselves. This dissertation investigates longitudinally the pre-reading linguistic skills of children with and without familial risk for dyslexia. The goal of this dissertation is to investigate language-related processes to correct vs. incorrect morphological constructs in real words and pseudowords, as seen at the brain and behavioral level. Hence, we used magnetoencephalography (MEG) to measure the brain responses of Finnish pre-school (Study I) and first-grade children (Study II) to correctly and incorrectly derived Finnish nouns and pseudo nouns. Additionally, we longitudinally compared the morphological information processing of children at pre-school age (Study I) and later at first grade age (Study II). Then, we aimed to examine how derivational morphology in the Finnish language, concomitant accuracy and reaction times are associated with reading skills in first grade, in addition to the pre-school age reading-related cognitive skills (Study III). Results of Study I showed that both groups of children with and without risk for dyslexia acquired derivational morphology skills, as revealed at the behavioral and brain level, but no differences were observed between the groups with different risk profiles. Results of Study II demonstrated that typically developing children showed sensitivity to morphologically correct vs. incorrect contrast only for real words, while children at-risk for dyslexia showed sensitivity to morphological information processing both for real words and pseudowords. Yet, no significant differences emerged between the two groups. Moreover, Study II revealed significant developmental differences as seen in the behavioral and brain domain when comparing children at pre-school age with children at first grade age for the morphological processing of real words and pseudowords. Last, results of Study III replicated earlier findings; various pre-school cognitive skills were correlated with various first grade cognitive skills. In addition, pre-school children's reaction time for correctly derived words was correlated with first-grade children's performance in rapid automatized naming for letters. However, there were no significant correlations between brain activation or behavioral measures of morphological processing and first-grade reading skills. Overall, the findings of this dissertation showed the developmental changes of derivational morphology over time and that derivational morphology, even if it is acquired at pre-school age, does not seem to greatly influence reading acquisition. Further studies are still needed to compare, for example, inflectional and derivational morphology skills in children.

Keywords: morphological processing, derivational morphology, pre-school children, first grade children, risk for dyslexia, magnetoencephalography, reading

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Louleli Natalia
Morfologiseen prosessointiin liittyvät aivojen herätevasteet esikoulua ja ensimmäistä luokkaa käyvillä lapsilla, joista osalla on perinnöllinen lukivaikeusriski
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Lukemaan oppiminen edellyttää kirjoitettujen muotojen (ortografia) muuntamista puhutuksi kieleksi (fonologia) sekä kykyä käsitellä tehokkaasti kielen pienimpiä merkitysyksiköitä eli morfeemeja. Dysleksia eli lukivaikeus kuitenkin hankaloittaa tavanomaisen luku- ja kirjoitustaidon oppimista ja kehittymistä. Lukivaikeuden perinnöllisyydestä johtuen lapsella on suurempi riski saada se, jos sitä on esiintynyt sukulaisilla. Tätä väitöskirjaa varten selvitettiin pitkittäistutkimuksen avulla lukutaitoa edeltäviä kielellisiä valmiuksia lapsilla, joilla on perinnöllinen lukivaikeusriski ja toisaalta lapsilla, joilla tätä riskiä ei ole. Tavoitteena oli tutkia kieleen liittyviä prosesseja suhteessa oikeisiin vs. vääriin morfologisiin rakenteisiin aidoissa sanoissa ja keksityissä pseudosanoissa siten, kuin ne näkyvät aivo- ja käytöstasolla. Tähän käytimme aivomagneettikäyrää (MEG), jolla mitattiin suomalaisten esikoululaisten (tutkimus I) ja peruskoulun ensimmäisen luokan oppilaiden (tutkimus II) aivojen herätevasteita oikein ja väärin johdettuihin suomen substantiiveihin sekä pseudosubstantiiveihin. Lisäksi vertasimme keskenään pitkittäistutkimuksella esikoulua ja myöhemmin ensimmäistä luokkaa käyvien lasten morfologista tiedonkäsittelyä (tutkimus II). Pyrimme myös selvittämään, miten suomen johtomorfologia sekä siihen liittyvät reaktioajat ja virheettömyys ovat yhteydessä lukutaitoon ensimmäisellä luokalla samoin kuin lukemiseen liittyviin kognitiivisiin taitoihin esikouluiässä (tutkimus III). Tutkimuksen I tulokset osoittivat sekä lukivaikeusriskiryhmän että kontrolliryhmän oppineen johtomorfologisia taitoja, mikä näkyi käytös- ja aivotasolla, mutta eroja ei havaittu eri riskiprofiilit omaavien ryhmien välillä. Tutkimuksen II perusteella tyypillisesti kehittyvät lapset osoittivat herkkyyttä morfologisesti oikean vs. väärän kontrastille vain, kun kyseessä olivat aidot sanat. Lukivaikeusriskiryhmän lapset sen sijaan osoittivat herkkyyttä sekä aitojen että pseudosanojen morfologisen informaation prosessoinnille. Ryhmien välillä ei kuitenkaan ollut merkitseviä eroja. Lisäksi tutkimus II toi esiin merkitseviä käytös- ja aivotason kehityseroja verrattaessa esikouluikäisiä vuotta vanhempiin siinä, kuinka he prosessoivat aitoja ja pseudosanoja morfologisesti. Tutkimuksen III tulokset vastasivat aiempia tuloksia; useat esikoululaisten kognitiiviset taidot korreloivat ensimmäisen luokan oppilaiden kognitiivisten taitojen kanssa. Myös esikouluikäisten lasten reaktioaika oikein johdettuihin sanoihin oli yhteydessä vuotta vanhempien lasten suoriutumista kirjainten nopeassa sarjallisessa nimeämisessä. Merkitseviä korrelaatioita ei kuitenkaan löytynyt morfologiseen prosessointiin liittyvän aivojen aktivaation tai käytösmittausten ja ensimmäisen luokan lukutaidon välillä. Kaiken kaikkiaan tulokset toivat esiin johtomorfologisen kehityksen muutoksia ajan kuluessa sekä sen, että johtomorfologialla – vaikka sitä opittaisi esikouluiässä – ei näytä olevan suurta merkitystä lukemaan oppimiselle. Tarvitaan lisätutkimuksia, joissa vertaillaan lasten taivutus- ja johtomorfologisia taitoja.

Asiasanat: morfologinen prosessointi, johtomorfologia, esikouluikäiset lapset, peruskoulun ensimmäisen luokan oppilaat, lukihäiriöriski, magnetoenkefalografia, lukeminen

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Jyväskylä, 14/06/2021
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LIST OF ORIGINAL PUBLICATIONS

The dissertation is based on the following original publications:

I. Louleli, N., Hämäläinen, J. A., Nieminen, L., Parviainen, T., & Leppänen, P. H. T., (2020). Dynamics of morphological processing in pre-school children with and without familial risk for dyslexia. *Journal of Neurolinguistics, 56*. https://doi.org/10.1016/j.jneuroling.2020.100931.

II. Louleli, N., Hämäläinen, J. A., Nieminen, L., Parviainen, T., & Leppänen, P. H. T., (2021). Neural correlates of morphological processing and its development from pre-school to the first grade in children with and without familial risk for dyslexia. Submitted manuscript.

III. Louleli, N., Hämäläinen, J. A., & Leppänen, P. H. T., (2021). Behavioral and brain measures of morphological processing in children with and without familial risk for dyslexia from pre-school to first grade. *Frontiers in Communication*. https://doi.org/10.3389/fcomm.2021.655402.

For Studies I, II, and III, the author of the doctoral dissertation considered the instructions given and the comments made by all the co-authors and contributed to the original publications as follows: she designed the experiment and the stimuli, collected the MEG data, conducted the data analyses, wrote the manuscripts of the three articles, and contributed to the review process.

FIGURES

TABLES

CONTENTS

ORIGINAL PAPERS

1 INTRODUCTION

1.1 Typical reading acquisition

Reading acquisition is a continuous developmental process that is quite complex; however, unlike language acquisition, it is not an innate skill in the human brain. Reading is a cultural invention whose roots go thousands of years back in time. In all societies, teaching young children how to read (reading acquisition) and how to use reading for learning (reading development) have been the core objectives of formal literacy education. The majority of people start to acquire pre-reading skills quite early, usually at kindergarten or pre-school age, shortly before the initial start of literacy education at school.

Learning to read requires the capability to connect arbitrary graphic forms (graphemes) of a specific writing system with the phonological and morphological units (phonemic/phonological and morphological awareness) of a language. Thus, successful reading skills require successful conversion of written forms (orthography) into spoken language and successful manipulation of the smallest units of language containing grammatical or semantic meaning—the morphemes (morphological awareness) (Kuo & Anderson, 2006). In the early phases of reading acquisition, the transparency of correspondence between phonology and orthography significantly affect reading acquisition. The relationship between phonology and orthography varies within languages; for example, some orthographies have consistent grapheme–phoneme associations (shallow orthographies: Finnish, Greek, Spanish, Italian), while other orthographies have more inconsistent grapheme to phoneme mappings (deep orthographies: English, French, Danish) (Seymour et al., 2003; Ziegler et al., 2010). In general, the development of learning to read diverges for children mastering different linguistic systems (Seymour et al., 2003).

Successful learning of the correspondences between graphemes (letters) and phonemes (sounds) is vital for learning to read in transparent languages and Finnish. Finnish language is a non-Indo-European language with approximately six million native speakers, and it belongs to the Uralic language family. Finnish language has an alphabetic writing system, and it is an almost fully transparent language with shallow orthography, where each letter corresponds to one phonemic sound (Aro, 2017; Lyytinen et al., 2015; Seymour et al., 2003). Despite its easy phonological system, the Finnish language owns a quite complex morphological system; Finnish is characterized by its rich inflectional and derivational morphology; a high amount of nominals (nouns, adjectives, pronouns, and numerals) are produced by derivational operations (Kiefer & Laakso, 2014). Children can learn accurately how to read in Finnish quite fast after one year of formal reading instruction (Lerkkanen et al., 2004; Soodla et al., 2015).

The overarching goal of this dissertation is to examine the pre-reading linguistic skills of children with familial risk for reading disorders, especially morphological processing skills. This is achieved by observing modulations of brain activity to correct and incorrect morphological constructs. More specifically, the impact of correctness (correct vs. incorrect derived words), the impact of early morphological skills (morphological development in pre-school and first grade children) and the impact of familial profile (children with and without risk for dyslexia) are examined. The secondary overarching goal is to examine longitudinally how morphological processing skills and brain activity develop/change by age (from pre-school to first grade). The third overarching goal is to link the familial risk factors with the cognitive and brain data and to examine how the familial risk factors for dyslexia detected at pre-school age, can affect reading performance after one year at school in children with and without familial risk for dyslexia.

The knowledge gained about brain responses to derivational morphology measured longitudinally by following children's reading skills development over time has practical importance; first, it can help us to pick apart developmental time courses that are not visible in behavioral data. Second, it can help us to identify a brain-basis for well-targeted interventions, which require deep understanding of the underlying deficits. Also, identifying differences between developmental deviance and developmental delay can help in the early identification of children at-risk for reading difficulties. Thus, development of well-targeted training programs for the field of special education focusing on children at-risk for reading problems would prevent exclusion and dropout track from school.

1.2 Language development

The acquisition of language involves the development of sophisticated cognitive skills. The acquisition of phonetic and phonological representations of a language is one of the infants' initial steps in language acquisition. Within weeks after birth, infants can display phonetic level discriminations, which by age becomes more language-specific (Werker & Hensch, 2015), and within months after birth, infants can identify better native phonetic units compared to non-native units (speech perception) (Kuhl, 2004; Werker & Yeung, 2005). By their first year of age, infants possess a significant number of words stored in their lexicon (Swingley & Aslin, 2007), and toddlers gradually start to produce words (speech production); the words that toddlers usually produce first are nouns relative to concrete objects or other everyday words, then they start to produce grammatical terms (Marjanovič-Umek et al., 2013; Papaeliou & Rescorla, 2011).

Thereafter, young children progressively develop morphological awareness. Their morphological awareness skills are constructed based on the morpho-phonological representations of their language, and the children are using them as a rule-based mechanism to succeed in language-related functions, such as the ability to correctly inflect words (Jessen et al., 2017; Lyytinen & Lyytinen, 2004) or the ability to differentiate correctly and incorrectly derived words and pseudowords (Louleli et al., 2020). Finally, children can handle complex morphosyntactic processes happening at the sentence level (Cantiani et al., 2013; Cantiani et., al 2013b; Rispens et al., 2006).

1.3 Morphological information processing

Morphological awareness contains implicit knowledge about how to associate the phonemic structures with the meaning of morphemes, and how to discriminate, identify, and manipulate morphemes within a word (Kuo & Anderson, 2006). Morphemes are the smallest components of each linguistic system that include meaning; they are involved in three morphological processes: inflection, derivation, and compounding.

Morphological awareness starts very early in life. Ladanyi and colleagues (2020) investigated behaviorally with the head-turn preference paradigm infants' skills related to early morphological processing. Specifically, they found that 15-month-old infants could decompose a word into its constituents (stem and suffix) in Hungarian, only when the words involved highly frequent suffixes (Ladanyi et al, 2020). This is a very early indication of how morphological awareness starts to develop gradually from infancy (Ladanyi et al., 2020).

Another study investigating the relationship between morphological awareness and reading development has shown that morphological awareness (derivational and inflectional morphology) is well acquired before formal reading instruction, but it requires a long developmental process (Casalis & Louis-Alexandre, 2000). Specifically, Casalis and Louis-Alexandre (2000) tested French-speaking children from kindergarten to second grade with behavioral morphological awareness tasks, including five subtests for derivations and four subtests for inflections. The researchers showed that children’s performance increased from kindergarten to first grade and from first grade to second grade, elaborating that morphological awareness increases with age (Casalis & Louis-Alexandre, 2000).

1.3.1 Inflectional morphology

Inflectional morphology is a morphological process utilized for the alteration of grammatical information in a word stem, such as number, gender, and tense (e.g., English plural number [boy-s]; English past tense [open-ed]; Spanish gender [enfermer-a "nurse"]). In some languages, inflections are used to form nouns with distinct cases (Greek: genitive case is applied to express possession, i.e., "to vivlio tou matheetee", "the book of the student"), and adjectives agree with the nouns that they modify (Spanish: "la rosa blanca" = the red rose) (Kuo & Anderson, 2006). The inflectional morphemes lack the ability to change the class of a word, and usually, they can be attached to every word of the same grammatical class. Awareness of inflectional morphology has been studied in adults with event-related potentials (ERPs) (Leminen et al., 2014; Newman et al., 2007; Rastle et al., 2015; Regel et al., 2017), event-related fields (ERFs) (Leminen et al., 2011; Vartiainen et al., 2009), and fMRI studies (Bozic et al., 2015; Lehtonen et al., 2006; Lehtonen et al., 2009).

The majority of ERP studies have used paradigms assessing violations of inflectional morphology (violated verbal and plural inflections, violations on formation of past tenses). Results of adults' ERP studies on inflectional morphology for the comparisons of regular and/or irregular correctly vs. incorrectly inflected verbs showed strong LAN (Left Anterior Negativity) and P600 responses (Allen et al., 2003; Newman et al., 2007) alongside N400 and P600 responses (Regel et al., 2017). The LAN responses emerge N400 responses at 250 and 500 ms after the starting point of the stimuli in sentences containing endings with incongruent meanings (Kutas & Federmeier, 2011; Silva-Pereyra et al., 2005), and the P600 responses are elicited for violations to the structure of sentences at the syntactic and morpho-syntactic level (Friederici, 2005). Moreover, the comparisons between monomorphemic vs. inflected visually presented words elicited N400 responses (Lehtonen et al., 2007), and the comparisons between visual inflected vs. derived single words elicited Mismatch-negativity (MMN) responses (Leminen et al., 2013). A few ERF studies investigating inflectional morphology reported N400, LAN, and M350 (N400-like responses measured with MEG) responses in the auditory domain when comparing regular, irregular, and pseudo irregular inflected verbs (Leminen et al., 2011), while N400 responses in the visual domain were reported for comparison between simple and inflected words (Vartiainen et al., 2009). The fMRI studies on inflectional morphology showed that visually presented inflected verbs evoked stronger brain activity in the left frontal and temporal areas compared to simple verbs for Finnish monolinguals (Lehtonen et al., 2006) and Swedish-Finnish bilinguals (Lehtonen et al., 2009) alongside the left inferior frontal gyrus and temporal areas for auditorily presented inflected vs. simple verbs for English speakers (Bozic et al., 2015).

1.3.2 Derivational morphology

Derivational morphology is one of the three morphological processes used for the formation and creation of words (Kuo & Anderson, 2006). Usually, the process of deriving new words is recursive, which means that the speaker can formulate words by adding one or more morphemes per stem or word, i.e. “happy”, “happi-ness”, “un-happi-ness”. The derivational operations require that the morphemes are bound to a stem, either before it, as a prefix (prefix: **un**-lucky) or posterior to it, as a suffix (suffix: sing-**er**). Infixes are also used, where the morpheme is placed within a word (i.e., Greek: present tense: la**m**bano, past tense: elabon), but they are not so frequent within languages.

Derivational morphemes generate new words by either altering the meaning of a stem (i.e., the prefix /-un/ alters the meaning of the adjective “happy” and it creates the word “unhappy”) or its grammatical category (e.g., “strong-ly” is the adverbial form of the adjective “strong”); however, there are nouns that are derived from other nouns (“farm” - “farmer” = used to refer to a person who runs a farm). In all languages, derivational morphology results in the production of more words compared to inflectional morphology because derived words can allow larger changes in meaning compared to inflected words (Verhoeven & Perfetti, 2003).

A study by Ramirez and colleagues (2009) examined awareness of derivational morphology at the behavioral level with two cognitive measures; one was measuring morphological structure and the other was measuring morphological production in Spanish, a language with transparent orthography and a rich morphological system (Ramirez et al., 2009). Children at fourth and seventh grades with Spanish as their native language participated in the study. It was found that participants’ performance in the morphological tests explained a percentage of 11% of the variance in Spanish word reading (Ramirez et al., 2009).

Derivational morphology has mainly been studied in adults, native speakers of Indo-European and Uralic languages in the visual and the auditory domain. Experiments assessing awareness of derivational morphology with event-related potentials (ERPs) have been using paradigms, including violations of derivational morphology rules (auditory: Janssen et al., 2006; Leminen et al., 2010, visual: Leinonen et al., 2008), passive-listening oddball paradigms (Hanna & Pulvermuller, 2014; Leminen et al., 2013; Leminen et al., 2013), visually presented masked, and unmasked priming tasks (Lavric et al., 2007; Morris et al., 2013; Morris et al., 2011; Smolka et al., 2015). Results of ERP studies on derivational morphology found strong N400 responses for the comparisons between words and incorrectly derived pseudowords (Leminen et al., 2010) for morphosyntactic violations (Janssen et al., 2006) and for the visual detection of lexical anomalies related to correct and incorrect derivations (Leinonen et al., 2008). MMN responses were elicited during auditory processing of correctly and incorrectly derivational forms (Hanna & Pulvermuller, 2014); additionally, N250 and N400 responses were elicited when comparing stem-suffix related and unrelated derivational forms (Lavric et al., 2007; Morris et al., 2013; Morris et al., 2011; Smolka et al., 2015).

Similarly, experiments investigating sensitivity of derivational morphology with ERFs have been using paradigms, such as passive listening paradigms (Leminen et al., 2013; Leminen et al., 2011; Whiting et al., 2015), lexical decision tests (Fruchter & Marantz, 2015;; Solomyak & Marantz, 2010; Zweig & Pylkkänen, 2009), and synonym judgement paradigms (Bölte et al., 2010). Results from the aforementioned MEG studies on derivational morphology at the auditory level demonstrated enhanced activation for derivations at the 300 to 370 ms time window located in the left temporal areas (Whiting et al., 2015) longside activations in the left middle temporal, left middle-anterior fusiform, and inferior temporal areas (Fruchter & Marantz, 2015). Activations at 170 ms (M170, mainly associated with letter strings and perception of faces) and at 350 ms (M350) were reported in visual tasks for English single words (Solomyak & Marantz, 2010; Zweig & Pylkkänen, 2009).

Moreover, some fMRI studies have studied derivational processing in the brain by testing which brain areas are activated during the processing of morphologically complex words. The fMRI studies reported that derived words evoked larger responses compared to morphologically simple words in areas including the left inferior frontal region (Bozic et al., 2007; Meinzer et al., 2009), the left and right occipital and temporal regions (Gold & Rastle, 2007), and bilaterally the occipito-temporal region (Meinzer et al., 2009) as well as in the right parietal areas (Meinzer et al., 2009).

1.3.3 Finnish derivational morphology

Finnish language is a synthetic language with a very rich morphological system. Being a synthetic language implies that the formation of new words is very frequent; actually, derivational operations and compounding (morphological operation for the formation of words by combining words or stems together) are considered the two most frequent ways for the construction of new words in Finnish (Kiefer & Laakso, 2014). For the Finnish language, derivational operations can be applied to all major word classes, making derivational morphology the most productive morphological operation (Kiefer & Laakso, 2014). There is an extensive number of derivational suffixes (approximately 140), which are used in a recursive way; a native Finnish speaker could produce words with either one or multiple morphemes per stem or word, i.e. “onnellinen” “happy”, “onnellisuus” “happi-ness”. Typically, there are one or two derivative suffixes in a word; however, the practical limit is to use up to five morphemes (Koivisto, 2013). It is noteworthy that fewer than 10% of all lexemes in the largest Finnish dictionary cannot be derived (Koivisto, 2013). The productivity of the Finnish language is enormous, and interestingly, the most productive derivative words (containing multiple morphemes) are not included in dictionaries because of their straightforward meaning. The actual number of non-derived stems is approximately 6000 stems, with loan words excluded (Koivisto, 2013).

In Studies I, II, and III, we focused on Finnish derivational morphology. Although there are several derivational suffixes in the Finnish language, in our morphological paradigm, we used the derivational suffix /-jA/. The suffix /-jA/ is a highly productive suffix in Finnish, as it produces frequent words used in everyday life (e.g., opetta-ja = teacher) and derives new words based on verbs only (e.g., opetta-ja = teacher; Kiefer & Laakso, 2014). Previous behavioral studies assessing young children in languages with transparent orthographies and rich morphological systems have demonstrated that awareness of derivational morphology is closely linked with accurate word reading (i.e., Italian: Burani et al., 2002; Spanish: Ramirez et al., 2010; Greek: Diamanti et al., 2017; Manolitsis et al., 2017).

Finnish derivational morphology has been studied with electroencephalography (EEG) (Leminen et al., 2013) and MEG techniques (Leminen et al., 2010) in adults. A study by Leminen and colleagues (2013) used an auditorily presented oddball paradigm to examine adults' brain responses to derived word processing. The results showed larger brain responses at the 130–170 ms time window for derived words compared to derived pseudowords (Leminen et al., 2013). These enhanced brain activations were interpreted as lexicality effects (words vs. pseudowords), where the derived words seemed to form morphological representations in the adults' brain, probably stored and retrieved as a whole-form morphological representation (Leminen et al., 2013).

Another study by Leminen and colleagues (2010) examined the auditory effects of morphological manipulations with ERPs in Finnish adults (Leminen et al., 2010). The paradigm included single words, and the participants made lexical decisions for auditory presented stimuli. Brain activation was enhanced at the 274–314 time window for the comparison between illegally derived pseudowords and real words in Finnish (Leminen et al., 2010). As far as the visual domain is concerned, awareness of derivational morphology was studied by measuring adults' EEG responses to Finnish visually presented stimuli (Leinonen et al., 2008). Stronger responses at the 400–550 ms were emerged for lexical decision tasks when adults detected lexical anomalies related to derivational morphology (Leinonen et al., 2008).

1.4 Reading difficulties: Developmental dyslexia

Dyslexia is a language-related difficulty related to inaccurate and/or slow reading that precipitates the acquisition of typical reading and writing skills (Lyon et al., 2003; Vellutino et al., 2004). Dyslexia is a language-related disorder that manifests itself in children regardless of adequate levels of intelligence or conventional school instruction (Ramus et al., 2003; Vellutino et al., 2004). The characteristics of a writing system seem to have an influence on underlying difficulties during typical reading acquisition (Seymour et al., 2003). Specifically, in languages with transparent orthography (one-to-one grapheme to phoneme correspondences), reading difficulties manifest with sluggish reading performances and mistakes during reading aloud, whereas in languages with opaque orthography, reading difficulties appear with more mistakes but also slowness during reading aloud (Seymour et al., 2003).

In dyslexia, potential underlying factors for compromised reading development have been considered the neural underpinnings of dysfunctions in the phonological and auditory-based domains (Goswami et al., 2002; Ramus et al., 2003; Vellutino et al., 2004). These studies have shown that children with dyslexia are poorer performers in measures, testing phonological awareness, phonological short-term memory, speech perception compared to non-dyslexic individuals, and conscious manipulation of phonological representations (Ramus et al., 2003; Ramus & Sveknovits, 2008; Shaywitz & Shaywitz, 2005; Ziegler & Goswami, 2005), and they had poorer performances in tests, assessing rapid automatized naming skills (RAN) (de Jong & van der Leij, 2003; Lohvansuu et al., 2018; Papadopoulos et al., 2016; Puolakanaho et al., 2007; Torppa et al., 2007). Similarly, previous studies have demonstrated that some dyslexic individuals exhibited difficulties with the processing of stimuli in the auditory (Ramus et al., 2003; Lohvansuu et al., 2021) and visual domains when assessing visual perception processing; reading difficulties were related to impaired visual attention span skills (Bosse et al., 2007; Lallier & Valdois, 2012; Lobier et al., 2012; Valdois et al., 2004).

In general, there is extensive diversity across individuals, as the majority of them have impaired reading skills due to multiple cognitive deficits (Joanisse et al., 2000). In simple words, not everyone with dyslexia has a phonological deficit (Pennington et al., 2012; Valdois et al., 2011), but other deficits are also involved. Dyslexia has been shown to be interrelated with attention deficit/hyperactivity disorder (Carroll et al., 2005; Germanò et al., 2010; Greven et al., 2011; Maughan & Carroll, 2006;), with math difficulties (Landerl & Moll, 2010), and language impairment (Pennington & Bishop, 2009). Following the aforementioned studies showing that one deficit could not explain all the individual differences and comorbidity in dyslexia, Pennington's multiple deficit model of dyslexia considered that a child with familial risk for dyslexia would probably inherit the parents' risk factors for dyslexia; thus, the child will have higher chances to develop dyslexia later on in life; further, the child will have difficulties in several cognitive skills already before reading acquisition and probably he/she will exhibit lower performances in reading-related cognitive skills when compared with children without risk for dyslexia (Pennington et al., 2006).

1.4.1 Familial risk for dyslexia

There is a strong familial risk for dyslexia within families, as dyslexia comes as a consequence of a strong genetic predisposition (Byrne et al., 2006; Olson et al., 2015; van Bergen et al., 2011), which means that a child is very likely to inherit dyslexia from his/her parents (Pennington & Lefly, 2001; Puolakanaho et al., 2007; 2008).

Longitudinal studies examining the familial risk for the development of reading-related difficulties have demonstrated that a strong relationship exists between parental and children's reading skills (Puolakanaho et al., 2008). More specifically, two big longitudinal studies, the JLD study (Lyytinen et al., 2001, 2004; Lohvansuu et al., 2021) and the DDP study (van Bergen et al., 2011; van der Leij et al., 2001) measured newborn infants and children with and without familial risk for dyslexia to examine early auditory processing, reading-related skills, and brain pathways from birth to adulthood. Results from the Jyväskylä longitudinal study showed that brain responses of newborns at risk for dyslexia measured with ERPs revealed difficulties in specific characteristics of speech (change detection) in comparison to newborns (Guttorm et al., 2005; Guttorm et al., 2010; Leppänen et al., 2010) or 6-month-old babies without risk (Richardson et al., 2003). Following the aforementioned longitudinal studies, a meta-analysis study reported that in a percentage of 29%–66% of the individuals with familial risk will develop reading-related deficits (Snowling & Melby-Lervåg, 2016).

Additionally, studies examining the relationship between familial risk factors for dyslexia in acquiring language and reading-related skills using ERPs have also illustrated predictive effects from early infancy to school age. Specifically, the brain responses of Finnish infants (six months old) with familial risk for dyslexia were found to correlate with the reading skills of children in second grade (Leppänen et al., 2010), and they were found to predict reading speed in 14-year-old adolescents (Lohvansuu et al, 2018). Similarly, the brain responses of Italian infants at 6 months was found to predict expressive language in babies at 20 months with and without risk for dyslexia (Cantiani et al., 2016; Cantiani et al, 2019). Moreover, brain responses of 17-month-old babies with and without risk for dyslexia measured with ERPs were associated with language comprehension skills measured at 4–4.5 years and with reading fluency skills measured at second grade (van Zuijen et al., 2012).

1.4.2 Cognitive risk Factors of reading difficulties

Specific knowledge of the underlying aspects, which are crucial for typical reading development, is crucial for the early identification of the individuals in need of additional help and for the development of functional interventions based on the individuals' needs. The early steps for reading acquisition are the development of pre-literacy and language skills during pre-school and kindergarten, which have a major influence on later reading skills. Pre-literacy and language skills developed at pre-school age and kindergarten can strongly influence the development of typical and atypical reading skills (reading difficulties). Fluent reading performance has been found to be predicted by early developed cognitive skills. Awareness of phonology, short-term memory for phonology, letter knowledge, and RAN were observed to be the best predictors of fluent reading performance across numerous orthographies (meta-analyses: Araújo et al., 2015; Clayton et al., 2019; Landerl & Wimmer, 2008; Melby-Lervåg et al., 2012; Puolakanaho et al., 2008; Ziegler et al., 2010).

The predictive link between phonological awareness skills and reading skills has been broadly investigated (Ramus et al., 2003; Castles & Coltheart, 2004). Fluent phonological awareness skills include the conscious ability to classify and utilize the phonetic parts and syllables of a language (Goswami & Bryant, 1990). For years, deficits in phonological awareness have been considered the main cause affecting individuals with dyslexia (Vellutino et al., 2004). Several studies have reported that reading acquisition are highly predicted by phonological awareness, phonological short-term memory, and RAN (Georgiou et al., 2008, 2012; Papadopoulos et al., 2009; Puolakanaho et al., 2008; Ziegler et al., 2010).

Letter knowledge is the explicit knowledge that connects the graphic symbols used in a language (letters) and the phonemes (the acoustic sounds of a language). Earlier studies have already indicated that letter knowledge strongly predicts reading acquisition (Puolakanaho et al., 2008; Torppa et al., 2010). Letter knowledge predicts later reading skills very accurately because the knowledge of the grapheme-phoneme pairings is one of the core teaching strategies for learning to read, especially to read unknown words "letter-by-letter" (Share, 1995, 1999).

Finally, many studies have demonstrated that RAN is an important predictive measure of reading skills (reading fluency) in many languages (Eklund et al., 2013; Georgiou et al., 2016; Kirby et al., 2010; Landerl et al., 2019; Lervåg & Hulme, 2009; Moll et al., 2014; Protopapas et al., 2013; Torppa et al., 2016), equally strong independently of the transparency of the language (Landerl et al., 2019). RAN task is a cognitive measurement that estimates the individuals' ability to name out loud very quickly (naming time) and accurately (naming accuracy) visually presented items (objects, letters, colors, or digits) (Denckla & Rudel, 1976).

1.5 Morphological processing and reading development

Several studies have elaborated on the critical aspect of phonological processing in reading acquisition, especially the essential role of phonological awareness, phonological short-term memory, and RAN as predictors of reading acquisition (Georgiou et al., 2008, 2012; Papadopoulos et al., 2009; Puolakanaho et al., 2008; Ziegler et al., 2010). However, it is noteworthy that the acquisition of typical reading skills is also linked with the acquisition of excellent morphological awareness of a language (Carlisle, 2003; Kuo & Anderson, 2006; McBride-Chang et al., 2013).

As stated before, successful reading development is acquired when small children can map graphic symbols into phonological components (phonological awareness) as well as when they can identify and handle morphemes, which are components of a language with semantic meaning (morphological awareness) (Carlisle, 2003; Kuo & Anderson, 2006). From our perspective, the morphological representations and their link to phonological representations and speech perception could be used as important predictors for dyslexia, especially for dyslexic individuals, native speakers of the Finnish language, because Finnish is a synthetic language with a rich morphological system.

Previous behavioral studies have demonstrated that awareness of morphology is closely linked with the development of reading skills in a number of languages, independently of their writing system (alphabetic: English: Kirby et al., 2012; French: Casalis & Louis-Alexandre, 2000; Dutch: Rispens et al., 2008; Greek: Diamanti et al., 2017, and non-alphabetic: Japanese: Muroya et al., 2017; Arabic: Tibi & Kirby, 2017). Morphological awareness has been reported to act as a predictor of reading skills in children (Kirby, Deacon et al., 2012) as well as to be strongly correlated with vocabulary across different grades (Nagy et al., 2006), word reading (Levesque et al., 2017; Wang et al., 2009), and reading comprehension in children (Kirby, Deacon et al., 2012; Muller & Brady, 2001; Wang et al., 2009) and adults (Kotzer et al., 2021).

A recent study by Vernice & Pagliarini (2018) examined morphological awareness skills of 6- to 11-year-old monolingual (Italian) and bilingual (Arabic-Italian) children with low socio-economic backgrounds. In their study, they measured three different aspects of morphological awareness: nominal derivational morphology, morphological production with object–picture relations, and morphological production with sentences (Vernice & Pagliarini, 2018). The results showed that morphological awareness, especially awareness of derivational morphology, was found to perform as a predictor of reading fluency performances in first and second grade children (Vernice & Pagliarini, 2018).

Another study examined behaviorally in a longitudinal sample of children at 1st, 2nd, and 9th grade the common contribution of awareness in phonology, morphology, and semantics measured at pre-school to reading comprehension skills during school ages (Lyster et al., 2020). The results showed that pre-school linguistic awareness in phonology, morphology and semantics together defined a 69.2% percentage of the variance in reading comprehension in 9th grade children (Lyster et al., 2020). Nonetheless, it is noteworthy that first, compounding morphology was the target of the study, and second, the study did not examine the variance explained by morphological awareness only; rather, it accounted for all the pre-linguistic skills simultaneously as one variable (Lyster et al., 2020).

1.5.1 Morphological processing, reading development and reading difficulties

Previous studies measured the behavioral performance and morphological processing skills of children with and without risk for dyslexia with morphological awareness tasks (Cunningham & Carroll, 2015; Law et al., 2017; Law & Ghesquière, 2017; Lyytinen & Lyytinen, 2004). Morphological processing of children with and without risk for dyslexia at pre-school age was examined in the Finnish language (Lyytinen & Lyytinen, 2004). The task was assessing inflectional morphology, especially the production of inflected words in Finnish

(Lyytinen & Lyytinen, 2004). Results showed that young children start to produce morphologically complex words, the production of inflectional words, between the ages of two and four years old (Lyytinen & Lyytinen, 2004). Additionally, it was found that language skills in 5-year-old children at risk for dyslexia were predicted by the production of inflectional morphology in 2-year-old children (Lyytinen & Lyytinen, 2004). In contrast, for the typically developing group, inflections were not found to predict language skills until the age of 3.5 years old (Lyytinen & Lyytinen, 2004). These findings suggest that young children with familial risk and low inflectional skills have higher probabilities for later language impairments compared to typically developing young children (Lyytinen & Lyytinen, 2004).

Furthermore, research by Cunninghan and Carroll (2015) investigated morphological awareness skills of first-grade children with three tasks; a dynamic morpheme production task, assessing inflectional morphology, a pseudoword list reading task with morphologically complex words (10 words included a derivational morpheme, four included an inflectional morpheme, and two included compounding words), and a spelling test of pseudowords including derived or inflected pseudowords. Their results showed that pre-school phonological processing could predict morphological awareness skills in first-grade children (Cunningham & Carroll, 2015). Additionally, in another study, awareness of phonological and morphological skills was examined with the Wug test, which involved 29 assessments for inflectional morphology and eight assessments for derivational morphology. Results showed that phonological and morphological skills were simultaneously impaired in pre-school children with familial risk for dyslexia (Law et al., 2017). These results illustrated that awareness of phonology and morphology are related to each other, and it was suggested that possibly the pre-reading deficit in phonological awareness causes the deficits in morphological awareness (Law et al., 2017; Law & Ghesquière, 2017), although it is clear that this direction was not explicitly tested in their study.

1.5.2 Morphological processing: Impaired or intact morphological skills in dyslexia?

There are contradictory results regarding the role that morphological awareness and processing play in dyslexic individuals across different languages. On one hand, previous studies have reported that dyslexics exhibited poorer performance in morphological tasks, assessing behaviorally derivational morphology (Casalis, Cole, & Sopo, 2004). In agreement with these results, the brain responses of dyslexic adults appeared to evoke slower responses at 600 ms (P600 responses) during tasks testing morphosyntactic processing skills in various languages (Dutch, German, and Italian speakers) (Dutch: Rispens et al., 2006; German: Cantiani et al., 2013; Italian: Cantiani et al., 2013b), demonstrating that dyslexic adults have compromised morphological skills. In addition, difficulties with morphosyntactic processing skills were evident when measuring 8- to 13-year-old Italian children with dyslexia for the production of derivational and inflectional morphology (Cantiani et al., 2015). Similarly, a previous study by Chung et al. (2010) investigated morphological awareness in dyslexia and showed that Chinese children from 1st to 4th grade had lower performances in two morphological tasks (morpheme discrimination and morpheme production) compared to chronologically matched children without dyslexia (Chung et al., 2010).

On the contrary, a few studies have also demonstrated typical morphological processing skills when testing children with and without dyslexia (Casalis, Cole, & Sopo, 2004; Egan & Price, 2004) or pre-school children with and without risk for dyslexia (Law, Wouters, & Ghesquière, 2016). Similar results have been reported for high-functioning dyslexic adults (Law et al., 2018). Specifically, results suggested that morphological processing is flawless in high-functioning dyslexics compared to reading-and age-matched controls (Law et al., 2018). Overall, all the aforementioned studies demonstrated that the relationship between morphological processing and reading difficulties is not clear; thus, more studies are needed to establish the role that morphological skills play in reading development and reading difficulties.

1.6 Aims of the research studies

The overall aim of this dissertation is to examine the development of morphological processing skills at the cognitive and brain level in children before and after formal reading instruction. It aims to investigate the development of morphological processing by examining the aspect of derivational processing skills from pre-school to first grade age in children with or without predisposition (familial risk) for dyslexia. The purpose is to investigate pre-school morphological processing and familial risks for the development of reading difficulties. It seeks to identify ways to predict the development of reading skills and reading difficulties in children who have not yet received reading instruction (pre-school children) and early readers (first grade children) with the use of early morphological processing skills. Particularly, it seeks to broaden the knowledge of how familial risk for dyslexia, cognitive skills at the behavioral level, and morphological information processing skills (derivational morphology) at the brain level affect reading development and reading difficulties during school. Moreover, there are studies on Finnish derivational morphology conducted in adults with EEG (Leminen et al., 2013) and MEG (Leminen et al., 2010). Yet, research on Finnish derivational processing in children had not been accomplished before, and to our knowledge, this is the first dissertation thesis that focuses on Finnish derivational morphology in young children.

The use of MEG was essential for our research studies. MEG is a neuroimaging technique that records the magnetic field changes induced by electrical currents in the brain. MEG provides a high degree of temporal resolution, which allows us to tease apart events on particular timescales (N400, P600) without being affected by different brain tissues (e.g., skull and scalp) compared to EEG technique. Therefore, MEG has an essential scientific value and the study of magnetic brain signals is increasingly becoming a research trend in the fields of cognitive neuroscience and neurolinguistics.

Study I focused on morphological processing and awareness regarding the reading skills of children with and without familial risk for dyslexia. It was the first study to investigate auditory ERFs in response to derivational morphology in children at pre-school age in Finnish language. Specifically, for this study, we created an innovative morphological task and examined the brain activity of pre-school children with typical development to find out whether they could differentiate pairs of sentences including correct and incorrect derivational suffixes separately for words and pseudowords. We also explored the sensitivity of pre-school children with familial risk for dyslexia to differentiate correctly and incorrectly derived morphological words and pseudowords to determine possible different pathways of brain responses between children at risk for dyslexia and typically developing children.

In Study II, the brain basis of morphological processing in early readers (first grade) with and without risk for dyslexia was the focus of interest. Similar to Study I, we examined auditory brain responses during MEG recordings of first grade children with typical development as depicted in their sensitivity to the difference between correctly and incorrectly derivational real words and pseudowords in Finnish language. We tested the differences in brain activity for the same morphological contrast in first grade children with familial risk for dyslexia, and then we ran within group comparisons to identify possible brain activity differences between typically developing and at-risk for dyslexia children. Moreover, we explored over time from pre-school to first grade at the behavioral and brain levels whether the neural underpinnings of morphological information processing showed developmental changes in children with and without familial risk for dyslexia.

Study III examined children’s morphological information processing skills longitudinally from pre-school age to first-grade age and within first-grade children (first-grade readers with different levels of reading performance). We first aimed to compare cognitive skills (phonological processing, rapid naming, and verbal short-term memory) at both pre-school and first-grade ages to check the developmental differences before and after formal literacy education. Then, our main goal was to investigate the association between morphological information processing at pre-school and reading development in first grade to shed light on whether morphological processing at pre-school age can affect reading performance after one year at school. We tested this by correlating pre-school behavioral performance (accuracy and reaction time) during the MEG morphological task with first grade reading-related cognitive skills. Finally, we aimed to examine the predictive value of pre-school morphological processing skills at the brain level and their association with reading acquisition. We examined this by correlating pre-school brain activity responses to correctly and incorrectly derived word forms with first grade’s reading skills.

2 METHODS

2.1 Participants

A summary of the demographic information of all the participants who participated in Studies I, II, and III are shown in **Table 1**. In Study I, the sample of participants were 6.5–7 years old pre-school aged children, who participated in the study. In Study II, participants comprised a sample of first grade, 7.5–8 years old children previously measured at pre-school age. In Study III, for the cross-sectional analyses, participants were the same samples of children as those measured at pre-school (Study I) and first-grade age (Study II).

All participants included in these three studies were healthy children, native speakers of the Finnish language with normal or corrected vision (in some cases, using special goggles for MEG measurements). Any of the recruited participants had been diagnosed with hearing or neurological problems, head injuries, or was under medication influencing the central nervous system and the brain. Before taking part in the tasks, all children and their parents were fully informed about the goals and the aims of the studies, and they were asked to give their written consent. The participants at risk for dyslexia were defined as having at least one family member (parent, brother or sister) with a dyslexia diagnosis and/or with self-reported reading problems, based on a questionnaire completed by the parents. The Committee of Ethics of the University of Jyväskylä following the Declaration of Helsinki gave permission for the conduction of the three aforementioned studies.

The groups of children with familial risk for dyslexia were evaluated based on their parents' pre-completed questionnaires. This questionnaire included questions and statements about whether each of the parents in a family dealt with or had been diagnosed with a delay in language, specific language impairment, attention deficit, epilepsy, or any other neurological disease. Also, each parent was asked to state whether another close relative of the family had problems with reading and/or writing.

TABLE 1 Summary of the demographic information of the participants included in Studies I, II, and III. Studies I and II included the same children measured at two different time points.

Study I and III: Pre-school children				
Morphological task	**Real words**		**Pseudowords**	
Participants per task	**Pre-school: typically developing**	**Pre-school: at risk for dyslexia**	**Pre-school: typically developing**	**Pre-school: at risk for dyslexia**
N of Participants	22	18	17	17
Age (average)	6.5 - 7 years old			
Gender	12 girls and 10 boys	7 girls and 11 boys	9 girls and 8 boys	7 girls and 11 boys
Handedness	21 right-handed	18 right-handed	16 right-handed	17 right-handed
Study II and III: First grade children				
Morphological task	**Real words**		**Pseudowords**	
Participants per task	**First grade: typically developing**	**First grade: at risk for dyslexia**	**First grade: typically developing**	**First grade: at risk for dyslexia**
N of Participants	21	13	20	9
Age (average)	7.5 - 8 years old			
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

2.2 Behavioral measurements

Several behavioral tests were carried out by the participants at both ages in each measurement session on a different appointment to the Department of Psychology at the University of Jyväskylä. In Studies I and II, some behavioral tests were used to describe pre-school and first grade children's cognitive characteristics. In Study III, all the behavioral tests were used for correlation analyses to test the relationship between pre-school and first grade cognitive skills and to investigate the association between pre-school children's performance in the MEG morphological task and first grade children's cognitive skill levels.

The participants' visuospatial reasoning, expressive vocabulary, and working memory skills were tested using three subtests of the Wechsler Intelligence Scale for Children—Fourth Edition (WISC IV: Wechsler, 2003).

In the *block design* for visuospatial reasoning, the children were instructed how to arrange a set of blocks to look like a specific design, and then they were asked to execute the same design.

In the *vocabulary* test for measuring the expressive vocabulary, a specific word was told to the children, and then the children were asked to define the meaning of that word.

In the *digit span* (forward and backward) for working memory, a string of numbers in random order was said out loud to the participant, and each participant had to repeat them. First, the participant was asked to repeat the numbers in forward order and then in backward order. The series of numbers were first started with two digits (e.g., 3, 5), and they were ended with a series of much more digits (e.g., 4, 6, 5, 8, 2, 7, 1, 3).

Children's phonological awareness and verbal short-term memory skills were measured using the *Repetition of Nonsense Words* subtest from NEPSY I (Korkman et al., 2007). During the subtest, the participants had to repeat out loud words with no meaning.

Participants' phonological awareness skills were assessed with the *Phonological Processing Task* (NEPSY II: Korkman et al., 2007). During the task, the participant was asked to recognize words from phonological units (word segment recognition) and to perform phonological elisions by saying a word out loud and then repeating the same word while skipping a phoneme or a syllable (e.g., say the word "koti" ("home") by skipping the second syllable "ti,", so the correct answer should be "ko").

Participants' memory skills for linguistic information were tested with the *Sentence Repetition Test*. During the test, each participant was instructed to repeat sentences of increasing length and complexity.

In Studies I-III, we measured children's ability to quickly name familiar objects with RAN (Denckla & Rudel, 1976), and in Studies II and III, we tested children's ability in rapid naming of letters with RAN. For this task, the participants were asked to name quickly and accurately five objects (Study I) or letters (Studies I-III). The objects were very frequent objects presented in five rows with 10 objects per row; the letters were frequent ones, also presented in five rows with 10 letters per row. Both RAN objects and RAN letter tasks were audio-recorded to estimate later their accuracy rates based on the recordings.

In Study I, the reading skills of the participants at pre-school age were assessed with the word list reading and nonword list reading tests. During the *word list reading,*the children were asked to read out loud a list of 105 words in 45 seconds. The test started with 3-letter words and the trial contained more letters, resulting in the final 17-letter word.

In the *Nonword list reading* assessment, children's decoding skills for rule-based representations based on real words were assessed. This test was a modified version from the Tests of Word Reading Efficiency (Torgesen et al., 1999), in which the participants was asked to read out loud a list of 90 pseudowords in 45 seconds as quickly and correctly as possible (e.g., *nalosta, *okan, *nalhajat). In both tests, the participants' performance was calculated based on the total number of correctly read words or non-words and the total reading times.

In Studies I–III, the reading skills of the children of first-grade age were measured with three reading tests (*word list reading, nonword list reading*, and *nonword text reading*).

The *word list reading* and *nonword list reading* tests were the same tests as in pre-school-age (Study I).

Pseudoword text reading assessed the participants' decoding fluency skills (Eklund et al., 2015). During the test, each participant had to read a text comprising pseudowords; the number of correctly read words and total reading time were used as the scores from a maximum of 38 pseudowords.

Also, in Studies II and III, *dictation* was assessed; the participants were asked to write down 20 frequent everyday life words on a sheet of paper. The correctly written words were used as the score.

All the aforementioned behavioral assessments, measured at pre-school and first grade age were used in Study III to run correlation analyses between the children's brain and behavioral responses and cognitive skill levels.

2.3 Morphological task

For Studies I–III, we developed a morphological task for Finnish language to activate specific language-related systems (derivational morphology) during brain activity recording. This task was created in a child-friendly way with its core purpose being to examine young children's brain sensitivity in relation to morphologically complex Finnish derivational morphology.

2.3.1 Stimuli

The morphological task was created with 216 pairs of sentences. The first sentence contained a third-person pronoun (*Hän "He/She"*) and a third-person verb (*johtaa* "to lead" [verb]). The second pair of sentences comprised the same third-person pronoun (*Hän "He/She"*), a third-person verb (*on "is"*), and a noun derived from the verb with the derivational suffix *–jA* (/-ja/ - /-jä/) *johta**ja*** ("lead**er**" [noun with the agentive marker) (Figure **1**).

The pairs of sentences were created under two conditions: real words and pseudowords. One hundred and eight pairs of sentences comprising real words were selected from a Finnish corpus of word frequencies (2010), which was based on the language of the newspapers. This corpus of word frequencies includes the 9,996 most common Finnish lemma, and it is a representation of the most commonly used words in everyday Finnish language (https://github.com/GrammaticalFramework/GF/blob/master/lib/src/finnish/frequency/src/suomen-sanomalehtikielen-taajuussanasto-utf8.txt). One hundred and eight pairs of sentences comprising pseudowords were created following the phonological, morphological, grammatical, and syntactic rules of the Finnish language. The pseudowords were matched with the real words in the number of syllables (trisyllabic), in the number of letters (11 words with six letters, 24 words with seven letters, and 19 words with eight letters), and in the number of derivational endings (42 derivational forms ended with /-ja/ and 12 derivational forms ended with /-jä/).

Additionally, within each condition (real words and pseudowords), we added two more sub-conditions: 54 derivational nouns were correctly derived from the verbs, and 54 derivational nouns were incorrectly derived from the verbs. The correctly derived nouns were represented by derivational forms derived from a verb in a correct grammatical way (e.g., johtaa □ johtaja), where the last vowel before the suffix /-jA/ was either the same as the last vowel of the verb from which it derived or it could be different (tekee □ tekijä). On the contrary, the incorrectly derived nouns were represented by derivational forms created with an incorrect morpho-phonological replacement in the last vowel before the derivational suffix /-jA/ (e.g., johtaa □ joht**i**ja).

For the 108 incorrectly derived forms existing in real words and pseudowords, the last vowel of the derived noun was always replaced with another vowel without violating the Finnish vowel harmony rules. Specifically, for the vowel replacements, we chose to replace each vowel with its most distant vowel, based on the place and manner of articulation, because we did not want to raise irrelevant complexity or the failure to perceive the vowel replacements when testing young children. For example, the vowel /a/ was replaced by /i/ (johtaja - johtija), the vowel /o/ was replaced by /a/ (velkoja - velkaja), and so on. There were two vowels, which were not used in the replacements: the vowel /-e/, and the vowel /-o/, because the first one is not used before the derivational form /–jA/ and the second one together with the suffix /-jA/ can produce real words, e.g., maksaa ("to pay") + jA = maksaja "payer"). The vowels were replaced identically in real words and pseudowords. Diphthongs were completely skipped. For native speakers of Finnish, the knowledge of which form is correct or not has its basis in the learned morpho-phonological representations during language acquisition and development.

The stimuli were auditory recordings recorded in a studio at the University of Jyväskylä. A female Finnish speaker was used to record them with a 44 kHz sampling frequency and 32-bit quantization recorded in stereo channels as settings. The auditory stimuli were edited with Sound Forge Pro 11.0. Moreover, Praat (Boersma & Weenink, 2018) was used to add 5 ms at the starting and ending point of each sentence as a baseline in each sound file to avoid clicking sounds.

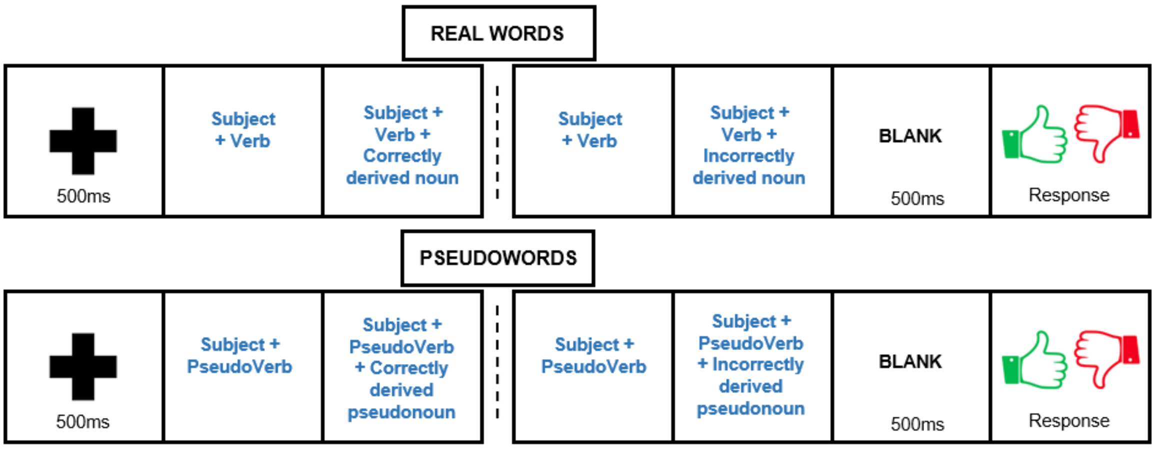

FIGURE 1 Stimuli and procedure of the morphological task.

2.3.2 MEG acquisition

For studies I–III, we recorded the children's brain activity with MEG. MEG is a direct, silent, and non-invasive neuroimaging method. It provides high temporal resolution (millisecond-level information) on brain activity and good estimates of brain regions activating in different tasks. With MEG, we aimed to measure how the brain deals with linguistic information (derivational morphology), which is important for reading. Brain data are especially important when measuring underlying processes that are not visible in overt behavior.

All brain data included in Studies I, II, and III were collected in a magnetically shielded and soundproof room in the Jyväskylä Centre for Interdisciplinary Brain Research (CIBR) at the University of Jyväskylä. Both the preparation room and the MEG room were offering a child-friendly environment in which small children (pre-school and first grade age) were feeling comfortable. All the brain recordings were collected with a whole-head MEG device, the Elekta Neuromag TRIUX system (Elekta AB, Stockholm, Sweden), comprising 306 channels (204 orthogonal planar gradiometers and 102 magnetometers) overall, which measures the magnetic field of the brain. Before the measurement, each child sat in a chair for the preparation process before the MEG recording. Specifically, while sitting on the chair, five head position indicator coils (HPI coils) were carefully taped to the participant's head; three of them were taped to the front of the head and one behind each ear. The coordinate system of the head was defined by the exact location of the HPI coils, which were digitized with a digitizer pen, the Polhemus Isotrak digitizer (Polhemus, Colchester, VT, United States) regarding three anatomical points (nasion, right, and left pre-auricular points). Additional digitized points (~120 points) were also collected from each child's head to later identify additional head movements inside the helmet. Moreover, each participant's eye blinks and eye movements were recorded with two pairs of electro-oculograms (EOGs): one pair was taped diagonally (VEOG) to the child's right eye, and the other pair was taped horizontally (HEOG). Finally, an additional EOG was taped into the participant's right collarbone as a ground reference. After the preparation, participants sat in the MEG room, where a pair of soft, and spongy headphones were inserted into their ears.

2.3.3 Procedure

Inside the MEG room, participants were asked to comfortably sit in the MEG chair, and then a projecting screen with a projector using a refresh rate of 60 Hz was placed at one-meter distance from them. The stimuli were presented with Presentation software (Neurobehavioral Systems, Inc., Albany, CA, United States) on a Microsoft Windows computer. The stimuli were projected from outside the MEG room into a mirror and then reflected into the projection screen. All the MEG data were acquired in an upright gantry position of 68 degrees with a sampling rate of 1000 Hz and a band-pass filter of 0.1–330 Hz.

Detailed instructions were given to the participants before entering the MEG room as well as when sitting in the MEG chair through the inserted headphones at 60 dB (SPL). The instructions for the morphological task were created as small stories to be understandable and interesting for such young children. The first two blocks of the morphological task contained real words, and the next two blocks contained pseudowords. The two conditions, one with words and the other with pseudowords, were not counterbalanced. This was necessary for our studies because it helped the participants to understand better and go through a complex, morphological task with escalating difficulty. For small pre-school-aged children, it would have been too difficult to start with words without meaning. However, all the stimulus pairs within each category (real words and pseudowords) were randomly mixed, however the pairs of sentences (verb and derived noun) were always presented together.

After hearing the instructions, participants completed a practice trial task with six trials: three trials contained pairs of sentences with correctly derived real words and three contained pairs of sentences with incorrectly derived real words. The criterion was that each child had to respond correctly in a minimum of four trials before the start of the morphological task. On the contrary, the task was being explained again, and the participants had to complete the practice trials for a second time. This way, we were making sure that each child understood the task correctly.

After the practice trials, the morphological task started. Each trial was starting with a black fixation cross presented on the screen for a duration of 500 ms followed by the auditory presentation of the pairs of sentences (e.g., /Hän johtaa. Hän on johtaja/) (= He leads. He is a leader), followed by an empty screen for 500 ms. Then, the participants had to respond through button presses: right button press for the correctly derived pairs and left button press for the incorrectly derived pairs of sentences. It is noteworthy that button assignment was not counterbalanced, because the button press happened 500 ms after the last syllable, so timewise it could not influence the brain responses regarding the correctness of the morphological endings. Finally, animated videos were presented after each block of trials to reassure that the participants were paying attention to the task. Overall, the morphological task lasted approximately 40 minutes.

2.4 MEG data analyses

Data analyses for MEG data included in Study I, II, and III were first pre-processed with Maxfilter 2.2 (Elekta AB, Stockholm, Sweden) to estimate the position of the head, to remove external magnetic disturbance and noise interference, and to compensate for head movements during the MEG recording using a signal space separation (tSSS) method (Taulu & Kajola, 2005; Taulu & Simola, 2006). Bad channels were manually checked and marked during each measurement and then reconstructed in Maxfilter 2.2.

Then, all the MEG data were analyzed with BESA 6.1 (BESA GmbH, Munich, Germany) by first applying an independent component analysis (ICA; infomax algorithm) in a 60-second time window to remove eye blinks, eye movements, and cardiac artifacts separately for magnetometers and gradiometers. The MEG signal was high-pass filtered at 0.5 Hz (zero phase, 12db/oct) and low-pass filtered at 30 Hz (zero phase, 24db/oct). After filtering, the MEG signal was divided into trial-based epochs of 1300 ms (from −200 to 1100 ms), with a pre-stimulus baseline of 100 ms considering the starting point of the derivational suffix /-jA/. The trial-based epochs were averaged separately for the correctly and incorrectly derived real words and pseudowords. Remaining artifacts were removed from further analysis by rejecting epochs exceeding the 1,200 fT/cm rejection level for gradiometers and 4,000 fT/cm for magnetometer peak-to-peak amplitudes. In Study I and II, the percentages of the accepted trials was more than 70% (38/54 trials), except for three participants in Study I and two participants in Study II, who had 50% accepted trials (28/54 trials), because we visually checked that these individuals were not different from the other participants. Overall, the groups of children by age or by risk profiles did not differ regarding the removed trials.

For the detailed examination of the brain processes for the correctly and incorrectly derived words and pseudowords, additional triggers were added in Matlab R2015b using the Fieldtrip toolbox (Oostenveld et al., 2011): triggers were inserted for the starting point of correctly and incorrectly derived real words and pseudowords (johtaja-johtija, *lattaja-*lattuja) and for the starting point of the suffix /-jA/ for real words and pseudowords. The starting point of the suffix /-jA/ was chosen as the trigger point, although it is located at ca. 100 ms after the time point of interest because it is a clear syllable acoustically, existing in all the conditions. The time point of interest was the last vowel before the suffix /-jA/, where deviation or illegality could be detected, as the vowel determines the illegality of the whole word. Then, the MEG signal from the combined gradiometers was chosen for further analyses, because it was less sensitive to external noise than the magnetometers, although the use of gradiometers or magnetometers does not change the MEG results (Carcés et al., 2017).

Differences in brain activity were examined in three time windows of interest: 0–300, 300–700, and 700–1100 ms. First, brain activation occurring in the 0–300 ms time window was examined because this time window was previously found to be linked with adults' or children's visual responses to morphological processes (M170 response) (Zweig & Pylkkänen, 2009; Solomyak & Marantz, 2010; Parviainen et al., 2006). Second, brain responses emerging in the 300–700 ms time window were investigated because this time window included the N400 responses previously found in adults (Cavalli et al., 2016; Solomyak & Marantz, 2010). In general, the N400 responses emerge in response to semantic difficulties when engaging an incorrectly word with the semantic context of a sentence (Kutas & Federmeier, 2011), or N400 responses were found to be related to lexico-semantic manipulations (Helenius et al., 2002). Third, brain activation taking place in the 700–1100 ms time window aimed to test the late positivity responses (P600-like responses), which were found to emerge for syntactic and morphosyntactic violations inside sentence structures (Friederici, 2005).

2.5 Statistical analysis

In Studies I and II, cluster-based permutations tests (Maris & Oostenveld, 2007) were performed within and between groups with BESA Statistics 2.0 (BESA GmbH, Munich, Germany) for the pre-school (Study I) and first grade children (Study II). In both studies, the within-group analyses included the ERF responses for the difference between correctly vs. incorrectly derived real words and pseudowords. Similarly, the between-group analyses were conducted to examine the ERF responses for the difference between the typically developing and the at-risk for dyslexia children. Combined gradiometer data were used for the sensor-level statistical analysis. The cluster α was set at 0.05, the number of permutations was set at 3000, and the distance between sensors was set at 4 cm.

In Study II, accuracy and reaction times in the morphological task were examined with 2 × 2 repeated measures ANOVAs in IBM SPSS for the within-subjects contrast of age (pre-school and first grade) and the between-subjects contrast of the groups (typically developing and at-risk for dyslexia children). Moreover, with cluster-based permutation tests, we compared the brain differences within the typically developing group (difference waveform between 16 pre-school typically developing children vs. 16 first grade typically developing children) and each morphological contrast (real words and pseudowords). The same within-group comparisons were conducted for the group at risk for dyslexia.

In Study III, correlation analyses (Spearman's correlation coefficients) were conducted in IBM SPSS to explore a) the relationship between pre-school and first-grade cognitive skills, b) the relationship between pre-school and first-grade morphological skills (accuracy and reaction times during MEG), and c) the relationship between preschool morphological measures during MEG and first-grade cognitive skills. Finally, correlation analyses were conducted in BESA Statistics 2.0 (BESA GmbH, Munich, Germany) to explore the relationship between pre-school children's brain responses to the correctly vs. incorrectly derived words and pseudowords and the first grade children's cognitive skills.

All the comparisons and correlations included in Studies I, II, and III were corrected by applying a false discovery rate (FDR) correction value of 0.05 (Benjamini & Hochberg, 1995) into the p-values. The FDR correction was applied separately for the within-and between-group comparisons and separately for real words and pseudowords.

3 RESULTS

3.1 Study I: Dynamics of morphological processing in pre-school children with and without familial risk for dyslexia

In Study I, the sensor-level dynamics of brain activation in response to morphological information processing (Finnish derivational morphology) were examined in pre-school typically developing and at-risk for dyslexia children using a morphological task including correct and incorrect derivational constructs for real words and pseudowords.

First, behavioral differences in the accuracy and reaction time performance were examined in both groups. Significant differences between groups were observed for the accuracy for correctly derived real words; the typically developing group was more accurate than the group at-risk for dyslexia. No significant differences were observed in any of the other measures.

Second, brain activity was examined with ERF responses for real words in both pre-school typically developing and at-risk for dyslexia children. Brain responses of pre-school typically developing children were sensitive to the morphological contrast for correctly vs. incorrectly derived words at 15–55 ms in the left occipitotemporal region, at 300–312 ms in the left frontotemporal region, at 469–494 ms in the right frontal region, at 467–547 ms in the right occipitotemporal region, and at 1000–1071 ms in the right fronto-temporal region. Brain responses to the morphological information processing of children at risk for dyslexia showed comparable activity to the typically developing group. Specifically, brain activity of pre-school children at risk for dyslexia also showed sensitivity to the correctly vs. incorrectly derived real words at 58–120 ms in the left occipito-temporal region, at 56–204 ms in the right and left parietal regions, at 269–300 ms in the right parietal, occipital, and temporal regions, at 358–372 ms in the left frontal region, at 504–533 ms in the left frontal region, and at 587–626 ms in the right occipital region, at 542–583 ms in the left parieto-occipital region, and at 1004–1057 ms in the right fronto-parietal region.

Third, the averaged ERF responses for pseudowords were examined in both pre-school groups for pseudowords. The brain responses of typically developing children assessing the correct vs. incorrect contrast for pseudowords showed significant clusters at 247–267 ms in the left temporo-parietal region and at 562–602 ms in the right fronto-temporal region. In addition, the ERF responses of the children at risk differed between the correctly and incorrectly derived pseudowords at 69–100 ms in the left and right parietal region and at 1032–1076 ms in the left occipital region.

Finally, we tested the between-group differences for the processing of the correctly and incorrectly derived real words and pseudowords. For real words and pseudowords, the magnetic fields for the correct vs. incorrect morphological contrast, and the cluster-based permutation tests separately for the correctly and incorrectly derived words and pseudowords did not differ between children with and without risk for dyslexia in any of the time windows tested (0–300 ms, 300–700 ms, 700–1100 ms).

A summary of the cluster-based permutation tests for ERFs and the averaged combined gradiometer waveforms are reported in Figure 2 for real words and in Figure 3 for pseudowords.

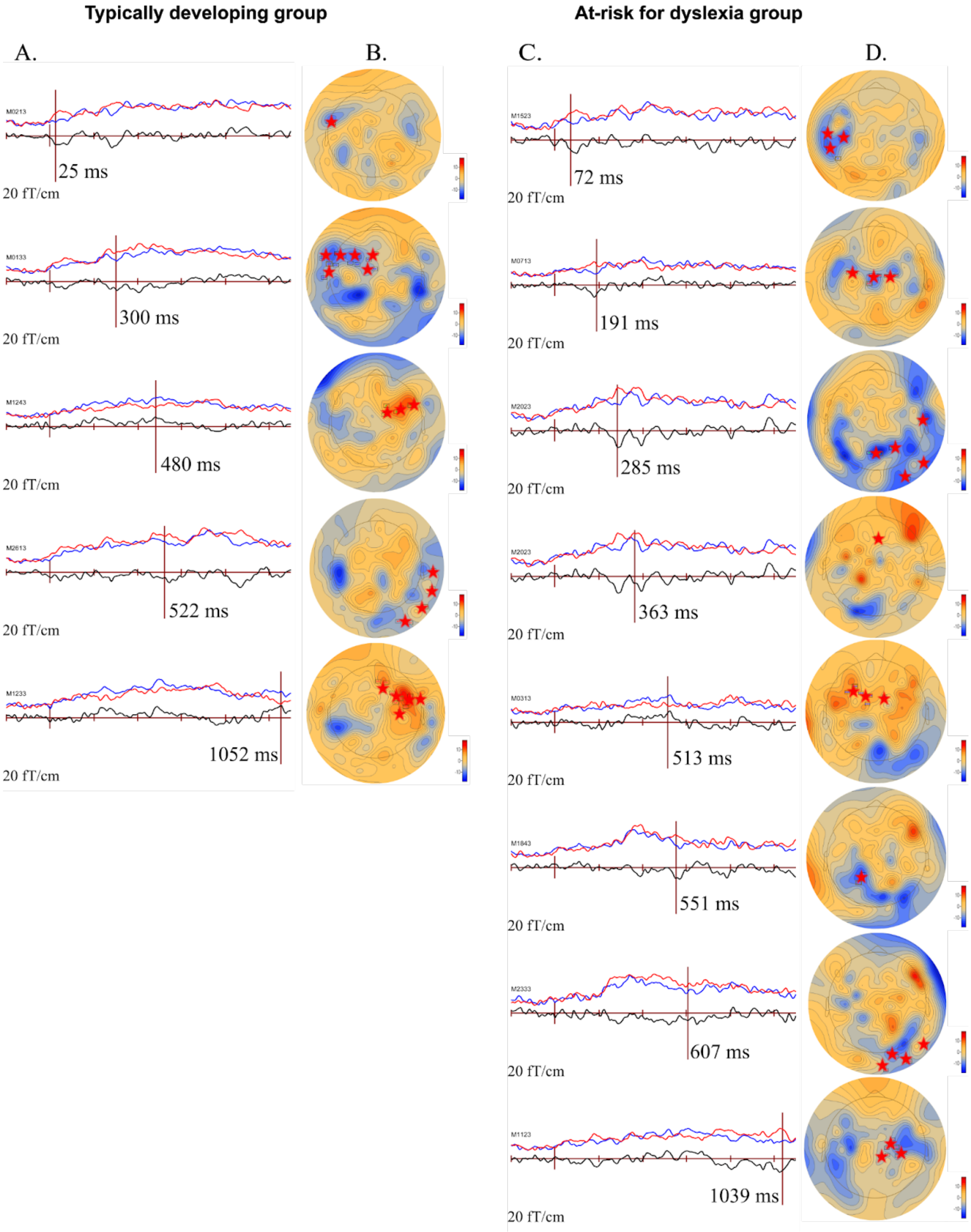

FIGURE 2 Real Words. Brain and Statistical Results of Morphological Processing Effects in Pre-school Children. A. Averaged combined gradiometer waveforms of pre-school typically developing children and C. of pre-school at-risk for dyslexia children for correctly derived (blue line) and incorrectly derived (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 of pre-school typically developing children and D. of pre-school at-risk for dyslexia children for the correct vs. incorrect contrast shown at the time point marked in A. The red stars indicate the significant clusters after FDR correction.

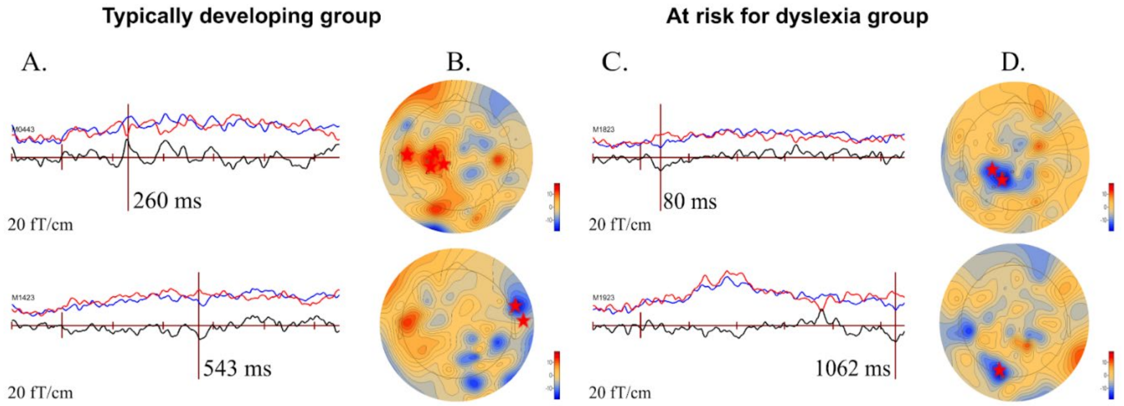

FIGURE 3 Pseudowords. Brain and statistical results of morphological processing effects in pre-school children. A. Averaged combined gradiometer waveforms of pre-school typically developing children and C. of pre-school at-risk for dyslexia children for correctly derived (blue line) and incorrectly derived (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 of pre-school typically developing children and D. of pre-school at-risk for dyslexia children for the correct vs. incorrect contrast shown at the time point marked in A. The red stars indicate the significant clusters after FDR correction.

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

Similar to Study I (Louleli et al., 2020), Study II investigated the neural correlates of derivational morphology in children attending first grade. The children were either typically developing or had a familial risk for dyslexia. To assess derivational morphology, we used the same morphological task as in pre-school children (Louleli et al., 2020), which assessed auditory brain responses to correct and incorrect derivational real words and pseudowords. Also, we examined the developmental differences in morphological processes from the pre-reading to the early reading phase, especially in children with familial risk for dyslexia by comparing the data from pre-school children with the data from the same children when in first grade.

First, the accuracy and reaction time differences during the MEG morphological task were examined in both groups. There were no significant differences in any of the tested conditions between typically developing and at-risk children with dyslexia during first grade. Second, within group differences of auditory event-related fields (ERFs) were investigated in first grade children with and without risk for dyslexia. The ERFs of the children without risk showed sensitivity to morphological information at 14–141 ms in the right fronto-temporal region, at 51–106 ms in the left temporal region, and at 266–300 ms in the left occipito-temporal region, at 381–406 ms in the left temporo-parietal region, at 472–555 ms in the left frontal region and the right parietal region, at 451–622 ms in the left temporal region, and at 633–687 ms in the left frontoparietal region, at 781–816 ms in the left fronto-parietal region. The children at risk for dyslexia showed similar brain responses to typically developing children for real derived nouns and pseudo nouns at 56–86 ms in the left fronto-temporal and right frontal region, at 160–269 ms in the occipitotemporal region, and at 372–424 ms in the left frontal, parietal, and temporal regions.

Second, for pseudowords, the averaged ERFs of the typically developing children did not differ between the correctly vs. incorrectly derived pseudowords at any time window of the analyses. However, the averaged ERFs of the children at risk showed differences for the correct vs. incorrect derivational pseudowords at 303–355 ms in the left parietal, temporal, and occipital regions and at 542–677 ms in the left temporal region. Third, there were no significant differences between the first grade children with and without risk for dyslexia for the processing of the correct vs. incorrect morphological nouns and pseudo nouns.

Also, the developmental differences between pre-school and first grade morphological skills were tested by longitudinally comparing both the behavioral performance and the brain activity patterns across ages. The between group comparisons for the main effect of age (pre-school vs. first grade) demonstrated significant differences in the accuracy for the correctly derived pseudowords; the first grade children were more accurate than the pre-school children, but no other significant differences when comparing longitudinally the participants' accuracy and reaction times were observed. Moreover, the between-group comparisons for the main effect of risk (with vs. without risk for dyslexia) did not show any significant differences in any of the conditions tested.

Moreover, for the developmental comparisons within the typically developing children, significant brain differences were observed, when contrasting the difference waveform between pre-school typically developing children vs. first grade typically developing children with the difference waveform for correctly vs. incorrectly derived real words. Developmental differences in brain activity were found at 0–285 ms in the left and right frontoparietal regions, at ca. 45–291 ms in the left and right frontoparietal regions, at ca. 300–694 ms in the left and right frontal and right parietal regions, at ca. 300–694 ms in the left and right frontal regions, at ca. 750–900 ms in the left temporo-parietal region, and at ca. 790–1100 ms in the right frontal region. Similarly, significant differences emerged for the difference waveform of the pre-school vs. the first grade typically developing children for incorrectly derived real words at ca. 700–980 ms. No significant developmental changes were found for the comparisons among the children at risk for dyslexia.

Finally, we compared the between-group developmental comparisons by contrasting the between-age difference waveform of pre-school vs. first grade children in typically developing and at-risk for dyslexia children. The results showed significant differences in the typically developing children for the correctly derived real words at ca. 18–300 ms in the right and left frontal and right parietal regions, but no significant between-group differences were observed for the incorrectly derived real words or for any conditions relative to pseudowords. Likewise, there were no significant developmental differences within the group at risk for dyslexia in any of the conditions tested.

Summary of the within-group cluster-based permutation statistics during first grade for the correctly vs. incorrectly derived contrasts and the longitudinal statistical MEG results are reported in Figure 4 for real words and in Figure 5 for pseudowords.

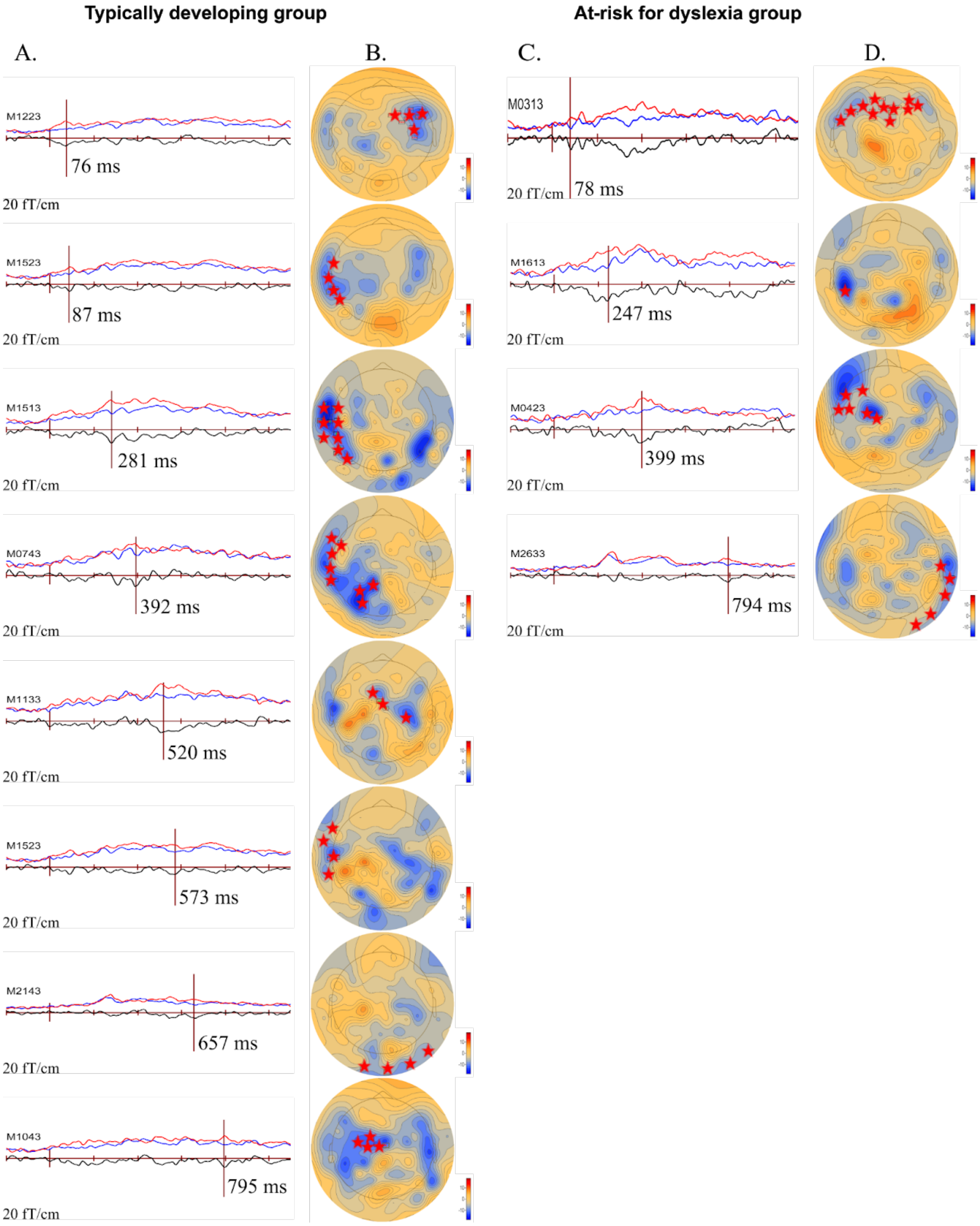

FIGURE 4 Real Words. Brain and Statistical Results of Morphological Processing Effects in First Grade Children. A. Averaged combined gradiometer waveforms of first grade typically developing children and C. of first grade at-risk for dyslexia children for correctly derived (blue line) and incorrectly 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 of first grade typically developing children and D. of first grade at-risk for dyslexia children for the correct vs. incorrect contrast shown at the time point marked in A. The red stars indicate the significant clusters after FDR correction.

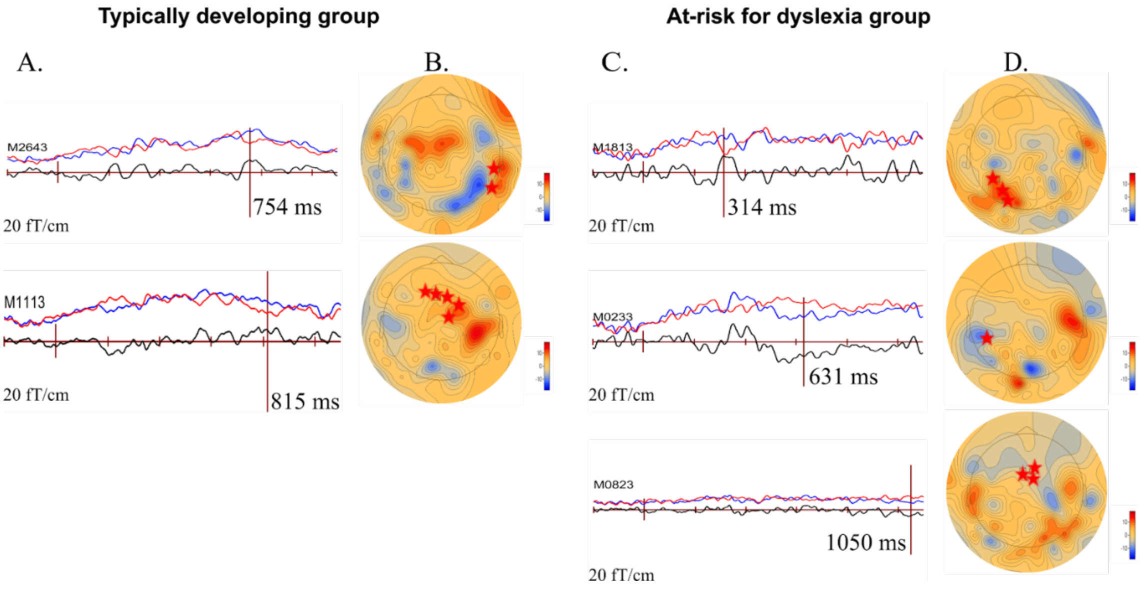

FIGURE 5 Pseudowords. Brain and Statistical Results of Morphological Processing Effects in First children. A. Averaged combined gradiometer waveforms of first grade typically developing children and C. of first grade at-risk for dyslexia children for correctly derived (blue line) and incorrectly derived (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 of first grade typically developing children and D. of first grade at-risk for dyslexia children for the correct vs. incorrect contrast shown at the time point marked in A. The red stars indicate the significant clusters after FDR correction.

3.3 Study III: Behavioral and brain measures of morphological processing in children with and without familial risk for dyslexia from pre-school to first grade

In Study III, the relationship between morphological information processing skills and reading skills in children with and without risk for dyslexia was examined in pre-school and first-grade aged children (Louleli et al., 2021).

First, the majority of pre-school children’s cognitive skills were found to be strongly correlated with first grade children’s cognitive skills. Specifically, strong correlations were found between ages for the block design, vocabulary, digit span, phonological processing, RAN objects, word list reading, and nonword list reading tasks. Phonological processing skills of pre-school children were systematically associated with first-grade children’s repetition of nonsense words, sentence repetition, RAN objects, RAN letters, word list reading, and nonword list reading. Pre-school children’s word list reading was correlated with first-grade children’s sentence repetition, RAN letters, dictation and nonword list reading. Additionally, pre-school children’s nonword list reading was found to be associated with first grade children’s repetition of nonsense words, sentence repetition, RAN letters, dictation, and word list reading. There were no significant correlations were observed between nonword text reading and any other cognitive skill measures.

Second, morphological processing skills during MEG recordings (accuracy and reaction time performance) for real words and pseudowords were compared in pre-school and first grade aged children with and without risk for dyslexia; however, no significant correlations were observed for accuracy or reaction time performance between the two age groups. Third, we examined whether the pre-school morphological measures during MEG were associated with the first-grade cognitive skills. Reaction time for correctly derived real words in pre-school children was found to be significantly correlated with rapid naming of letters in first grade children ($r = .730$, $p < 0.001$).

Next, we tested longitudinally whether the brain responses of pre-school children during the MEG morphological task were associated with first grade cognitive and reading skills. However, no significant correlations were observed for these comparisons. Furthermore, we tested with correlations the relationship between the pre-school brain responses for the correctly vs. incorrectly derived real words and pseudowords and the first grade children's behavioral performance (accuracy and reaction time) during the MEG morphological task. No significant correlations were found for the aforementioned comparisons. Then, correlation analysis cross-sectionally was run to investigate the first grade morphological measures (both behavioral and brain measures) and reading-related cognitive skills (phonological awareness, RAN, letter knowledge, and verbal short-term memory). No significant correlations were observed for the aforementioned comparisons. Finally, between-group differences in first grade children with high and low reading performance were examined using cluster-based permutation tests. Differences in brain activity were compared between 11 first grade children with high reading performance and 11 first grade children with low reading performance for the difference between the correct vs. incorrect derivational real words. There were no significant between-group brain differences for correct vs. incorrect morphological contrast.

A summary of the significant correlations between pre-school children's and first grade children's cognitive skills is reported in **Table 2**.

TABLE 2 Summary of the significant correlations between pre-school cognitive skills and first grade cognitive skills in children (N = 27, 16 Controls & 11 At-risk).

Correlations between pre-school and first grade cognitive skills												
Behavioral assessments	**Block design_1gr**	**Vocabulary_1gr**	**Digit span_1gr**	**Repetition of nonsense words_1gr**	**Phonological processing_1gr**	**Sentence repetition_1gr**	**RAN objects_1gr**	**RAN letters_1gr**	**Dictation_1gr**	**Word list reading_1gr**	**Nonword list reading_1gr**	**Nonword text reading_1gr**
Block design_pre	**.789* p<.001**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Vocabulary_pre	ns	**.596* p=0.001**	ns	ns	**.549* p=0.003**	**.523* p=0.005**	ns	ns	ns	ns	ns	ns
Digit span_pre	ns	**.623* p=0.001**	**.563* p=0.002**	ns	**.551* p=0.003**	**.772* p<.001**	ns	**-.474* p=0.013**	**.560* p=0.002**	**.518* p=0.006**	**.596* p=0.001**	ns
Repetition of nonsense words_pre	ns	ns	**.465* p=0.015**	ns	ns	ns	ns	ns	ns	ns	ns	ns

continues

TABLE 2
continues

Phonological processing_pre	ns	ns	ns	**.471* p=0.013**	**.474* p=0.012**	**.741* p<.001**	**-.506* p=0.007**	**-.472* p=0.013**	ns	**.569* p=0.002**	**.560* p=0.002**	ns
Sentence repetition_pre	ns	**.456* p=0.017**	ns	ns	ns	**.687* p<.001**	ns	ns	ns	ns	ns	ns
RAN objects_pre	ns	ns	ns	**-.578* p=0.002**	ns	ns	**-.532* p=0.004**	**.618* p=0.001**	ns	**-.490* p=0.009**	**-.476* p=0.012**	ns
Word list reading_pre	ns	ns	ns	ns	ns	**.655* p=0.015**	ns	**-.646* p=0.017**	**.686* p=0.010**	**.895* p<.001**	**.863* p<.001**	ns
Nonword list reading_pre	ns	ns	ns	**.492* p=0.009**	**.554* p=0.003**	**.667* p<.001**	ns	**-.546* p=0.003**	**.519* p=0.006**	**.952* p<.001**	**.733* p<.001**	ns

4 DISCUSSION

This dissertation investigated the brain activity and behavioral performances of children with and without familial risk for dyslexia regarding derivational morphology. These include the morphological sensitivity when listening to sentences containing correctly and incorrectly derivational word forms at pre-school age (Study I) and at first grade age (Study II), the sensor-level brain activity differences and behavioral differences between children with and without risk for dyslexia (Study I & II), the developmental aspect of morphological processing skills within pre- and early readers (Study I, II, & III) as well as the predictive link between pre-school morphological processing skills and first grade reading skills (Study III).

Study I examined the ERFs of pre-school children regarding the sensitivity to differentiate between correctly and incorrectly derived nouns and pseudo-nouns. To examine this, an auditory morphological experiment was conducted in which the participants' ERF brain responses and behavioral performance were measured. The target derivational forms were embedded at the end part of sentences. One group of Finnish pre-school children with typical development and one group of Finnish pre-school children at risk for developing dyslexia participated in this study. Sensor-level analyses showed that the brain responses of both typically developing and at risk children with dyslexia were sensitive to the morphological contrast for correctly and incorrectly derived words and pseudowords. However, the brain responses did not differ between the two groups when testing the morphological processing of correctly and incorrectly derived words and pseudowords.

Study II investigated morphological processing skills from the aspect of derivational morphology in the same children as in Study I, but one year after, when children were attending first grade at school. The most important results reported in Study II were that the brain responses of children without risk showed sensitivity to derivational contrasts only for real nouns, while the brain responses of children at risk were sensitive for real derived nouns and pseudo nouns. In addition, no group differences were reported when comparing the two groups.

Regarding longitudinal differences between ages and risk profiles, Study II found significant developmental differences between the pre-school and first grade children at the behavioral level; the children in first grade were more accurate in identifying the correctly and incorrectly derived real words, and they were faster in finding the correctly and incorrectly derived pseudowords. Yet, no group differences were shown between the groups (control vs. at-risk for dyslexia) in the longitudinal subgroup in any of the conditions tested. At the brain level, significant differences emerged for the difference waveform of pre-school age vs. first grade age for the correctly derived real words at ca. 0–291 ms, at ca. 300–694 ms and at ca. 750–1100 ms. In all comparisons, the pre-school children had larger responses from the first-grade children, except at ca. 750–900 ms, where the first grade children had larger responses from the pre-school children. Moreover, significant differences were found for the difference waveform of the pre-school vs. the first grade typically developing children for the incorrectly derived real words at ca. 700–980 ms; the pre-school children had enhanced responses compared to the first grade children.

Study III longitudinally investigated the development of Finnish derivational morphology from pre-school age to first grade age early reading skills in children with and without risk for dyslexia. Hence, we tested with correlations the relationship of pre-school ERF brain responses with the behavioral performance (accuracy and reaction time) to correct vs. incorrect derived real nouns with first grade reading assessments. Moreover, we measured pre-school and first grade cognitive skills (phonological processing, rapid naming, and verbal short-term memory), and we examined the relationship between morphological and cognitive skills. Finally, we explored whether first grade morphological skills on derivational morphology could be linked to first grade reading performance. The most substantial finding of Study III was the replication of previous studies; reading-related cognitive skills at pre-school and first-grade age were linked with each other. Another important finding was that pre-school reaction time performance for correctly derived real words was significantly correlated with first grade performance in the RAN letters task. Finally, Study III found out that pre-school children's brain responses did not predict first grade children's reading performance.

4.1 Pre-school and first grade children with and without familial risk for dyslexia can differentiate the correctly and incorrectly derived words

The most substantial findings of Study I were that the brain activation of both typically developing and at-risk for dyslexia children showed sensitivity to morphological information processing for real words and pseudowords. Likewise, the brain responses to correctly vs. incorrectly derivational real nouns in children with familial risk for developmental dyslexia showed comparable activity to that of typically developing children. Behavioral differences were observed for the accuracy of correctly derived real words ($p = 0.006$); the typically developing group was more accurate than the group at risk for dyslexia.

Study II also examined morphological information processing in the same Finnish children (as in Study I) with and without risk for dyslexia attending first grade. The most important findings of Study II were that the brain ERF responses of children without risk were sensitive only for correctly vs. incorrectly derived real nouns, whereas the brain ERF responses of children at risk for dyslexia showed sensitivity for correctly vs. incorrectly derived real words and pseudowords. In general, no behavioral differences were found between the two groups of children.

At the neural level, for real words, Study I reported that brain responses were different for the correctly vs. incorrectly derived words at ca. 20–50 ms in pre-school typically developing children and similarly at ca. 60–200 ms and at ca. 50–200 ms in pre-school children with familial risk for dyslexia. The aforementioned brain activity responses observed in both groups were enhanced at a similar time window (first time window of analyses: 0–300 ms, ca. 100–400 ms from the beginning of the vowel, which determines legality vs. illegality), and they involved a similar cluster's location (left occipito-temporal region). Similar to Study I, the findings of Study II demonstrated that the neural processing of typically developing first grade children was sensitive to the morphological information at ca. 14–141 ms in the right fronto-temporal region, at ca. 51–106 ms in the left temporal region, and at ca. 266–300 ms in the left occipito-temporal region; similarly, the brain processes of children at risk for dyslexia showed sensitivity to correct vs. incorrect derived words at ca. 56–86 ms in the left frontotemporal and right frontal region and at ca. 160–269 ms in the left occipitotemporal region; both groups had larger amplitudes for the incorrectly derived stimuli than the correctly derived stimuli.

It seems that the upcoming morphological information was processed in a similar way regarding timing and topography between groups. The significant cluster differences between the groups (typically developing and at-risk for dyslexia) and developmentally (pre-school and first grade children) were observed to be enhanced in similar topographies; left fronto-temporal region and left occipito-temporal region were found to be significant across ages in both children with and without risk for dyslexia. These very early brain activations observed in all groups could suggest that, independently of their risk profiles and ages, children were engaging in phonetic/phonological processes, which happen in the brain when the children perceived and recognized native phonetic and phonological units, the real words; these phonetic/phonological processes were found to be activated during speech perception of native phonetic contrasts since infancy (Kuhl, 2004; Werker & Yeung, 2005). Notably, the strict estimation of timing and clusters' topography cannot be indicated with absolute certainty, considering the limitations of cluster-based permutation tests in estimating time points and topography with precision (Sassenhagen & Draschkow, 2019).

Moreover, Study I revealed a significant difference for the derivational contrast at ca. 300 ms in pre-school typically developing children and at ca. 270–300 ms in children at risk for dyslexia; these brain activity differences were more enhanced for the incorrectly derived nouns in both groups, but the cluster's topographies were different between the groups. Children at risk for dyslexia had additional brain differences, being more enhanced for the correctly derived words emerging at ca. 360–370 ms and at ca. 500–530 ms. Our results (Study I) showed that the timing of the appearance of the enhanced responses in children at risk for dyslexia occurred a bit later than the observed timing of occurrence compared to the typically developing group's enhanced responses. Our results also demonstrated that both groups had a very similar clusters' topography in the left frontal region, but the group at risk had stronger brain activations for the correctly derived words dissimilar to the typically developing group.

Following this observation, Study II also indicated the existence of a significant activation for the difference between correctly and incorrectly derived words in first-grade typically developing children at ca. 280 ms in the left occipitotemporal region, being more enhanced for the incorrectly derived words. A similar response emerged at ca. 250 ms in first grade children at risk for dyslexia in the left occipitotemporal region and at ca. 400 ms in the left frontal, parietal, and temporal regions; both clusters were stronger for the incorrectly derived words. In general, our results found many similarities between typically developing and at-risk for dyslexia children's activations regarding timing (approx. at 300 ms) and topography (left occipitotemporal region).

All the aforementioned clusters' approximate timing of activation found in both groups (typically developing and at risk for dyslexia) at both ages (pre-school and first grade) were also observed across a similar time window in an ERP study by Leminen and colleagues (2010), in which they tested auditory brain responses with morphological manipulations in a group of Finnish adults (Leminen et al., 2010). Similar to our results in pre-school children, their adult participants showed enhanced brain activation at ca. 274–314 ms, with the activations being larger for illegally derived pseudowords compared to real words (Leminen et al., 2010). In our Study I and their study (Leminen et al., 2010), the differences around 300–400 ms clearly couple with the classical N400 responses. The N400 component has been found to emerge between 250 and 500 ms after stimulus onset, mainly in sentences with semantically incongruent endings, and it reflects the individual's attempt to access the semantic representations of a given word/sentence (Kutas & Federmeier, 2011; Silva-Pereyra et al., 2005). Also, significant N400 responses were found in the visual domain when adults were detecting lexical anomalies in Finnish correctly and incorrectly derived words (Leinonen et al., 2008) and comparing visually presented stem-suffix related and unrelated derivational forms (Lavric et al., 2011; Morris et al., 2013; Morris et al., 2011; Smolka et al., 2015) or when adults were contrasting morphologically congruent and incongruent words presented visually (Cavalli et al., 2016; Solomyak & Marantz, 2010).

Although studies have suggested that larger activations at the 400 ms (N400 responses) appear as a reflection of lexico-semantic processing (Kutas & Federmeier, 2011), Vartiainen and colleagues (2009) suggested that the N400 activation could represent two dissimilar processing stages; first, the lexical representations are triggered and chosen at around 300 ms after the starting point of the stimulus and then at around 400 ms lexical integration occurs (Vartiainen et al., 2009). However, given the timing, earlier studies have shown that lexical access and lexical integration occur within 200 ms after the word/stimulus onset (Hauk et al., 2006; Pulvermuller et al., 2006).

On one hand, there are many similarities between pre-school and first grade children (typically developing and at-risk for dyslexia) with adults; young children and adults were found to produce larger N400 responses for the lexico-semantic processing of words in the auditory (Leminen et al., 2010) and visual domain (Lavric et al., 2011; Leinonen et al., 2008; Morris et al., 2013; Morris et al, 2011; Smolka et al., 2015) as well as young, school-aged children, and adults were found to process semantic information around the same time (Nora et al., 2017). Thus, our results (Studies I and II) seem to be reasonably well matched between young children and adults regarding timing for the processing of lexico-semantic information. On the other hand, it is also obvious that there are many dissimilarities between children's and adults' brain responses in the timing and processing of auditory information (Parviainen et al., 2011, 2019; Ponton et al., 2000), and for certainty, more studies need to be conducted to reach more general conclusions.

Furthermore, in Study I, significant brain activation differences for correct vs. incorrect morphological contrast emerged at ca. 470–550 ms time window in the right occipitotemporal region in the pre-school typically developing children, as well as at ca. 540–580 ms time window and at ca. 590–630 ms time window in the left parieto occipital and right occipital regions in pre-school children at risk for dyslexia. Similarly, Study II showed that the first grade typically developing group had stronger brain activity at ca. 381–406 ms in the left temporoparietal region, at ca. 472–555 ms in the left frontal region and the right parietal region, at ca. 451–622 ms in the left temporal region, and at ca. 633–687 ms in the left frontoparietal region. In all cases, the differences were larger for incorrectly derived nouns. The first grade children at risk for dyslexia did not show any significant differences at this timing.

In Studies I and II, these aforementioned differences around 500–700 ms clearly match the P600 responses. The P600 responses are related to semantic and syntactic violations that could alter the meaning of a whole sentence (Friederici, 2002; Friederici & Weissenborn, 2007). Previous studies have suggested that the P600 responses involve two dissimilar processing phases; the first phase occurs at ca. ~ 500–750 ms and could depict syntactic integration difficulties (Kaan et al., 2000), and the second phase appears at ca. ~ 750–1000 ms and could represent an attempt to reanalyze and compensate for the integration difficulties (Friederici et al., 2002; Molinaro et al., 2008; Molinaro et al., 2011).

The enhanced responses found in the pre-school group without risk most likely resemble the P600 responses related to syntactic integration difficulties (Kaan et al., 2000), while the brain responses of pre-school children with risk for dyslexia seem to deal with difficulties with processes of syntactic assimilation (Kaan et al., 2000), and they seem to engage themselves in reanalysis and reconstruction processes (Friederici et al., 2002; Molinaro et al., 2008; Molinaro et al., 2011). Another possibility is that the group at risk for dyslexia simply demonstrated slower timing of appearance of the P600 responses for syntactic integration processes compared to the typically developing group's P600 responses, or that these latency differences could be driven by noise.

The results of Study II agree with this observation. The timing of effects found in first grade children is also linked to the P600 responses emerging at ~500–750 ms, when difficulties in syntactic processing are caused (Kaan et al., 2000) and later at ~750–1000 ms, when the individual attempts to restore these compromised processes (Friederici et al., 2002; Molinaro et al., 2008, 2011). It is worth mentioning that typically developing first grade children demonstrated significant effects 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.

In general, Study I demonstrated that children with and without risk were engaging in similar processing stages of the syntactic violation, but the topography of the significant clusters and the time points were different. The differences in topography and timing illustrate that both pre-school groups probably process language in a slower and less automatic way considering their young age; moreover, already at pre-school age they seem to follow dissimilar brain pathways for the processing of upcoming semantico-syntactic information processing. Accordingly, Study II indicated that the typically developing children were found to engage in both early and late P600 processes, which illustrates that they not only come across with challenges with syntactic processing, but also seem to be efficient in going through the reanalysis/repair process of the syntactically compromised stimuli.

Lastly, in Study I, both groups of pre-school children showed enhanced responses in the last time window; at ca. 1000–1071 ms in the typically developing group and at 1000–1070 ms in the at-risk children; both groups had very similar timing and clusters' topographies; for the typically developing group, the significant cluster was located in the right frontotemporal region and for the group at risk for dyslexia, the significant cluster was located in the right frontoparietal region. The clusters' topography (near the motor cortex at the right frontotemporal and frontoparietal channels) could be a consequence for the preparation of the motor response, since the participants were asked to engage themselves in the morphological task with button presses. Moreover, regarding pseudowords, the group at risk for dyslexia also had enhanced brain activity at ca. 1030–1080 ms in the left occipital region, with larger responses for the incorrectly derived pseudowords. These late responses likely reflect preparation for motor response processes (button press) similar to the late responses observed for the processing of real words in both groups of pre-school children.

Overall, Studies I and II offered a broad perspective on the neural dynamics for derivational processing in pre-school and first grade children, as it confirmed previous literature (Leminen et al., 2010) and demonstrated that both groups exhibited somewhat similar response patterns to the morphological contrast for the real words as their pre-school counterparts (Studies I and II). Probably, more research and larger sample sizes are needed to disentangle possible brain differences between typically developing and children at risk for dyslexia in the way that they develop and process morphological information at first grade age. It is probable that the use of at-risk samples rather than the use of diagnosed samples might reduce statistical power, since not all the individuals in the at-risk group will develop dyslexia later on in life. The best approach to this line of research would be to examine at-risk samples longitudinally from pre-school age until second or third grade, when some of them are officially diagnosed as dyslexics, but of course such an approach would not work in the context of a PhD due to time constraints.

4.2 Brain responses during morphological information processing of pseudowords at pre-school and first grade age

Studies I and II investigated the role of correctly vs. incorrectly derived pseudowords from the scope of derivational morphology. Knowing the correct morphological forms is based on learned representations built during language development. In general, small children develop early morphological processing skills by creating morphophonological representations of their language, which are used as basic principles in linguistic operations, including inflectional operations (Jessen et al., 2017; Lyytinen & Lyytinen, 2004) as well as derivational operations (Louleli et al., 2020).

For pseudowords, Study I reported that typically developing children's brain activation at pre-school age showed differences for the correctly vs. incorrectly derived pseudowords at ca. 250–270 ms with larger responses for correctly than incorrectly derived pseudowords in the left temporal and centro-parietal region, as well as at ca. 530–600 ms with stronger responses for incorrectly than correctly derived pseudowords at the right frontotemporal region. The activation at ca. 250–270 ms, with somewhat similar timing to the real words, could be linked to an attempt for lexical access based on long-term phonological representations, since the pseudowords represent potential and not real words. A review paper by Salmelin (2007) suggested that when lexical violation is observed (i.e., incorrectly derived pseudowords), then additional activation is evoked in the right frontotemporal areas at the ca. 530–600 ms time window (Salmelin, 2007). Additionally, fMRI studies have reported that children might have the ability to use a widespread network of activation compared to adults (Gaillard et al., 2000; Holland et al., 2001) by using bilateral language-related processing areas (Brauer & Friederici, 2007).

Brain activation for pseudowords in pre-school children at risk for dyslexia demonstrated that processing differences also occurred bilaterally, as the children's brain responses showed sensitivity to the difference for the morphological correct vs. incorrect pseudo nouns at ca. 69–100 ms in the left and right parietal regions. This significant difference occurring very early in time probably activates phonetic/phonological representations/expectations in the brain when hearing a pseudoword, which included a pseudostem and a real suffix /-jA/ because the pseudowords were created without violating the rules of Finnish vowel harmony. Overall, Study I provided a comprehensive view of the brain dynamics for derivational information processing, as it showed novel results regarding the neuronal time course of processing derivational morphology for real words and pseudowords in children at pre-school age with and without familial risk for dyslexia.

Further, Study II demonstrated that first grade children with typical development could recognize and differentiate the correctly and incorrectly derived pseudowords at the behavioral level (70.74% accuracy for correctly derived and 70.37% accuracy for incorrectly derived pseudowords). Nonetheless, when we tested first grade children for the same difference (correctly vs. incorrectly derived pseudowords) at the brain level, we were unable to indicate the corresponding sensitivity in the brain because this difference did not survive the FDR correction for typically developing children. On the contrary, first grade children at risk for dyslexia showed significant brain activity for the morphological differences for pseudowords at ca. 303–355 ms in the left parietal, temporal, and occipital regions, being larger for the correctly derived pseudowords and at ca. 542–677 ms in the left temporal region, being larger for the incorrectly derived pseudowords. The effect at ca. 300–350 ms could represent the at-risk children's attempt at lexical processing of the upcoming stimuli, where the correctly derived pseudowords seem to be potential Finnish words, as they were created according to the morphophonological rules of the Finnish language compared to the incorrectly derived ones. Moreover, the later effect at ca. 542–677 ms in the left temporal region, being stronger for the incorrectly derived pseudowords, emerged due to both the semantic violation (pseudostem) and the syntactic violation (incorrectly derived pseudowords).

Generally, it is somewhat surprising that only the at-risk children showed sensitivity at the brain level for the morphological contrast of the correct vs. incorrect derivational pseudowords. In a recent study by Beyersmann et al. (2020) tested morphological processing in the visual and auditory domain of German and French adults (Beyersmann et al., 2020). Specifically, they compared words (stem + suffix) with nonwords (stem + pseudo suffix, pseudo stem + suffix, and pseudo stem + pseudo suffix). Their results demonstrated that the existence of a real stem or a real suffix in a word made it more difficult for the participants to identify and reject a pseudoword during a lexical decision task (Beyersmann et al., 2020). These aforementioned results could explain the non-significant differences found in the first grade typically developing children between correctly and incorrectly derived pseudowords. Similarly, Leinonen et al (2009) reported that adults had slower behavioral performance for inflected Finnish words compared to monomorphemic words, and the adults' ERP results showed that inflected words elicited a more negative N400 compared to monomorphemic words, which suggested a difficulty in word form identification. Therefore, their study concluded that pseudowords involving a stem and a real suffix (-jA) could be processed in a different way compared to real words when testing first grade readers without familial risk for dyslexia.

Overall, Studies I and II offered new interesting findings for the derivational processing of pseudowords in pre-school and first-grade children. It is noteworthy that more studies and larger sample sizes are necessary to demonstrate possible brain differences and/or similarities between typically developing and children at risk for dyslexia at both ages.

4.3 Longitudinal behavioral and brain differences between pre-school and first grade children

All the previous similarities at the behavioral and neural level in morphological processing between pre-school and first grade children led us to examine both age groups longitudinally. Specifically, Study II investigated the behavioral performance and brain responses of children longitudinally to investigate the developmental changes during morphological information processing (derivational morphology skills) from pre-school to first grade age in children with different familial risk profiles.

First, Study II longitudinally compared the behavioral performance in the MEG morphological task in the same children between pre-school behavioral performance and first grade behavioral performance within one year. The results of Study II indicated developmental differences. Children in first grade were more accurate for the division between correctly and incorrectly derived words and pseudowords than children at pre-school. Behavioral differences were also observed between pre-school and first grade children for the reaction times for correctly and incorrectly derived pseudowords; the children in first grade responded faster than their pre-school counterparts. However, there were no between group differences when comparing the behavioral performance of children with and without risk for dyslexia in any of the conditions tested. These results contradict previous results showing that dyslexic adults have lower performance than typical adults in behavioral tasks measuring derivational morphology (Casalis et al., 2004). Yet, due to the small number of individuals when testing the between group differences (16 typically developing vs. 11 at-risk for dyslexia), our results need confirmation by testing larger samples of participants.

Second, Study II longitudinally tested the brain responses during MEG recordings in children at pre-school and first grade age. The developmental comparisons per age within the typically developing group showed significant differences for the comparison of the difference waveform between pre-school age vs. first grade age for the correctly derived real words and for the incorrectly derived real words at various time points. Specifically, in all the cluster-based comparisons, the preschool children showed larger responses compared to the first-grade children, except at ca. 750–900 ms, where the first grade responses were larger than the pre-school responses. The results of Study II clearly demonstrated developmental brain differences between pre-school and first grade children. Specifically, we speculate that children in first grade have developed more automatic derivational morphology skills (smaller brain responses probably show less effort during morphological information processing) compared to pre-school age (larger responses probably indicate more effort during morphological information processing) when they were younger, they had less linguistic experience, less morphological representations, and no formal literacy education.

Last, we longitudinally investigated the developmental changes in the neural domain between typically developing children (difference waveform of pre-school vs. first grade) and at-risk for dyslexia children (difference waveform of pre-school vs. first grade). The results of Study II revealed significant group differences at ca. 18–300 ms for correctly derived real words, where the typically developing children showed larger brain responses than the children at risk for dyslexia. Overall, it seems that our results revealed interesting developmental test–retest changes within only one year of literacy education. It is noteworthy that the group without risk for dyslexia changed more over time, possibly because the children with familial risk for dyslexia need more time, more linguistic experience, and more exposure to literacy to exhibit significant developmental changes in their neural and behavioral responses during morphological information processing. Our results agree with a previous study suggesting that the automaticity of morphological information processing depends upon a longer developmental process as it develops from kindergarten throughout adulthood (Casalis & Louis-Alexandre, 2000).

4.4 Behavioral measures of morphological processing in pre- and early readers

Study III behaviorally investigated the link between pre-school and first grade cognitive skills. Specifically, we examined with correlation analyses whether pre-school cognitive skills could be predictors of first grade cognitive skills. Results of Study III confirmed previous literature (Louleli et al., 2021). The phonological processing of pre-school children was significantly associated with the behavioral performance of first grade children in tasks of repetition of nonsense words, sentence repetition, RAN objects, RAN letters, word list reading, and nonword list reading. Additionally, the behavioral performance of pre-school children in word list reading was significantly correlated with the behavioral performance of first grade children during sentence repetition, RAN letters, dictation and nonword list reading. Furthermore, the behavioral performance of pseudoword reading in pre-school children was linked with the repetition of nonsense words, sentence repetition, RAN letters, dictation, and word list reading in first grade children. The results of Study III agree with previous studies, which have already illustrated that the behavioral performance of pre-school children in tasks including phonological processing, RAN, letter knowledge, and verbal short-term memory could be considered good predictors of school-age reading skills (Araújo et al., 2015; Clayton et al., 2019; Landerl & Wimmer, 2008; Melby-Lervåg et al., 2012; Puolakanaho et al., 2008; Ziegler et al., 2010;).

Study III also explored the relationship between morphological skills at pre-school age and their developmental association with morphological skills at first grade age. Interestingly, none of the correlations for accuracy or reaction time measures were significant. The inability to show a link between pre-school morphological skills and first grade morphological skills could either be due to small correlations, or it could propose that morphological processing and especially skills in derivational morphology do not develop similarly in the majority of children at this early developmental phase.

Studies have shown that children acquire morphological awareness at pre-school age and that derivational and inflectional morphology skills develop continuously from kindergarten to adulthood (Casalis & Louis-Alexandre, 2000). Moreover, a previous study that examined the input of phonological, morphological, and semantic awareness to reading comprehension in children attending first, second, and ninth grade demonstrated that awareness of phonology, morphology, and semantics was vital for reading comprehension until the ninth grade (Lyster et al, 2020). Nonetheless, the aforementioned study examined the overall input of linguistic awareness as one variable, but it did not examine phonology, morphology, and semantics separately for each linguistic process, so more general conclusions cannot be made.

Previous studies that examined the association between phonological and morphological awareness found that pre-school children's phonological processing could predict first grade children's morphological awareness skills (Cunningham & Carroll, 2015). Another study tested behaviorally morphological awareness in children with and without familial risk for dyslexia using the classical Wug test containing questions for inflectional and derivational morphology (Law et al., 2017). Their results illustrated that children at risk for dyslexia had deficits in both phonological and morphological awareness (Law et al., 2017), so they suggested that phonological and morphological awareness were associated and that phonological awareness deficits in pre-school age probably had an influence on the acquisition of typical morphological awareness skills (Law et al., 2017; Law & Ghesquière, 2017).

Additionally, in an intervention study by Casalis and Colé (2009), they examined the relationship of pre-school phonological and morphological processing and its possible predictive link with first grade reading skills (Casalis & Colé, 2009). Their participants were French children and they were divided into three groups; the first group received phonological training (i.e., blending, segmentation tasks, phoneme deletion, etc.), the second received morphological training (morphemic segmentation, inflectional, and derivational processes), and the third received no training. Their results showed that both phonological and morphological training were efficient (pre- and post- improvements) (Casalis & Colé, 2009). Additional analyses demonstrated that training of morphological awareness strengthened phonological sensitivity in general, but not in tasks including phonemic manipulation, while training of phonological awareness helped to improve children's performance in morpheme segmentation tasks, but not in tasks including the derivation of words (Casalis & Colé, 2009). Overall, we could conclude that phonological and morphological processes seem to influence each other; however, they also have domains that might develop independently of each other.

4.5 Relationship between pre-school neural responses and behavioral performance on morphological processing and first grade reading skills

In Study III, the predictive role of pre-school morphological information processing through the scope of Finnish derivational morphology was examined in relation to the development of typical reading skills in first grade children. Study III tested this relationship with correlations analyses between pre-school accuracy and reaction time measures during the MEG morphological and first grade reading-related cognitive tasks. Results of Study III found a significant correlation between the reaction time performance for correctly derived real words at pre-school age and the RAN letters task ($r = .730$, $p < 0.001$) at first grade age.

Previous literature has already illustrated the importance of RAN in predicting reading fluency skills in the Finnish language (Eklund et al., 2013, Torppa et al., 2016) and in other orthographies (Georgiou et al., 2016; Kirby et al., 2010; Landerl et al, 2019; Moll et al., 2014). This association between pre-school morphological information processing and naming of letters at first grade brought up new understanding about morphological processing; it seems that morphological processing is closely associated with reading fluency measured by RAN letters, and RAN letters measure the fluency of lexical access (letters, words, objects, etc.) to already built up lexical representations (Eklund et al, 2013; Torppa et al, 2016). Nonetheless, it is noteworthy that we did not observe any association between pre-school morphological information processing and reading tasks measured in first grade, so general conclusions cannot be drawn.

Another suggestion is that our morphological task is characterized by a repetitive mode of presenting the auditory stimuli (Hän verb - Hän on verb stem + /jA/), which definitely brings automatization effects to the children's responses. This characteristic is also present in the rapid naming tasks, and thus this might be the reason for the strong correlation between the pre-school reaction time for correctly derived words and the first grade performance in RAN letters. In conclusion, it is possible that morphological processing and the rapid naming of letters might include common strategies regarding automatization. More studies are needed to identify the aforementioned relationship between the tasks.

Furthermore, Study III examined the predictive role of pre-school morphological information processing based on children's responses for the correct vs. incorrect morphological contrast during MEG recordings and its relationship with reading acquisition in first grade children, but we did not find any significant correlations. Our results suggest that morphological processes measured with reaction times might be a better measure of morphological processing skills compared to ERF responses, which represent temporal dynamic processes in the brain. Probably, testing brain activity in the frequency domain could reveal further possible connections at the brain level.

Our results showed the absence of a strong relationship between brain activity for derivational morphology and reading (decoding) skills. Previous literature that assessed morphological skills in pre-school children mainly focused on inflectional morphology (Lyytinen et al., 2004; Torppa et al., 2010). Specifically, Lyytinen et al. (2004) demonstrated that children could perform basic inflectional operations in the Finnish language by the age of three years old. Similarly, another study by Torppa et al. (2010) examined the association between inflectional morphology skills and phonological skills in pre-school children at various ages. Their results showed that inflectional morphology skills were linked with phonological skills in 3-year-old children; moreover, they reported a direct correlation between inflectional morphology skills and reading accuracy and fluency in 5-year-old and 5.5-year-old children (Torppa et al., 2010). They proposed that pre-school skills in inflectional morphology and phonological skills could be pre-school pre-cursors of later reading accuracy and fluency (Torppa et al., 2010).

Also, Diamanti et al. (2018) assessed children's skills in inflectional and derivational morphology with two production tasks for inflectional morphology and two judgement tasks for derivational morphology. They found that the production of derivational morphemes resulted to be more demanding for children compared to the production of inflectional morphemes and judgement of derivational morphemes. These results indicated that derivational morphology skills might be acquired later compared to inflectional morphology skills, especially at pre-reading ages (Diamanti et al., 2018).

Moreover, another study by Leminen et al. (2013) investigated adults' brain processes during inflectional and derivational processing with EEG with an oddball paradigm (Leminen et al., 2013). Brain responses for derivational forms elicited stronger effects for derived words than derived pseudowords, emerging at 130–170 ms, whereas brain activity for inflectional forms exhibited stronger brain responses for pseudo-inflected forms than for real inflected forms (Leminen et al., 2013). The aforementioned results suggest that there are probably different brain mechanisms responsible for either inflectional or derivational operations based on the brain activation of adults. Also, they suggest that derivations are most probably stored in the mental lexicon as whole forms of brain representations, while inflections are stored and retrieved from the mental lexicon based on the grammatical rules during morpho-syntactic processing (Leminen et al., 2013). Therefore, more research is needed to examine inflectional and derivational processes in the brain.

4.6 General Discussion

This dissertation mainly investigated aspects of morphological processing related to derivational morphology in children with divergent familial risk profiles (typically developing vs. at risk for dyslexia) at pre-school and first grade age using MEG and behavioral measures.

Study I brought up new knowledge about pre-school morphological information processing related to brain sensitivity for correctly and incorrectly derivational word forms in children with and without risk for dyslexia. Study II was designed to capture the brain dynamics of derivational morphology in the same children during the first grade and to examine morphological development from pre-school to first grade age. In Study III, brain-behavior analyses were utilized to examine pre-school children's morphological skills regarding first grade children's reading skills.

If only behavior was considered, then the studies provided a very interesting pattern of results. Studies I and II demonstrated that pre-school and first grade children were sensitive to identifying and discriminating between correct vs. incorrect patterns of derivational constructs for real words and pseudowords when tested within age groups. In most cases, children with and without risk for dyslexia showed similar patterns of behavioral performance (accuracy and reaction time performance) when measured at pre-school and first grade age. The only behavioral difference between the groups was observed at pre-school age for the percentages of accuracy when identifying correctly derived words; the typically developing group exhibited higher accurate rates than the at-risk group for the identification of correctly derived words. No other between group differences were observed at the behavioral level of the responses.

Regarding brain activity responses for derivational processing, our studies (Study I and II) aligned with previous studies measuring adults' ERPs for auditory and visual N400 responses during morphological processing. Specifically, in Studies I and II, participants showed similar brain responses (N400 for incorrectly derived words and P600 for morphosyntactic violations) during auditory processing, which were previously found in adults for auditory (Leminen et al., 2010), visual processing (Leinonen et al., 2008; Morris et al., 2013; Morris et al., 2011; Lavric et al., 2011; Smolka et al., 2015; Cavalli et al., 2016; Solomyak & Marantz, 2010) and morpho-syntactic processing (Friederici et al., 2002; Molinaro et al., 2008; Molinaro et al., 2011). In Studies I and II, there were no between group differences when comparing the groups with and without risk for dyslexia at the neural level of responses.

Furthermore, for pseudowords, Study I illustrated that pre-school children with and without familial risk for developing dyslexia could discriminate between correctly and incorrectly derived pseudowords, as seen at the behavioral and brain levels. Nonetheless, no between group differences were found between typically developing and at-risk for dyslexia children at first grade, neither at the behavioral nor at the brain level of responses. Study II also showed that children with and without risk for dyslexia in first grade could discriminate between correctly and incorrectly derived pseudowords at the behavioral level. However, Study II brought up a considerably surprising result: only children at risk for dyslexia showed brain activity differences for the morphological contrast of the correct vs. incorrect derivational pseudowords. Based on previous studies in adults, we could assume that the presence of a real stem or suffix in a word made it more difficult to identify pseudowords in lexical decision tasks (Beyersmann et al., 2020; Leinonen et al., 2009).

Moreover, Study II examined the developmental changes regarding derivational skills in children before and after one year of literacy education. Our study found that the typically developing group showed more behavioral and brain changes compared to the group at risk for dyslexia. We could speculate that children at risk for dyslexia probably need more linguistic experience through time and more exposure to literacy to exhibit significant developmental changes in their neural and behavioral responses during morphological information processing.

Finally, Study III longitudinally investigated derivational morphology in children measured at pre-school and first grade ages, and Study III revealed whether pre-school morphological processing could be linked to reading skills at first grade age. First, at the behavioral level, Study III confirmed the previously found associations between reading-related cognitive skills at pre-school and first grade ages, as pre-school cognitive skills were significantly correlated with first grade cognitive skills for various behavioral measures. Second, Study III revealed interesting results for the relationship between pre-school morphological information processing and the first grade children's reading development; pre-school children's RT performance for correctly derived words was significantly correlated with first grade children's performance in the rapid naming of letters. It is interesting that pre-school RT performance for correctly derived words could be considered a precursor to fluent reading skills at first grade age. However, Study III did not find the same association at the brain level; there were no significant correlations when comparing pre-school children's brain responses to the correctly vs. incorrectly derived words or pseudowords and first grade children's cognitive performance or reading skills. Similarly, no significant correlations were observed between the pre-school's accuracy or reaction time during the MEG morphological task and the first grade's cognitive skill measures.

In conclusion, Studies I, II, and III extended the knowledge about morphological information processing as seen via derivational morphology skills in children with different risk profiles for developing dyslexia. The overall findings of this thesis could provide a better understanding of the neural dynamics that underlie morphological information processing and could be used to identify specific teaching strategies, which could help both families and teachers to develop better tools to help the children at risk. In the future, our results, together with additional research, could contribute to a comprehensive understanding of the developmental pathway of morphological processing from pre-school ages to adulthood.

4.7 Limitations

In Studies I, II, and III, we measured pre-school and first grade children's brain and behavioral responses while they were performing an innovative morphological task, assessing derivational morphology. Our morphological task was created with naturally produced stimuli that are ecologically more valid during speech perception than synthesized sentences, but these stimuli could have slightly different acoustic characteristics within each sentence, which could result in less clear ERF responses compared to synthesized stimuli. Second, even though our stimuli had their basis in naturally produced sentences, the task itself involved repetition of sentences auditorily, which in reality does not represent a naturalistic way of sentence perception during speech production; however, the repetition of sentences was helpful for young children to learn the structure of the morphological task and automatize their responses. Third, it is noteworthy that the correctness or incorrectness of the derivational ending was clearly determined by the last vowel before the suffix /-jA/, but in our design, we triggered the beginning of the suffix /-jA/, because it is a detectable syllable existing in every sentence; the last vowel was not chosen to be triggered due to its dependence on the vowel length, which could be slightly different in length

(~100 ms); thus the correctly or incorrectly derived noun matching or not with the verb could be detected at ca. 100 ms earlier than the trigger.

A few general limitations were also identified. All the participants' responses (correct and incorrect) during the MEG morphological task, included in Studies I, II, and III, were used in the ERF analysis because of the low number of stimuli per condition; however, using correct and incorrect responses provided a better signal-to-noise ratio for the investigation of brain responses, showing the typical processing of derivational morphology. Moreover, the small sample size was not optimal, especially for the correlation analyses included in Study III and for the between group comparisons (typically developing and at-risk for dyslexia children), included in Studies II and III, which could hinder reaching sensitivity to reveal either significant real correlations (Study III) or differences between groups (Studies I and II).

4.8 Future Directions

In Studies I and II, we measured pre-school and first grade children with and without risk for dyslexia, and in Study III, we examined the developmental and predictive link of pre-school derivational morphological to later reading skills. Interestingly, future research could involve the localization of the brain sources during morphological processing in pre-school and first grade children as well as functional brain connectivity and network analysis (Studies I and II) would be a fascinating approach for future studies to investigate the brain areas that are involved in morphological processing through the scope of derivational morphology. Deep knowledge of the underlying brain processes and areas that are involved in reading development could provide better understanding about typical and atypical reading development through a specific linguistic process (derivational morphology).

Additionally, future research could use our longitudinal study to further test derivational morphology in older children (third and fourth grade) and adolescents (sixth and seventh grade) and in adults, using our novel morphological task as a measurement of language-related skills to reveal the brain and behavioral pathways of morphological development from a pre-literate age throughout adulthood. Furthermore, these longitudinal follow-ups could examine the relationship between language-related skills (derivational morphology) and other areas of cognition, such as the speech perception skills of young children and visual attention skills in adults, especially in dyslexic individuals. Moreover, aspects of inflectional morphology should also be examined together with derivational morphology in young children to investigate how these two morphological processes are similar or deviate from each other at the behavioral and brain levels of responses. Overall, this dissertation thesis has found important temporal and spatial information that could be useful for future studies that use state-of-the-art designs for source localization. My research will bring new knowledge, which will help both families and special education teachers to develop better tools to focus our efforts to help children at-risk for dyslexia.

YHTEENVETO (SUMMARY)

Morfologiseen prosessointiin liittyvät aivojen herätevasteet esikoulua ja ensimmäistä luokkaa käyvillä lapsilla, joista osalla on perinnöllinen lukivaikeusriski

Lukemaan oppiminen edellyttää lapselta kykyä yhdistää ortografisesti kirjoitettuja yksiköitä puhutun kielen foneemisiin/fonologisiin yksiköihin sekä kykyä soveltaa morfologisia sääntöjä kielen morfeemeja käyttäessään. Dysleksia eli lukivaikeus hankaloittaa tavanomaista lukemaan ja kirjoittamaan oppimista. Se on kehityksellinen kielellinen vaikeus, joka esiintyy suvuissa ja on osittain perinnöllinen.

Tässä väitöstutkimuksessa pyrittiin selvittämään morfologisia prosesseja suomen kielen johtomorfologian näkökulmasta morfologisella tehtävällä, jossa mitattiin aivotoimintaan ja käytökseen liittyviä herätevasteita. Tehtävään sisältyi lausepareja, joissa oli oikein ja väärin johdettuja aitoja sanoja ja keksittyjä pseudosanoja. Mittasimme aivotoimintaa aivomagneettikäyrällä (MEG) kahdessa suomalaislasten ryhmässä lasten suorittaessa kyseistä morfologista tehtävää. Ensiksi teimme mittaukset esikoululaisille (tutkimus I), joista osalla oli perinnöllinen lukivaikeusriski ja osalla ei. Seuraavaksi testasimme samat lapset heidän käydessään peruskoulun ensimmäistä luokkaa (tutkimus II), kun he olivat saaneet lukutaito-opetusta vuoden ajan.

Tutkimusten I, II ja III poikittais- ja pitkittäistutkimuksissa analysoitiin näiden esikoululaisten ja ensimmäisen luokan oppilaiden aivojen herätevasteita ja käyttäytymistason aineistoa. Tutkimuksen I perusteella sekä riskiryhmän että riskittömän kontrolliryhmän esikoululaiset olivat jo kehittäneet johtomorfologisia taitoja, kuten reaktioaika-, tarkkuus- ja aivomittaukset osoittivat, mutta eri riskiprofiilin omaavien ryhmien välillä ei löytynyt merkitseviä eroja. Samoin tutkimuksen II perusteella ensimmäisen luokan tyypillisesti kehittyvät lapset osoittivat herkkyyttä oikeiden vs. väärien johdosten eroille vain, kun kyseessä olivat aidot sanat. Riskiryhmän lapset sen sijaan olivat herkkiä sekä aitojen että pseudosanojen oikeiden vs. väärien johdosten eroille. Vertailussa ei taaskaan ilmennyt merkitseviä ryhmien välisiä eroja. Tutkimuksessa II tarkasteltiin myös morfologisen prosessoinnin kehittymistä esikouluiästä ensimmäiselle luokalle. Oli kiinnostavaa havaita, että tutkimuksen II tulokset toivat esille merkitseviä kehityseroja käytös- ja aivotasolla esikoululaisten ja ensiluokkalaisten välillä, kun analysoimme aitojen sanojen ja pseudosanojen johtamisen prosessointia. Tutkimuksessa III selvitimme edelleen, kuinka esikoululaisten suomen kielen johtomorfologiset taidot – virheettömyyden, reaktioaikojen ja esikoulun kognitiivisten taitojen perusteella – voisivat olla yhteydessä lukutaitoon ensimmäisellä luokalla. Tutkimuksen III tulokset tukivat edellisten tutkimusten löydöksiä; useat esikoulussa mitatut kognitiiviset taidot korreloivat ensimmäisellä luokalla mitattujen kognitiivisten taitojen kanssa. Myös esikoulussa mitattu reaktioaika oikein johdettuihin sanoihin oli merkitsevässä yhteydessä vuotta myöhempään

suoriutumiseen kirjainten nopeassa sarjallisessa nimeämisessä. Merkitseviä korrelaatioita ei kuitenkaan havaittu mitattaessa esikoululaisten morfologisen prosessoinnin aikaisia aivojen herätevasteita tai käytäytymistason muuttujia ja lukemista ensimmäisellä luokalla. Kaiken kaikkiaan tämän väitöstutkimuksen keskeiset tulokset tuovat esille morfologisen prosessoinnin (johtomorfologian) kehityksellisiä muutoksia, kun sitä mitataan kahtena eri ajankohtana (esikoulu ja peruskoulun ensimmäinen luokka). Johtomorfologian merkitys ei kuitenkaan näytä olevan huomattava lukemaan oppimisen varhaisessa vaiheessa.

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ORIGINAL PAPERS

I

DYNAMICS OF MORPHOLOGICAL PROCESSING IN PRE-SCHOOL CHILDREN WITH AND WITHOUT FAMILIAL RISK FOR DYSLEXIA

by

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

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Reading acquisition

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

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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 & Pylkkänen, 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 & Pylkkänen, 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 & Pylkkänen, 2009). Effect of morphological manipulation in the ERPs of Finnish adults was significant at the 274–314 time-window while the participants were comparing illegally 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, Zoubrinetzky, & 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”) - johta**ja** (noun with the agentive marker, “lead**er**”). 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)
Number of Participants	22/17	18/17
Age (average)	6 y and 8 m (SD = 0.44–0.45)	6 y and 9 m (SD = 0.43–0.47)
Gender	12 girls and 10 boys/9 girls and 8 boys	7 girls and 11 boys/7 girls and 10 boys
Handedness	21/16 right-handed	18/17 right-handed
Parental Educational Level	**Control group (real words/pseudowords)**	**At-risk group (real words/pseudowords)**
PhD/Master's Degree	14 mothers and 6 fathers/11 mothers and 3 fathers	4 mothers and 2 fathers/4 mothers and 2 fathers
Bachelor's Degree	6 mothers and 11 fathers/5 mothers and 9 fathers	6 mothers and 5 fathers/6 mothers and 5 fathers
Vocational School and Comprehensive/Higher Secondary School	1 mother and 2 fathers/1 mother and 2 fathers	5 mothers and 8 fathers/4 mothers and 7 fathers
Total	21 mothers and 19 fathers/17 mothers and 14 fathers	15 mothers and 15 fathers/14 mothers and 14 fathers

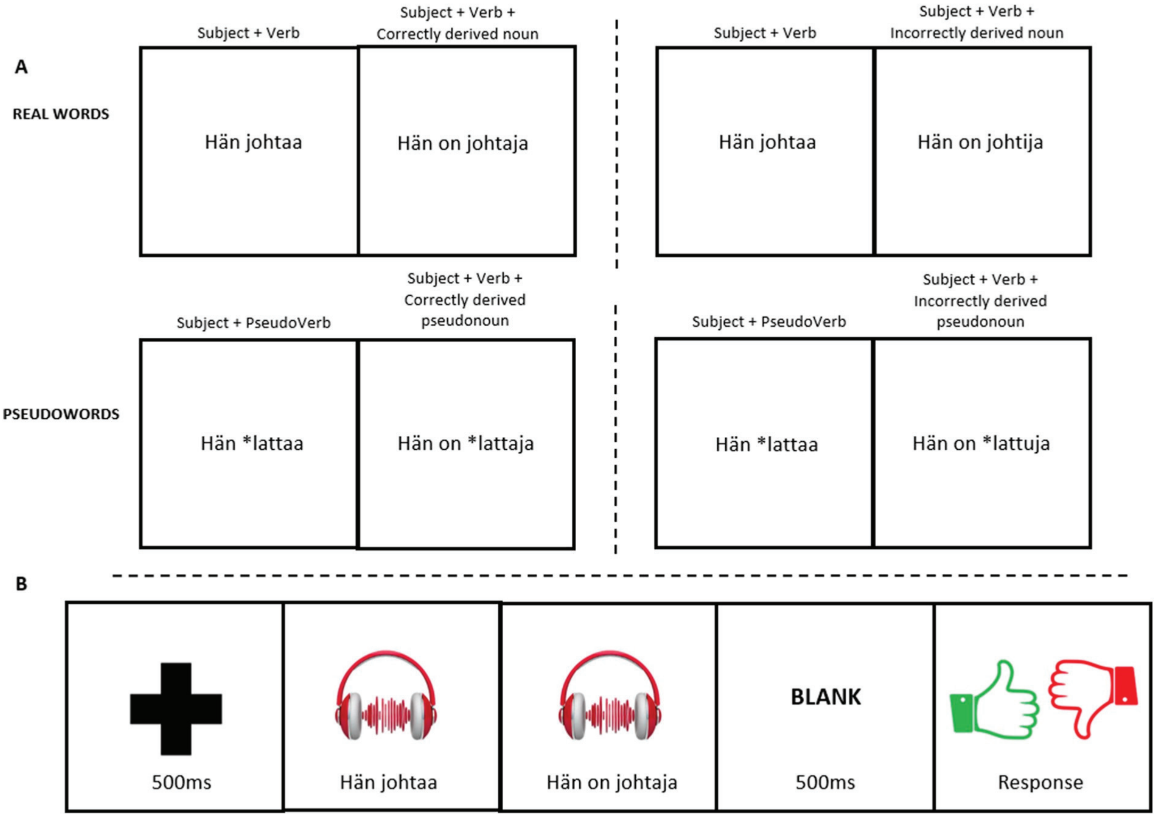

Fig. 1. Morphological awareness task. **A.** Stimuli consisted of real words with a correct or incorrect morpho-phonological change and pseudowords with a correct or incorrect morpho-phonological change. **B.** Procedure of the morphological awareness task. Each trial started with a 500 ms fixation cross, 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., johti**i**ja). 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 α 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				
	Mean (max.)	SD	Range	N (participants)	Mean (max.)	SD	Range	N (participants)	t-values, p-values
Block design	24.27 (68)	8.45	10–44	22	20.35 (68)	8.37	10–42	17	t(37) = 1.141, p = 0.158
Vocabulary	18.45 (66)	7.58	4–34	22	14.05 (66)	8.64	3–40	17	t(37) = 1.689, p = 0.100
Digit span	10.71 (32)	1.55	8–14	22	9.82 (32)	2.32	4–14	17	t(37) = 1.411, p = 0.167
Phonological processing	33.81 (53)	6.65	23–45	22	30.64 (53)	6.99	23–50	17	t(37) = 1.444, p = 0.157
RAN (objects)	69.21	15.94	47.34–103.75	22	75.81	16.94	49.20–121	17	t(37) = −1.248, p = 0.220
Letter knowledge	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
Correct responses for correctly derived nouns (max. 54)	48.9 (SD = 3.97) (90.57%)	43.6 (SD = 7.41) (80.76%)	t(38) = 2.888, p = 0.006
Correct responses for incorrectly derived nouns (max. 54)	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**
RT for correctly derived nouns (ms)	1170.30 (SD: 456.80)	1221.35 (SD = 386.88)	ns
RT for incorrectly derived nouns (ms)	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
0–300 ms	15–56 ms (max. 25 ms)	0.005*	Incorrect > Correct	left occipito-temporal region
300–700 ms	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
700–1100 ms	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).

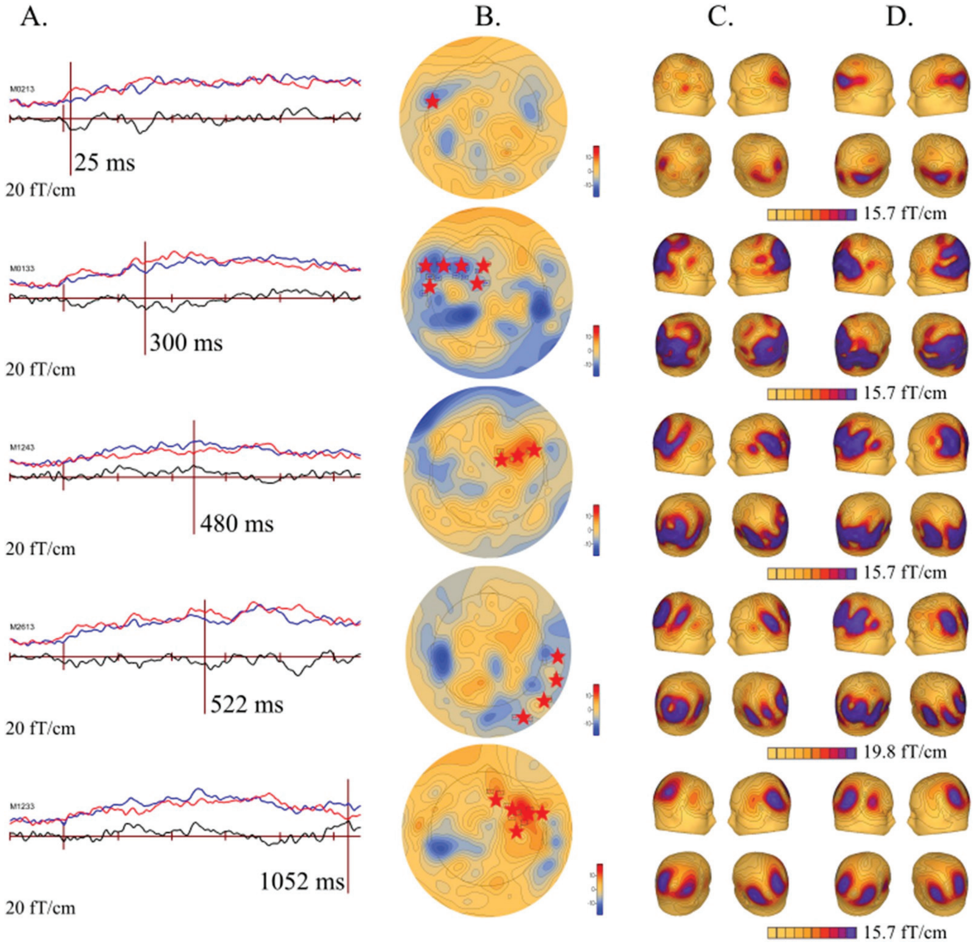

Fig. 2. **A.** Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns, and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs 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 μV–10 μV). 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

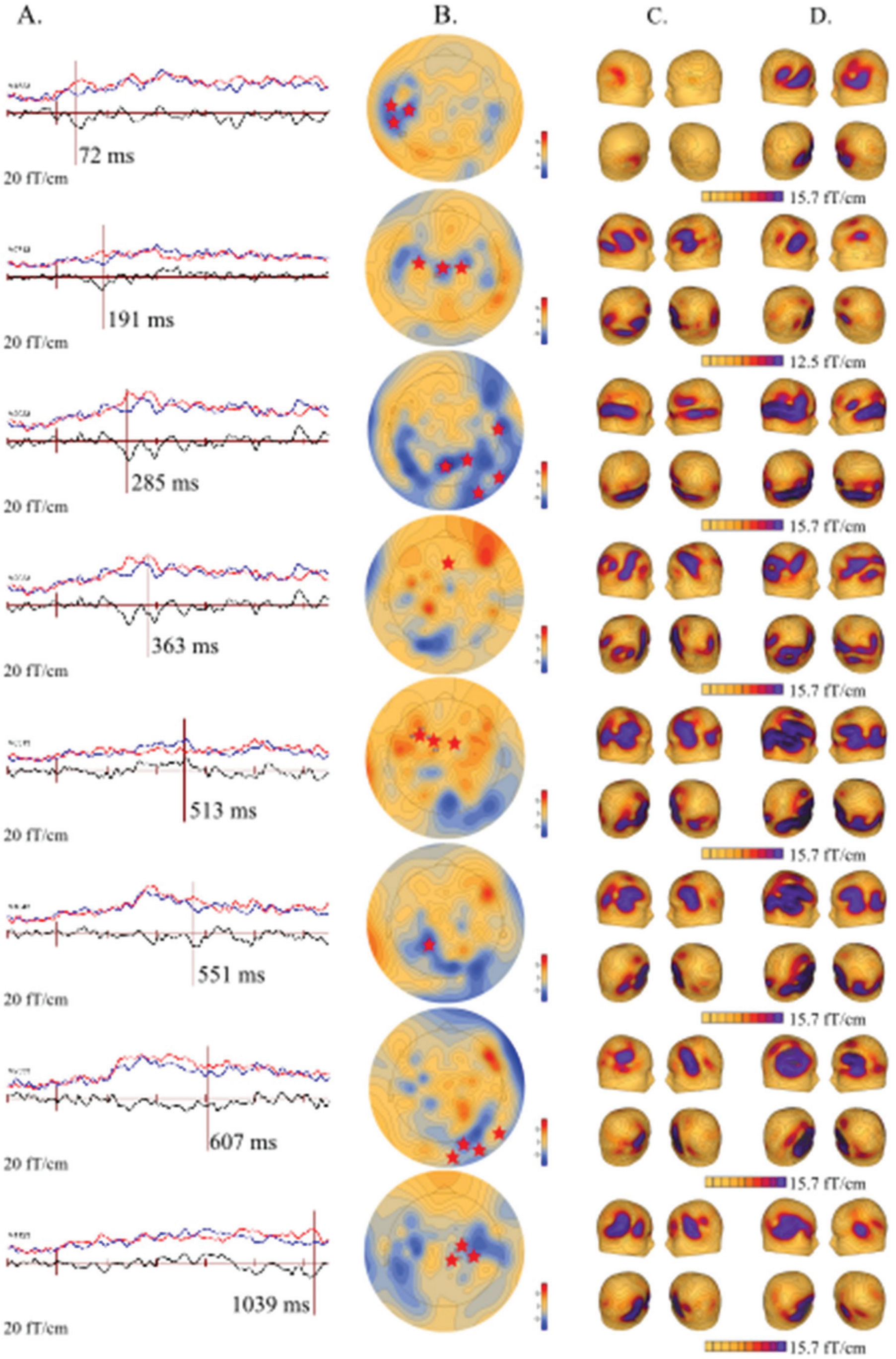

Fig. 3. A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs for 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 μV–10 μV). 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
RT per Group	**Controls (N = 16*)**	**At-risk (N = 17)**	**t-values, p-values**
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/was nevertheless used as the trigger point because of it being clear, whereas the preceding vowel might be slightly varied in length (~100 ms).

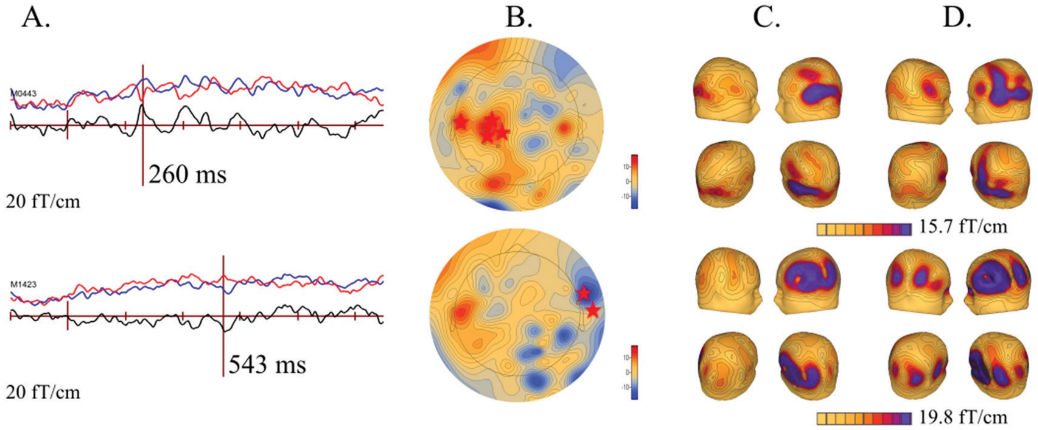

Fig. 4. A. Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs for 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 μV–10 μV). 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).

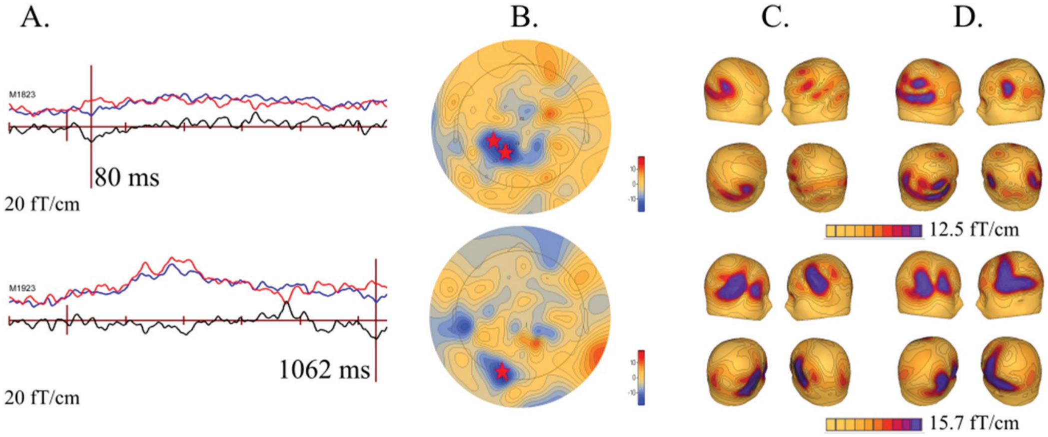

Fig. 5. **A.** Averaged combined gradiometer waveforms for correctly derived (blue line) and incorrectly derived (red line) nouns and the difference wave (responses to the correctly minus incorrectly derived nouns, black line). **B.** Results of the cluster-based permutation test topographies for ERFs 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 μV–10 μV). 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.)

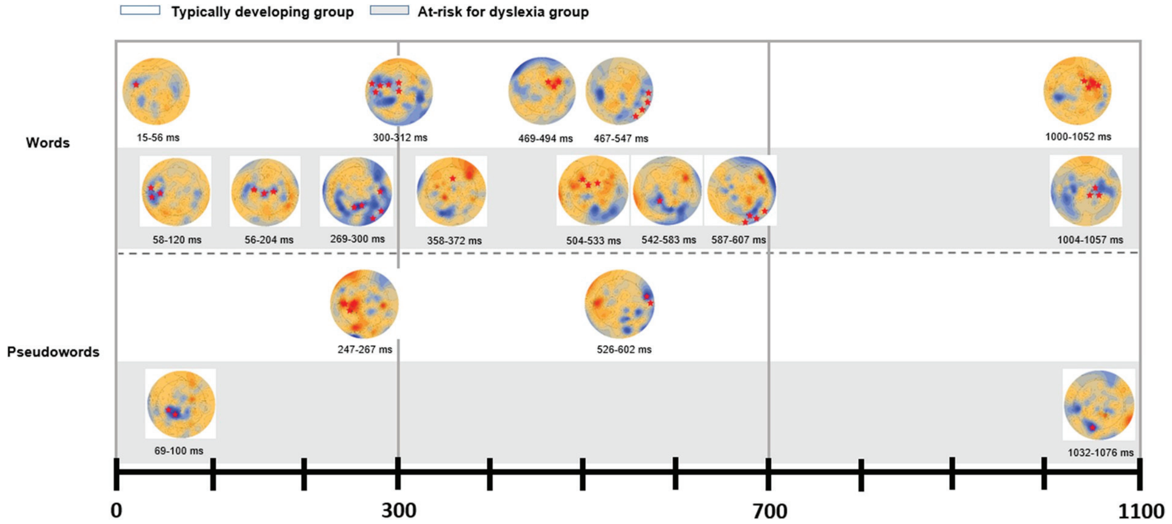

Fig. 6. Summary of the within-group differences of the cluster-based permutation statistics for the correct vs. incorrect morphological derivation per group (In white: typically developing children and in gray: at-risk for dyslexia children) per time-window (0–300, 300–700, and 700–1100 ms) separately for reals 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 μV–10 μV). 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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II

NEURAL CORRELATES OF MORPHOLOGICAL PROCESSING AND ITS DEVELOPMENT FROM PRE-SCHOOL TO THE FIRST GRADE IN CHILDREN WITH AND WITHOUT FAMILIAL RISK FOR DYSLEXIA

by

Natalia Louleli, Jarmo A. Hämäläinen, Lea Nieminen, Tiina Parviainen &
Paavo H.T. Leppänen, 2021

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III

BEHAVIORAL AND BRAIN MEASURES OF MORPHOLOGICAL PROCESSING IN CHILDREN WITH AND WITHOUT FAMILIAL RISK FOR DYSLEXIA FROM PRE-SCHOOL TO FIRST GRADE

by

Natalia Louleli, Jarmo A. Hämäläinen & Paavo H.T. Leppänen, April 2021

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Behavioral and Brain Measures of Morphological Processing in Children With and Without Familial Risk for Dyslexia From Pre-school to First Grade

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School-age reading skills are associated with and predicted by preschool-age cognitive risk factors for dyslexia, such as deficits in phonological awareness, rapid automatized naming, letter knowledge, and verbal short-term memory. In addition, evidence exists that problems in morphological information processing could be considered a risk factor for dyslexia. In the present study, 27 children at pre-school age and the same 27 children at first grade age performed a morphological awareness task while their brain responses were measured with magnetoencephalography. Our aim was to examine how derivational morphology in Finnish language, and concomitant accuracy and reaction times are associated with first grade reading, in addition to the preschool age reading-related cognitive skills. The results replicated earlier findings; we found significant correlations between pre-school phonological skills and first-grade reading, pre-school rapid naming and first-grade reading, and pre-school verbal short-term memory and first-grade reading. The results also revealed a significant correlation between the pre-school children's reaction time for correctly derived words in the morphological task and the first-grade children's performance in rapid automatized naming for letters. No significant correlations were found between brain activation measures of morphological processing and first-grade reading.

Keywords: derivational morphology, pre-school children, at risk for dyslexia, reading development, longitudinal, MEG, first-grade children

INTRODUCTION

The development of reading is a critically, increasingly important skill in our modern society. Learning to read is a continuous process that starts to develop during pre-school and kindergarten, before the starting point of formal education. Previous studies have demonstrated that pre-school linguistic and cognitive skills (such as phonological processing, rapid automatized naming (RAN), letter knowledge and verbal short-term memory) measured behaviorally predict school-age reading skills and/or reading difficulties (Landerl and Wimmer, 2008; Puolakanaho et al., 2008; Ziegler et al., 2010; Melby-Lervåg et al., 2012; Araújo et al., 2015; Clayton et al., 2019). Also, it is evident that morphological information processing is an essential feature of typical reading acquisition

(Carlisle, 2003; Kuo and Anderson, 2006). The aim of the current study was to longitudinally examine whether the neural underpinnings of morphological information processing in preschool children with and without familial risk for dyslexia can be predictors of reading development in first grade. Moreover, we aimed to examine whether poor morphological processing can be considered a risk factor for reading difficulties (Louleli et al., 2020; Louleli et al., under review), especially in a morphologically rich language such as Finnish.

Characteristics of the Finnish Language

Learning to read in a transparent language requires accurately learning the combinations between graphemes and phonemes—which, in Finnish, are nearly fully transparent (i.e., one grapheme corresponds to one phoneme; Seymour et al., 2003; Lyytinen et al., 2015; Aro, 2017). Learning to read accurately is a relatively fast process for Finnish children since most of them learn to read accurately after 1 year of formal reading instruction (Lerkkanen et al., 2004; Soodla et al., 2015). Despite its very transparent phonological system, the Finnish language has a complex morphological system with rich inflectional morphology and divergent derivational morphology; a significant number of words are produced by derivational operations (Kiefer and Laakso, 2014). Previous behavioral studies conducted in young children have shown that awareness of derivational morphology is correlated with accurate word reading, especially in languages with transparent orthographies and rich morphological systems (i.e., Italian: Burani et al., 2002; Spanish: Ramirez et al., 2010; Greek: Diamanti et al., 2017; Manolitsis et al., 2017).

In the current study, the focus is on Finnish derivational morphology. Derivation is a type of morphological operation used for the creation and production of new words, using from one to multiple morphemes per stem or word. During the derivational operations, the morphemes need to be attached either before the stem (prefix: **un**-happy) or after the stem (suffix: danc-**er**). Usually, the derived new words are somehow semantically connected with the stem (such as the cases of play–player and dance–dancer). There is a variety of derivational suffixes in the Finnish language (almost 140 different suffixes; Kiefer and Laakso, 2014). In the morphological task, we used the derivational suffix /-jA/, which is used to derive highly frequent words only from verbs (e.g., opetta-ja = teacher; Kiefer and Laakso, 2014).

Reading Difficulties: Dyslexia

Persistent difficulties in typical reading acquisition and reading development are characterized as developmental dyslexia (Ramus et al., 2003; Vellutino et al., 2004). Developmental dyslexia has a strong genetic background, which means that it is passed down from one generation to another; that is why an individual with a genetically inherited risk for dyslexia has a larger probability of developing dyslexia later on in life (Byrne et al., 2006; van Bergen et al., 2011; Olson and Keenan, 2015).

Some studies have reported that children with familial risk for dyslexia tend to have lower performance on phonological awareness tasks (Snowling et al., 2003; Boets et al., 2010; Torppa et al., 2010; van Bergen et al., 2011; Van Bergen et al., 2012) or that people with dyslexia have lower scores in tasks involving phonological short-term memory and speech perception (Ramus et al., 2003; Shaywitz and Shaywitz, 2005; Ziegler and Goswami, 2005; Hämäläinen et al., 2013). However, it is evident that dyslexic individuals also deal with other difficulties—for example, the processing of auditory information (Goswami, 2002), visual attention span (Valdois et al., 2004, 2011; Bosse et al., 2007; Lallier and Valdois, 2012; Lobier et al., 2012) and RAN (de Jong and van der Leij, 2003; Puolakanaho et al., 2007; Torppa et al., 2007; Papadopoulos et al., 2016; Lohvansuu et al., 2018). The comorbidity in dyslexia is illustrated by Pennington's (2006) multiple deficit model—in which, when reading difficulty is not based on a single deficit, dyslexia is typically an outcome of the interaction of multiple risk factors per individual.

Predictors of Reading Difficulties

Early pre-literacy and language skills developed before kindergarten can be strong predictors for later reading skills and reading difficulties. Previous studies have demonstrated that phonological awareness, phonological short-term memory, letter knowledge, and RAN are good early predictors for fluent reading performance across multiple orthographies (Landerl and Wimmer, 2008; Puolakanaho et al., 2008; Ziegler et al., 2010; Melby-Lervåg et al., 2012; meta-analyses: Araújo et al., 2015; Clayton et al., 2019).

Phonological awareness is the ability to consciously identify and manipulate the phonemes and syllables of a language (Goswami and Bryant, 1990). For several years, phonological awareness has been considered the core deficit in developmental dyslexia, and that is why its predictive link with reading skills has been studied extensively (review: Castles and Coltheart, 2004). Letter knowledge is the ability to accurately relate graphemes (letters) with phonemes (sounds), and previous studies have already shown its predictive role in reading acquisition (Puolakanaho et al., 2008; Torppa et al., 2010). A RAN task measures the ability to name accurately and as fast as possible visual items such as objects, letters, colors or digits (Denckla and Rudel, 1976). Many studies have established RAN's important value as a predictive measure of reading skills in many languages (Kirby et al., 2010; Moll et al., 2014; Georgiou et al., 2016), including both opaque and transparent languages (Landerl et al., 2019).

Morphological Information Processing as a Risk Factor

Morphological awareness is the explicit knowledge of morphemes, which are the smallest linguistic items with semantic properties (Carlisle, 2003; Kuo and Anderson, 2006). Morphological awareness has been found to predict later reading skills in first-, second, and third-grade children (Kirby et al., 2012) and explain the variance in reading comprehension (Müller and Brady, 2001; Kirby et al., 2012). A very recent study by Lyster et al. (2020) longitudinally examined, with behavioral measures, the joint contribution of pre-school linguistic skills (phonological, morphological, and semantic awareness) to the reading comprehension of first-, second-, and ninth-grade children. The results showed that these pre-school linguistic skills together accounted for 69.2% of the variance in reading comprehension in the ninth grade (Lyster et al., 2020). However, it is worth mentioning that the study focused on compounding morphology and did not examine the contribution of morphological awareness as a unique variable in the acquisition of typical reading skills but rather together with phonological and semantic awareness.

Many behavioral studies have shown that morphological awareness is associated with reading development across many languages (French: Casalis and Louis-Alexandre, 2000; Dutch: Rispens et al., 2008; English: Kirby et al., 2012; Greek: Diamanti et al., 2017; Japanese: Muroya et al., 2017; and Arabic: Tibi and Kirby, 2017). Moreover, previous studies have focused their interest on examining morphological awareness and morphological processing skills in children with and without risk for dyslexia either behaviorally (Casalis et al., 2004; Egan and Price, 2004; Law et al., 2016) or by using neuroimaging techniques (Louleli et al., 2020; Louleli et al., under review). In the behavioral studies, the link between phonological and morphological awareness was examined. Specifically, morphological awareness skills of first-grade students were found to be predicted by phonological processing measured at pre-school age (Cunningham and Carroll, 2015). Similarly, pre-school children with familial risk for dyslexia were found to have both phonological and morphological awareness deficits (Law et al., 2017). These results indicate 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 and Ghesquière, 2017; Law et al., 2017).

To our knowledge, no studies have examined the brain basis of morphological information processing in pre-school and first-grade children and its predictive association with the acquisition of typical reading skills. Our previous studies have demonstrated awareness of derivational morphology in the brain responses of six- to seven-year-old pre-school children with and without risk for dyslexia (Louleli et al., 2020) and 7–8 year-old first-grade children with and without risk for dyslexia (Louleli et al., under review). Specifically, we created a morphological task with correctly and incorrectly derived words and pseudowords, and we measured the brain responses of children with magnetoencephalography (MEG) recordings in two phases: pre-school age and first-grade age (Louleli et al., 2020; Louleli et al., under review). The results showed that both groups were sensitive to correct and incorrect morphological constructs for real words and pseudowords in both ages. However, the at-risk group in both ages exhibited differences in brain activation patterns for derived morphology, compared to the typically developing group, presumably due to their familial risk for dyslexia. Specifically, there were differences in the temporal and spatial distributions of brain activation at the pre-school age between typically developing children and children at risk for dyslexia (Louleli et al., 2020), and differences were found in the timing of brain activation at first-grade age between typically developing children and children at risk for dyslexia (Louleli et al., under review).

Goal of the Study

The aim of our study was to examine, using a longitudinal design, the morphological information processing skills from pre-school age to first-grade age and the relationship between morphological information processing and reading skills in children with and without risk for dyslexia. Specifically, we aimed to test the relationship of brain responses measured with MEG, with accuracy and reaction time scores to auditorily presented correctly and incorrectly derived morphological constructs for real words and pseudowords at pre-school age, with reading measures at first-grade age (see Louleli et al., 2020). To gain a comprehensive understanding of the role of morphological processing, we also measured cognitive skills (phonological processing, rapid naming, and verbal short-term memory) at both pre-school age and first-grade age and examined the relationship between morphological skills and them, as well as their intercorrelations. Further, we examined whether derivational morphological skills at the first-grade age would be related to reading skills, when the children have been taught how to read during the first school year.

METHODS

Participants

A longitudinal sample of native Finnish-speaking children was tested at pre-school age (6.5–7 years) and again the same children were tested at first-grade age (7.5–8 years). The participants are the same as the ones at pre-school age (Louleli et al., 2020) and first-grade age (Louleli et al., under review) MEG data we reported previously. The number of participants at the pre-school age was 40 (22 typically developing and 18 at risk for dyslexia) for real words and 34 (17 typically developing and 17 at risk for dyslexia) for pseudowords (**Table 1**). The number of participants at first-grade age was 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. All of them were native Finnish speakers with normal or corrected-to-normal vision. The participants were screened with a questionnaire filled out by the parents for the following exclusion criteria: hearing problems, head injuries, neurological problems or medication that could affect the central nervous system. As in our previous studies (Louleli et al., 2020; Louleli et al., under review), at both ages, we included children with familial risk for dyslexia. The risk for dyslexia was defined by having one parent and/or sibling with diagnosed dyslexia and/or a parent with reading problems reported in the questionnaire.

For the longitudinal analyses, we used the data of 27 pre-school children (16 typically developing children and 11 children with familial risk for dyslexia) and the same children in first grade, who all participated in the behavioral assessments and the MEG measurements (**Table 1**).

This study was approved by the Ethical Committee of the University of Jyväskylä in accordance with the Declaration of Helsinki. Before each measurement (pre-school and first-grade ages), we fully informed the children and their parents about the aims and methods of the study. All the participants and their parents were asked to give their written consent before

TABLE 1 | Demographic information of the pre-school and first-grade children included in the data analyses.

Morphological task	**Real words**		**Pseudowords**	
Age of the measurement and groups	**Pre-school children: typically developing**	**Pre-school children: at risk for dyslexia**	**Pre-school children: typically developing**	**Pre-school children: at risk for dyslexia**
Number of participants	16	11	14	9
Age (average)	6 years and 7 months (*SD* = 0.36)	6 years and 8 months (*SD* = 0.44)	6 years and 8 months (*SD* = 0.37)	6 years and 8 months (*SD* = 0.49)
Gender	9 girls and 7 boys	4 girls and 7 boys	8 girls and 6 boys	3 girls and 6 boys
Handedness	15 right-handed	11 right-handed	13 right-handed	9 right-handed
Age of the measurement and groups	**First-grade children: typically developing**	**First-grade children: at risk for dyslexia**	**First-grade children: typically developing**	**First-grade children: at risk for dyslexia**
Number of participants	16	11	14	9
Age (average)	7 years and 7 months (*SD* = 0.36)	7 years and 8 months (*SD* = 0.44)	7 years and 8 months (*SD* = 0.37)	7 years and 8 months (*SD* = 0.49)
Gender	9 girls and 7 boys	4 girls and 7 boys	8 girls and 6 boys	3 girls and 6 boys
Handedness	15 right-handed	11 right-handed	13 right-handed	9 right-handed

participating in the study. For the MEG measurements, a movie ticket was given to each child as a compensation token for the time spent participating in the study. Both the pre-school and first-grade children undertook all the aforementioned behavioral assessments—except RAN (letters), dictation, and non-word text reading, which were carried out by only the first-grade children.

Behavioral Assessments

A number of behavioral tests were administered to the participants (pre-school and first grade) in each measurement session on a separate visit to the Department of Psychology at the University of Jyväskylä (**Table 2**). These behavioral tests were conducted to run correlation analyses between the children's performance in the MEG morphological task and cognitive skill levels.

From the Wechsler Intelligence Scale for Children—Fourth Edition (Wechsler, 2003), the following tests were administered: to assess visuospatial reasoning, a *block design* was used. In this test, the children were shown how to make a specific design of arranged blocks, and then they had to build the same design. In the test of expressive *vocabulary*, the children heard a specific word (e.g., "car," "legend," "posture," "rarely") and had to describe the meaning of that word. To assess working memory, the *digit span* test was used, where a series of numbers was said to a child. The series of numbers had increasing difficulty: starting with two digits (e.g., 2, 9) and they were ending with a series of eight digits (e.g., 4, 2, 6, 9, 1, 7, 8, 3). Each child had to repeat all the series of numbers first in forward order and then the series of numbers in backward order.

Phonological decoding and memory were assessed with the *Repetition of Nonsense Words* subtest from NEPSY I (Korkman et al., 2007). During the test, each participant was asked to repeat non-sense words (e.g., esse) out loud. Phonological awareness was tested using the *Phonological Processing Task* from NEPSY II (Korkman et al., 2007). In this task, the participant had to perform word segment recognition, where he/she had to identify words from segments and make phonological elision. He/she had to repeat a word and then repeat another word by omitting a phoneme or a syllable (e.g., say the word "pusero" ("blouse") without the syllable'se', for which the correct response would be "puro"). Memory for linguistic material was assessed by the *Sentence Repetition Test*, where the child had to repeat sentences of increasing length and complexity [e.g., "Koira juoksi kotiin" (The dog ran home)].

RAN (Denckla and Rudel, 1976) was used to test the ability to quickly name familiar objects. In this task, the participants had to name five objects as quickly and accurately as possible. The objects were frequent, everyday life objects arranged in 5 rows, with 10 objects per row. The task was recorded, and the performance of the participants was calculated in seconds based on the recordings. For the first-grade children, *RAN letters* was also measured: the participants had to name five letters as quickly and accurately as possible in a similar task.

The participants' reading skills at pre-school age were assessed with two reading tests (*word list reading* and *non-word list reading*) and at first-grade age with three reading tests (*word list reading, non-word list reading*, and *non-word text reading*). For *word list reading*, we used a standardized test (Lukilasse: Häyrinen et al., 1999) in which the participants had to read a list of 105 words in 45 s. These words were of increasing difficulty starting with 3 letters (e.g., "eli" = or) and ending with 17 letters (e.g., ratsastussaappaat = riding boot). The total number of correctly read words during this time was used as the score. *Non-word list reading* modified from the Tests of Word Reading Efficiency (Torgesen et al., 1999) was used to assess decoding skills independent of familiar representations for real words; the participants had to read as many non-words as possible in 45 s from a 4list of 90 pseudowords (e.g., *nalosta, *okan, *nalhajat). The number of correctly read non-words during this time was used as the score. *Pseudoword text reading* measured the participants' fluency in decoding skills (Eklund et al., 2015). During the task, the participant had to read a text consisting

TABLE 2 | Descriptive statistics of the participants' cognitive skill measures (*N* = 16 pre-school and first grade typically developing children, *N* = 11 pre-school and first grade at-risk for dyslexia children, separated by "/").

Behavioral assessments	**Pre-school children (27)**				**First grade children (27)**			
Groups	**Typically developing children /At-risk for dyslexia children**				**Typically developing children /At-risk for dyslexia children**			
Values	**Mean**	**SD**	**Range**	**N**	**Mean**	**SD**	**Range**	**N**
Block design (max. 68)	24.12/23.27	9.82/9.97	10–44/10–42	16/11	32.43/28.00	12.85/12.19	10–52/14–53	16/11
Vocabulary (max. 66)	16.87/16.72	7.28/9.00	4–34/5–40	16/11	16.28/22.90	9.04/7.02	14–46/13–37	16/11
Digit span (max. 32)	9.93/9.72	3.10/2.72	0–14/4–14	16/11	12.00/11.54	1.82/2.54	9–16/8–15	16/11
Repetition of nonsense words (max. 16)	9.00/8.27	2.36/2.45	5–13/4–12	16/11	10.87/10.90	1.66/2.16	7–13/8–14	16/11
Phonological processing (max. 53)	32.68/31.00	7.06/8.02	23–45/23–50	16/11	41.50/38.45	6.77/6.77	24–53/29–50	16/11
Sentence repetition (max. 34)	22.50/21.36	6.86/2.83	0–29/17–26	16/11	25.75/25.00	2.26/1.84	21–29/23–27	16/11
RAN objects	70.30/78.25	17.33/19.94	48.63–103.75/49.20–121	16/11	66.63/62.10	19.31/8.96	39.71–119.39/46.49–74.66	16/11
RAN letters	–/–	–/–	–/–	–/–	42.68/42.54	12.83/9.65	28.39–78.08/30.11–56.98	16/11
Dictation	–/–	–/–	–/–	–/–	30.87/28.81	8.07/7.82	15–40/16–40	16/11
Word list reading	31.40/44.66	35.79/38.88	0–100/0–71	3/10	59.37/45.45	21.27/20.25	32–102/18–83	16/11
Non-word list reading (max. 90)	10.06/6.90	16.36/15.47	0–46/0–42	16/11	32.18/25.63	10.74/10.95	15–52/10–45	16/11
Non-word text reading (max. 38)	–/–	–/–	–/–	–/–	106.88/146.68	54.71/74.44	13–38/18–36	16/11

The cognitive performance for RAN letters, Dictation and Non-word text reading were measured only in children at first grade. Max. means the maximum value of the cognitive measure.

of pseudowords; the number of correctly read words and total reading time were used as the scores from a maximum of 38 pseudowords.

Also, *dictation* was assessed; the participants heard 20 words and had to write them down on a sheet of paper (e.g., "suu" (mouth), "kani" (rabbit), "juusto" (cheese). The number of correctly written words was used as the score.

MEG Morphological Task

Stimuli

In this study, we used the MEG data acquired previously from our morphological task (Louleli et al., 2020; Louleli et al., under review). The task included 216 pairs of sentences (see **Table S1**).

For *real words*, the first pair of sentences consisted of a third-person pronoun (*Hän*) and a verb—for example, *johtaa* ("to lead" [verb])—while the second pair of sentences consisted of the same third-person pronoun (*Hän*), a verb (*on*) and a noun derived from the verb with the derivational suffix *–jA* (/-ja/ - /-jä/) *johta**ja*** ("lead**er**" [noun with the agentive marker]). The suffix *–jA* (/-ja/ - /-jä/) is frequently used in the Finnish language in derivational operations, in which a verb produces a noun (*johtaa—johtaja*). The word pairs (verb–noun) were selected based on their frequency and length from a Finnish corpus of words (2010; https://github.com/GrammaticalFramework/GF/blob/master/lib/src/finnish/frequency/src/suomen-sanomalehtikielen-taajuussanasto-utf8.txt).

Pseudoword pairs were created to test the ability to apply the derivational rules for new non-existing words. These were created based on the real words. The pseudowords were pairs of words (verb–noun) with no semantic meaning and were created according to Finnish morphophonological, grammatical, and syntactic rules (Louleli et al., 2020; Louleli et al., under review). The pseudowords were matched with the real words in the number of syllables and letters and derivational ending. Further, the correctly derived nouns were matched similarly with the incorrectly derived nouns in the word and pseudoword conditions. All the real words and pseudowords were trisyllabic, including 11 words with 6 letters, 24 words with 7 letters, and 19 words with 8 letters.

All the derivational nouns were subdivided into correctly and incorrectly derived nouns, with 54 stimuli in each subdivision. The correctly derived nouns were typical Finnish word forms, whereas the incorrectly derived nouns contained an incorrect morphophonological change in the last vowel before the derivational suffix /-jA/ (e.g., *joht**i**ja* instead of *johtaja*; for more details, see Louleli et al., 2020). All the incorrectly derived forms, including the pseudowords, were created based on Finnish vowel harmony rules (for more details, see Louleli et al., 2020).

All the items of the morphological task were recorded in stereo channels by a female native Finnish speaker in a recording studio at the University of Jyväskylä using a 44 kHz sampling frequency and 32-bit quantization. The recorded sound files were edited with Sound Forge Pro 11.0 (5 ms of silence was added to each sound file at the beginning and end of each sentence).

Procedure

The participants sat comfortably in a magnetically shielded soundproof room and at a one-meter distance from the projection screen. The projector's screen refresh rate was 60 Hz. Before each morphological task, instructions were presented via headphones at 60 dB (SPL). The instructions were small stories, which fit into the children's school life to make the task more interesting and child-friendly. For the real words, a small girl had to practice for a language school exam, and the participant was asked to give her an input about which word pairs she had learned correctly and which she had not. For the pseudowords, a girl in the story was trying to form a secret language to be able to talk secretly with her friends, and the participant was asked to consult her about which word pairs could be thought of as correct Finnish words and which ones could not. In both cases, the participant had to use the response buttons: a right-button press for the correct pairs for real words or pairs that could be thought of as Finnish for pseudowords and a left-button press for the incorrect pairs for real words or pairs that could not be considered Finnish for pseudowords. The morphological task was presented with Presentation software (Neurobehavioral Systems, Inc., Albany, CA, United States) running on a Microsoft Windows computer. After the instructional stories, there was a practice task with six trials to help the participants avoid possible misunderstandings. Each child had to respond correctly in at least four or more trials in order to start running the morphological task. Otherwise, the task was explained again to the participant and the practice trials rerun.

After hearing the instructions, the main task started immediately. For each trial of the morphological task, a black fixation cross was presented on the screen for 500 ms, followed by word 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 then the participants were asked to give their responses through the response buttons.

Four blocks of 54 word pairs (216 word pairs in total) were presented in each measurement session. The first two blocks always included real words (real words with a correct or incorrect morphophonological change), and the next two blocks included pseudowords (pseudowords with a correct or incorrect morphophonological change). The word pairs within a condition were always presented together (yoked/joined stimuli); however, all the pairs were randomly intermixed. After each block of trials, short (1-min) animated videos were presented to help the participants concentrate on the task. All the items were presented only once. In total, the morphological task lasted ∼40 min. *Accuracy and reaction times* during the MEG recordings were also recorded for each stimulus type.

MEG Data Acquisition

MEG data were collected at the Center for Interdisciplinary Brain Research at the University of Jyväskylä using a 306-channel whole-head device Elekta Neuromag TRIUX system (Elekta AB, Stockholm, Sweden) with 204 gradiometers and 102 magnetometers in a magnetically shielded room. The MEG system was in a 68° upright gantry position in all the measurements. The data were collected with a sampling rate of 1,000 Hz and an online band-pass filter of 0.1–330 Hz. Continuous head position monitoring was used based on five head-position indicator coils, with three placed at the forehead and two placed behind the ears. The locations of the head-position indicator coils were determined with the Polhemus Isotrak digitizer (Polhemus, Colchester, VT, United States) based on three anatomical landmarks (nasion, right and left pre-auricular points). Additional digitized points (∼120) were also taken on the scalp for each subject for head movement compensation after the recording session. Electro-oculography was recorded using two pairs of electro-oculograms; one pair was placed horizontally and the other vertically to the participants' eyes. They were used to capture eye blinks and eye movements produced by the participant during each measurement session. An additional electrode was placed on the participant's right collarbone as a ground reference.

Head movements were corrected offline, and external noise sources were attenuated using the temporal extension of the source subspace separation algorithm (Taulu and Kajola, 2005; Taulu and Simola, 2006) in the MaxFilter program (Elekta Neuromag, Finland).

MEG Data Analysis

First, all MEG data were preprocessed with the temporal extension of the signal-space separation method (tSSS; Taulu and Kajola, 2005; Taulu and Simola, 2006) of the MaxFilter 2.2 program (Elekta AB, Stockholm, Sweden) with 30s buffers to remove external noise sources and correct for possible head movements. Bad channels were identified by visual inspection during and after each measurement. They were manually marked and then reconstructed in the MaxFilter 2.2 program.

MEG data were analyzed with BESA Research 6.1 (BESA GmbH, Munich, Germany). Independent component analysis (infomax algorithm) was applied separately for the magnetometers and gradiometers in a representative 60 s time window to remove cardiac artifacts, eye blinks and eye movements. Data were low-pass filtered at 30 Hz (zero phase, 24dB/oct) and high-pass filtered at 0.5 Hz (zero phase, 12dB/oct). Then the continuous MEG recording was epoched into trial-based windows from−200 to 1,100 ms with respect to the onset of the derivational suffix /-jA/, with a pre-stimulus baseline of 100 ms. Actually, the correctness of the morphological ending /-jA/ takes place starting from the preceding vowel, but the beginning of the suffix /-jA/ was used as the trigger point because it is a clear identifier acoustically, whereas the preceding vowel might be slightly varied in length (∼100 ms). MEG epochs exceeding over 1200 fT/cm for gradiometers and 4000 fT for magnetometers peak-to-peak amplitudes were excluded from further analysis. Each participant from both groups (typically developing and at-risk for dyslexia children) had more than 70% accepted trials (38 trials out of 54 trials accepted for the further analyses) except for three participants (1 control and 2 at risk), who had 50% accepted trials. The groups of children (typically developing and at-risk for dyslexia) did not differ in terms of removed trials. Event-related fields were obtained by averaging trials for different conditions, separately for the correctly and incorrectly derived real words and pseudowords. The two orthogonal gradiometer channel pairs were combined in Matlab R2015b using the vector sum. Based on our previous studies (Louleli et al., 2020), three time windows were investigated: 0–300, 300–700, and 700–1,100 ms.

Statistical Analysis

First, for the longitudinal sample, descriptive statistics were calculated in SPSS for the children's cognitive measures during pre-school and the first grade (**Table 2**), as well as for the accuracy and reaction times of the participants during the MEG morphological task (**Table 3**). Second, correlation analyses (Spearman's correlation coefficients) were carried out to explore (a) whether pre-school cognitive skills were correlated with first-grade cognitive skills (**Table 4**), (b) whether there was a continuation in morphological skills (accuracy and reaction times during MEG) from pre-school to the first grade (**Table 5**) and (c) whether the pre-school morphological measures during MEG were associated with the first-grade cognitive skills (**Table S2**). Third, we correlated, in BESA Statistics 2.0 (BESA GmbH, Munich, Germany), the pre-school children's brain responses to the correctly derived words vs. the incorrectly derived words and pseudowords with the first-grade children's cognitive skills (**Table S3**). All the comparisons and correlations were corrected by applying a false discovery rate (FDR) correction value of 0.05 (Benjamini and Hochberg, 1995) into the p-values. The FDR correction was applied separately for the comparisons for real words and pseudowords.

RESULTS

Behavioral Assessments of Cognitive and Morphological Skills

The behavioral measures of cognitive skills in pre-school and first grade children are presented in **Table 2** for the control and at-risk groups.

Behavioral morphological processing measures during the MEG, accuracy and reaction times for real words and pseudowords, in pre-school and first grade children are presented in **Table 3**. The results are presented separately for the control and at-risk groups.

Longitudinal Results From the Analysis of Pre-school to First-Grade Children: Cognitive and Reading Skills

Pre-school children's cognitive skills were correlated with first-grade children's cognitive skills (**Table 4**). Consistent correlations were found between the ages (pre-school age and first-grade age) in the block design, vocabulary, digit span, phonological processing, RAN objects, word list reading and non-word list reading tasks after the FDR correction. No consistent correlations were observed between non-word text reading and any other cognitive skill measures. In addition, pre-school children's phonological processing showed systematic associations with first-grade children's repetition of non-sense words, sentence repetition, RAN objects, RAN letters, word list reading and non-word list reading. Consistent correlations were found between pre-school children's word list reading and first-grade children's sentence repetition, RAN letters, dictation and non-word list reading. A correlation pattern was also observed between pre-school children's non-word list reading and first grade children's repetition of non-sense words, sentence repetition, RAN letters, dictation and word list reading (**Table 4**). In general, we found that most of the cognitive skills measured at the pre-school age were associated with the majority of the cognitive skills measured at the first-grade age.

Longitudinal Results Between Pre-school and First Grade Children: Behavioral Performance During the MEG Morphological Task

Pre-school children's behavioral performance during the MEG morphological task was correlated with first grade children's behavioral performance during the MEG morphological task for real words and pseudowords (**Table 5**). No significant correlations were found for accuracy or reaction times between age groups after FDR correction.

Longitudinal Results From the Pre-school to First Grade Children: Correlations Between Pre-school Behavioral Morphological Measures and First Grade Cognitive Skills

We studied next, how morphological information processing during the MEG morphological task at pre-school is associated with reading at the first grade (see **Table S2**). A significant correlation was observed between the pre-school children's reaction time for correctly derived real words and the first grade children's performance in the RAN letters task ($r = 0.730$, $p < 0.001$) after FDR correction. No other significant correlations were found between the pre-school's accuracy or reaction time of the MEG morphological task with the first grade's cognitive skill measures.

Longitudinal Results Between Pre-school and First Grade Children: Correlations Between Pre-school Brain Responses and First Grade Cognitive and Reading Skills

We examined next, how brain responses during the MEG morphological task at pre-school are associated with cognitive skills and reading at the first grade. Specifically, the correlations between the event-related field responses (ERF responses) of pre-school children for the correct vs. incorrect morphological contrast for real words and pseudowords and the cognitive measures of first grade children were not significant after FDR correction (see **Table S3**).

TABLE 3 | Accuracy and reaction times for real words and pseudowords (% for correct responses) for the participants' behavioral performance during the MEG morphological task (*N* = 27 pre-school children with and without risk, *N* = 27 first grade children with and without risk), separated by "/").

Morphological task	**Real words**							
Age groups	**Pre-school children (27)**				**First grade children (27)**			
Groups	**Typically developing children/At-risk for dyslexia children**				**Typically developing children /*At-risk for dyslexia children***			
Values	**Mean**	**SD**	**Range**	**N**	**Mean**	**SD**	**Range**	**N**
Accuracy, correctly derived	89.22/*84.17*	7.59/*13.05*	*77.77–98.14/53.70–100*	16/*11*	93.85/*90.39*	5.35/*9.43*	79.62–100/*66.66*	16/*11*
Accuracy, incorrectly derived	88.07/*71.88*	15.92/*32.95*	31.48–98.14/*0–96.29*	16/*11*	95.24/*94.10*	4.53/*6.61*	85.18–100/*81.48–100*	16/*11*
RT, correctly derived	1735.12/*1238.03*	1945.31/*385.03*	821.90-8847.85/*557.55-1702.77*	16/*11*	1324.68/*1015.95*	868.80/*422.64*	548.33–4049.53/*552.79–1903.75*	16/*11*
RT, incorrectly derived	1172.56/*1114.55*	575.75/*376.51*	705.88–3038.25/*456.66–1639.29*	16/*11*	1055.03/*891.39*	485.79/*174.01*	472.33–2374.07/*556.37–1138*	16/*11*
Morphological task	**Pseudowords**							
Age groups	**Pre-school children (27)**				**First grade children (27)**			
Groups	**Typically developing children /At-risk for dyslexia children**				**Typically developing children /At-risk for dyslexia children**			
Values	**Mean**	**SD**	**Range**	**N**	**Mean**	**SD**	**Range**	**N**
Accuracy, correctly derived	41.44/*48.98*	29.41/*24.33*	1.85–85.18/*0–87.03*	13/*11*	73.78/*67.50*	17.70/*19.88*	50–98.14/*38.88–96.29*	16/*11*
Accuracy, incorrectly derived	68.79/*74.23*	25.50/*18.49*	20.37–98.14/*46.29–100*	13/*11*	68.16/*56.05*	15.77/*24.18*	46.29–92.59/*25.92–94.44*	16/*11*
RT, correctly derived	1351.32/*1424.69*	662.14/*682.42*	505.12–2371.98/*643.77–2895.85*	13/*11*	2029.94/*1672.01*	1442.11/*870.22*	61.11–5660.44/*579.44–3604.94*	14/*11*
RT, incorrectly derived	1323.22/*1355.38*	746.20/*651.37*	411.96–2663.40/*479.09–2414.98*	13/*11*	1955.46/*1580.55*	1164.70/*630.56*	614.68–5163.75/*482.79–2597.79*	16/*11*

Fifty-four (54) responses was the maximum number of responses per category.

TABLE 4 | Correlations (Spearman's) between cognitive skills of pre-school and first grade children ($N = 27$, 16 Controls & 11 At-risk).

Behavioral assessments	Correlations between pre-school and first grade behavioral cognitive measures											
	Block design_1gr	**Vocabulary_1gr**	**Digit span_1gr**	**Repetition of non-sense words_1gr**	**Phonological processing_1gr**	**Sentence repetition_1gr**	**RAN objects_1gr**	**RAN letters_1gr**	**Dictation_1gr**	**Word list reading_1gr**	**Non-word list reading_1gr**	**Non-word text reading_1gr**
Block design_pre	**0.789***	0.300	0.227	0.076	0.391*	0.163	−0.175	0.008	0.222	0.115	0.225	0.063
	$p < 0.001$	$p = 0.128$	$p = 0.255$	$p = 0.708$	$p = 0.043$	$p = 0.417$	$p = 0.382$	$p = 0.970$	$p = 0.266$	$p = 0.566$	$p = 0.260$	$p = 0.754$
Vocabulary_pre	0.305	**0.596***	0.147	0.354	**0.549***	**0.523***	−0.301	−0.221	0.114	0.205	0.212	−0.043
	$p = 0.122$	**$p = 0.001$**	$p = 0.465$	$p = 0.70$	**$p = 0.003$**	**$p = 0.005$**	$p = 0.128$	$p = 0.267$	$p = 0.570$	$p = 0.305$	$p = 0.289$	$p = 0.830$
Digit span_pre	0.425*	**0.623***	**0.563***	0.349	**0.551***	**0.772***	−0.347	**−0.474***	**0.560***	**0.518***	**0.596***	0.272
	$p = 0.27$	**$p = 0.001$**	**$p = 0.002$**	$p = 0.075$	**$p = 0.003$**	**$p < 0.001$**	$p = 0.076$	**$p = 0.013$**	**$p = 0.002$**	**$p = 0.006$**	**$p = 0.001$**	$p = 0.170$
Repetition of non-sense words_pre	−0.058	0.323	**0.465***	0.356	0.270	0.425*	−0.291	−0.348	0.093	0.361	0.344	−0.065
	$p = 0.774$	$p = 0.100$	**$p = 0.015$**	$p = 0.68$	$p = 0.174$	$p = 0.027$	$p = 0.141$	$p = 0.075$	$p = 0.645$	$p = 0.064$	$p = 0.079$	$p = 0.749$
Phonological processing_pre	0.135	0.206	0.322	**0.471***	**0.474***	**0.741***	**−0.506***	**−0.472***	0.437*	**0.569***	**0.560***	0.309
	$p = 0.502$	$p = 0.302$	$p = 0.101$	**$p = 0.013$**	**$p = 0.012$**	**$p < 0.001$**	**$p = 0.007$**	**$p = 0.013$**	$p = 0.023$	**$p = 0.002$**	**$p = 0.002$**	$p = 0.116$
Sentence repetition_pre	0.090	**0.456***	0.174	0.256	0.400*	**0.687***	−0.369	−0.325	0.022	0.147	0.185	−0.036
	$p = 0.656$	**$p = 0.017$**	$p = 0.384$	$p = 0.197$	$p = 0.038$	**$p < 0.001$**	$p = 0.058$	$p = 0.098$	$p = 0.915$	$p = 0.466$	$p = 0.355$	$p = 0.859$
RAN objects_pre	−0.156	−0.236	−0.354	**−0.578***	−0.013	−0.418*	**−0.532***	**0.618***	−0.297	**−0.490***	**−0.476***	−0.037
	$p = 0.437$	$p = 0.236$	$p = 0.070$	**$p = 0.002$**	$p = 0.948$	$p = 0.030$	**$p = 0.004$**	**$p = 0.001$**	$p = 0.133$	**$p = 0.009$**	**$p = 0.012$**	$p = 0.856$
Word list reading_pre	**0.576***	0.526	0.169	0.341	0.593*	**0.655***	−0.077	**−0.646***	**0.686***	**0.895***	**0.863***	0.416
	$p = 0.039$	$p = 0.065$	$p = 0.580$	$p = 0.254$	$p = 0.033$	**$p = 0.015$**	$p = 0.802$	**$p = 0.017$**	**$p = 0.010$**	**$p < 0.001$**	**$p < 0.001$**	$p = 0.157$
Non-word list reading_pre	0.313	0.357	0.279	**0.492***	**0.554***	**0.667***	−0.434*	**−0.546***	**0.519***	**0.952***	**0.733***	0.288
	$p = 0.111$	$p = 0.068$	$p = 0.158$	**$p = 0.009$**	**$p = 0.003$**	**$p < 0.001$**	$p = 0.024$	**$p = 0.003$**	**$p = 0.006$**	**$p < 0.001$**	**$p < 0.001$**	$p = 0.145$

Bold are the significant correlations, which remain significant after FDR corrections.

TABLE 5 | Correlations (Spearman's) between the pre-school children's behavioral performance during the MEG morphological task and the first grade children's behavioral performance during the MEG morphological task for real words (*N* = 27 pre-school children with and without risk, *N* = 27 first grade children with and without risk) and for pseudowords (*N* = 23 pre-school children with and without risk, *N* = 23 first grade children with and without risk).

Real Words

Behavioral assessments	**Accuracy for correctly derived_1gr**	**Accuracy for incorrectly derived_1gr**	**RT for correctly derived_1gr**	**RT for incorrectly derived_1gr**
Accuracy for correctly derived_pre	0.348	0.250	0.085	−0.022
	p = 0.076	*p* = 0.208	*p* = 0.675	*p* = 0.913
Accuracy for incorrectly derived_pre	0.332	0.199	0.113	−0.041
	p = 0.091	*p* = 0.320	*p* = 0.575	*p* = 0.838
RT for correctly derived_pre	−0.095	0.134	**0.465***	**0.464***
	p = 0.639	*p* = 0.505	***p* = 0.014**	***p* = 0.015**
RT for incorrectly derived_pre	−0.240	0.077	**0.505***	**0.428***
	p = 0.227	*p* = 0.702	***p* = 0.007**	***p* = 0.026**

Pseudowords

Behavioral assessments	**Accuracy for correctly derived_1gr**	**Accuracy for incorrectly derived_1gr**	**RT for correctly derived_1gr**	**RT for incorrectly derived_1gr**
Accuracy for correctly derived_pre	0.156	0.151	−0.272	−0.263
	p = 0.467	*p* = 0.482	*p* = 0.198	*p* = 0.214
Accuracy for incorrectly derived_pre	−0.090	0.271	0.097	0.174
	p = 0.675	*p* = 0.200	*p* = 0.652	*p* = 0.417
RT for correctly derived_pre	0.295	−0.084	0.317	**0.529***
	p = 0.162	*p* = 0.696	*p* = 0.132	***p* = 0.008**
RT for incorrectly derived_pre	0.304	−0.087	0.345	**0.529***
	p = 0.149	*p* = 0.687	*p* = 0.098	***p* = 0.008**

Bold are the significant correlations before FDR correction. No correlations remained significant after the FDR correction.

Longitudinal Results Between Pre-school and First Grade Children: Pre-school Brain Responses and First Grade Behavioral Performance During the MEG Morphological Task

Then, we investigated the relationship between the pre-school brain responses for the correct vs. incorrect morphological contrast for real words and pseudowords with the behavioral performance of first grade children during the MEG morphological task, using correlations. No significant correlations were found between pre-school children's brain responses to the correct vs. incorrect morphological contrast and the first grade children's performance (accuracy and reaction time) after FDR correction.

Cross-Sectional Results of First Grade Children

We also conducted corresponding correlation analyses cross-sectionally at the first grade between morphological measures (both behavioral and brain measures) and reading related cognitive skills (phonological awareness, rapid automatized naming (RAN), letter knowledge, and verbal short-term memory) and reading skills. No significant correlations were observed for the aforementioned comparisons. Also, we tested between-group differences in first grade children with high and low reading performance with cluster-based permutation tests. Specifically, we compared the brain responses of 11 first grade children with high reading performance with the brain responses of 11 first grade children with low reading performance for the difference between the correctly vs. incorrectly derived real words. No significant between-group brain differences emerged for the correct vs. incorrect morphological contrast after FDR correction.

DISCUSSION

Our study longitudinally examined the developmental changes of morphological information processing in pre-school and first-grade children with and without familial risk for dyslexia. To our knowledge, this is the first study to longitudinally investigate derivational morphology in children measured at pre-school and first-grade ages. Moreover, we investigated whether morphological processing is associated with reading skills at first-grade age.

The Associations Between Reading-Related Cognitive Skills at Pre-school and First-Grade Ages Confirm Previous Literature

One of the goals was to investigate whether pre-school cognitive skills known to predict reading later on are associated with first-grade cognitive and reading skills. The correlation analyses confirmed the general findings in the literature (**Table 4**). Specifically, significant correlations were found between the same skill tested at the two ages in the block design, vocabulary, digit span, phonological processing, RAN objects, word list reading and non-word list reading. More interestingly, and mostly in line with earlier studies, pre-school children's performance in phonological processing was found to be correlated with first grade children's performance in repetition of non-sense words, sentence repetition, RAN objects, RAN letters, word list reading and non-word list reading at the first grade children. In addition, significant correlations were found between pre-school word list reading and first grade sentence repetition, RAN letters, dictation and, as expected, non-word list reading. Likewise, pre-school pseudoword reading (in a non-word list reading task) was associated with the first grade repetition of non-sense words, sentence repetition, RAN letters, dictation and word list reading. Our results are in line with previous studies, which have shown pre-school phonological processing, rapid automatized naming (RAN), letter knowledge and verbal short-term memory measured behaviorally to be good predictors of reading skills throughout school-age (Landerl and Wimmer, 2008; Puolakanaho et al., 2008; Ziegler et al., 2010; Melby-Lervåg et al., 2012; Araújo et al., 2015; Clayton et al., 2019).

Preschool-Age Morphological Skills Were Only Partially Associated With the Morphological Skills at First-Grade Age

We then examined whether the morphological skills of pre-school children would be associated with the morphological skills at the first grade children, which would show how well the pre-school skills predict later skills in the domain of derivational morphology. We used a morphological task assessing Finnish derivational morphology during MEG recordings. Although none of the accuracy or reaction time measure correlations survived FDR correction (**Table 5**), reaction times showed rather consistent correlations for real words between the age groups suggesting tentatively that those who were faster at pre-school age in recognizing both the correct and incorrect derivation were also faster at the first grade. Interestingly, for pseudowords this kind of relationship was found only to the incorrectly derived word, suggesting tentatively that in case of non-existing words, only breaking the rule (incorrect derivations) was recognized faster by the same children at both ages. The failure to show correlations surviving FDR corrections could be due to a relative small sample for correlations. Alternatively, our results could suggest that behavioral differences in morphological information processing do not progress at the same pace in the majority of children at this developmental stage. Another study showed that morphological awareness is acquired at pre-school age and especially before formal reading instruction, but that it evolves continuously; children's performance in morphological tasks (tasks assessing derivational and inflectional morphology) increases from kindergarten to the first and second grades throughout adulthood (Casalis and Louis-Alexandre, 2000).

A study by Lyster et al. investigated with behavioral assessments the input of phonological, morphological and semantic awareness to reading comprehension at 1st, 2nd and 9th grade (Lyster et al., 2020). Their results showed that pre-school linguistic skills are very important for reading comprehension later on, even up to the 9th grade. However, it is noteworthy that this study itself, even though it demonstrates the importance of phonological, morphological, and semantic awareness in the acquisition of typical reading skills, it did not assess the contribution of phonological, morphological, and semantic awareness as unique variables, but rather as a sum all together (Lyster et al., 2020).

Previous studies investigated the relationship between phonological and morphological awareness (Law and Ghesquière, 2017; Law et al., 2017). Specifically, they found out that pre-school children with familial risk for dyslexia had problems in both phonological and morphological awareness skills (Wug test: 29 questions assessing inflectional and 8 questions assessing derivational morphology) (Law et al., 2017). Overall, these results indicated that phonological and morphological awareness are strongly related and that it is possible that the difficulties in morphological awareness arise from difficulties in phonological awareness (Law and Ghesquière, 2017; Law et al., 2017).

Morphological Information Processing Is Associated With Reading Development From Preschool Age to First-Grade Age in Children With and Without Risk for Dyslexia

Our main aim was to investigate the association between pre-school morphological information processing and the first grade children's reading development. For this purpose, we calculated correlations between the behavioral performance (accuracy and reaction time) of pre-school children during the MEG morphological task and the reading related cognitive skills and reading at the first grade (**Table S2**). A significant correlation was only found between the pre-school RT performance for correctly derived real words and the first grade performance in the RAN letters task ($r = 0.730, p < 0.001$) after FDR correction.

This correlation could indicate association between speed (or fluency) of emerging morphological information processing (Finnish derivational morphology) at pre-school and development of fluency in naming letters, an endophenotype or precursor of fluent reading. Previous studies have already shown the importance of RAN in predicting reading fluency in Finnish language (Eklund et al., 2015; Torppa et al., 2016) as well as in other orthographies (Kirby et al., 2010; Moll et al., 2014; Georgiou et al., 2016; Landerl et al., 2019). The new knowledge brought here is that morphological processing is linked to the processing or skill measured by RAN letters and RAN letters measures the fluency of lexical access to existing representations (Eklund et al., 2015; Torppa et al., 2016).

However, it should be noted that this association did not extend to actual reading skills, making strong conclusions difficult to draw. On the other hand, reading at the first grade is mainly reflecting accuracy of decoding, whereas RAN also predicts reading fluency which only starts to emerge at the first grade. It is also noteworthy that our morphological task contains a repetitive mode of morphological structure (Hän verb - Hän on verb stem + /jA/), which means that there might be automatization in the children's answers. This automatization in the response patterns is also in line with the characteristics of the rapid naming tasks, and thus that is possibly why we see a strong relationship between the pre-school children's reaction time for correctly derived real words in the morphological task and the first grade performance in RAN letters. Some forms of representations are also required for fluent morphological processing, as no correlations were found for pseudowords, which would require the ability to apply a rule to new words. Thus, it is possible that RAN letters and morphological processing might share common mechanisms related to fluency and automatization. Further studies are necessary in order to disentangle the aforementioned relationship between the tasks.

The Brain Responses of Pre-school Children With and Without Familial Risk for Dyslexia Did Not Predict Their Reading Performance 1 Year Later During First Grade

To our knowledge, this is the first study to examine the predictive value of pre-school morphological information processing at the brain level and its association with the acquisition of typical reading skills from kindergarten to first grade children. In our previous studies, we demonstrated that awareness of Finnish derivational morphology was depicted in the brain responses of both 6–7-year-old pre-school children and 7–8-year-old first grade children (with and without risk for dyslexia) (Louleli et al., 2020; Louleli et al., under review).

In the current study, we did not observe any significant correlations (after FDR correction) between pre-school children's brain responses to the correctly vs. incorrectly derived words or pseudowords and the cognitive performance or reading skills at the first grade. Even though we found the association between pre-school behavioral performance for morphological processing (reaction time for correctly derived words) and rapid naming of letters at the first grade, we did not observe the same association at the brain level. This indicates that the aggregate process reflected in reaction times seems to be a more robust measure of morphological processing compared to the ERFs which reflect specific neural processes evolving in time. Further, ERFs capture only part of the neural activity and examination of, for example, non-phase locked activity in the frequency domain could reveal further possible connection at the brain level. At any rate, our results show there is no strong link between brain activity for derivational morphological processing and emerging decoding skills.

Another reason for the lack of associations between morphological skills and reading could be due to the type of morphological skills tested, namely derivational morphology. The connection between morphological skills and reading skills has been studied before by assessing inflectional morphology (Lyytinen and Lyytinen, 2004; Torppa et al., 2010). Specifically, in the study by Lyytinen and Lyytinen (2004), Finnish inflectional morphology was investigated with behavioral tests in various pre-school ages. The results showed that children were able to manipulate units of inflectional morphology by the age of 3, which demonstrates the children's ability at pre-school age to perform basic inflectional operations of their language (Lyytinen and Lyytinen, 2004). Moreover, Torppa et al. (2010), also showed that there is an association between processing of inflectional morphology and phonological skills at the age of 3 years as well as a direct correlation between inflectional morphology and reading accuracy and fluency at 5 and 5.5 years old; these results suggest that inflectional morphology together with phonological skills could be considered as direct pre-school age pre-cursors of later reading accuracy and fluency (Torppa et al., 2010).

Leminen et al. (2013) have suggested that processing of inflectional and derivational morphology involves two different linguistic operations, which include different brain processes. In their study, they examined adults' brain responses with event-related potentials (with EEG) for both inflectional and derivational morphology (Leminen et al., 2013). They used auditory stimuli in an oddball paradigm design performed by Finnish participants. For derivational forms, they reported effects at the 130–170 ms time-window to be larger for derived words than for derived pseudowords (Leminen et al., 2013). However, for inflectional forms, they reported a different pattern; larger effects for pseudo-inflected forms than for real inflected words (Leminen et al., 2013). Their results suggest that there are distinct brain mechanisms for inflected and derived word processing based on the adults' brain activation (Leminen et al., 2013). They suggest that derivations most likely form unique brain representations, while inflections are more related with grammatical rules of morpho-syntactic processing (Leminen et al., 2013). Thus, it is possible that the acquisition of inflectional and derivational morphology enables different brain mechanisms in children as well, which still remains to be investigated, especially in native speakers of a rich morphological language like Finnish.

The morphological skills of 4–7 years old children for tasks including inflectional and derivational morphology were studied by Diamanti et al. (2018) in Greek language, which is a transparent language. In their study, they used four morphological awareness tasks to test domains of inflectional and derivational morphology (2 production tasks for inflectional morphology and 2 judgement tasks for derivational morphology). Their results showed that the production of derivational morphemes was more difficult for children than production of inflectional morphemes and judgement of derivational morphemes, which reveals that awareness of derivational morphology lacks behind that of inflectional morphology (Diamanti et al., 2018) at these early pre-reading ages.

Limitations

Our study was designed to bring new understanding about derivational morphological information processing with a longitudinal design assessing the performance of pre-school and first grade children. Our study has some limitations. For the current study, we designed our morphological task using naturally produced stimuli in order to create a more ecologically valid input for the children participating in the task. However, the naturally produced stimuli, even if they were of equal length, could be slightly different acoustically for each sentence, which might result in less robust brain responses. In addition, similar to our previous studies (Louleli et al., 2020; Louleli et al., under review), the morphological task consisted of sentences with a morphophonological change before the suffix /-jA/. However, the suffix /jA/ was rather used as the trigger point for the sensor-level analysis because it is a clear syllable acoustically, existing in all the conditions (correctly and incorrectly derived real words and pseudowords), but it was ∼100 ms after the timing of interest. Also, during the morphological awareness task, the participants had to give their responses for the correct and incorrect morphological pair of sentences through pressing right or left response buttons. The button assignment was not counterbalanced across participants, which might affect the results in terms of preparation of the motor response. However, in our study, the button press response occurred after the final syllable (500 ms waiting time and Reaction time range), which means that the button press did not likely have any effect on the responses regarding the correctly or incorrectly derived morphological endings. Moreover, the small number of participants is not ideal for correlation analyses because it could hinder to reach sensitivity to reveal significant real correlations. Also, our time did not allow us to include a comparison of inflectional vs. derivational morphology for Finnish language, which would need to be studied in the future.

CONCLUSIONS

In summary, this is the first study to examine developmentally the predictive value of processing Finnish derivational morphology from pre-school age to the first grade in children with and without risk for dyslexia both at the behavioral and neural level and their association to reading related cognitive skill and reading. First, we investigated and replicated the relationship between pre-school and first grade cognitive skills confirming the typical correlations found in the previous literature. We then examined processing of Finnish derivational morphology using both accuracy and reaction time measures in morphological tasks and the concomitantly brain responses with MEG. The significant correlation found between reaction time for correctly derived words and RAN letters could suggest an association between naming speed and fluency of morphological processing for Finnish derivational morphology at pre-school and development of fluency in naming letters. Thus, it is possible that RAN letters and morphological processing, especially derivational morphology, might contain analogous mechanisms in relation to fluency and automatization. We further compared the brain responses of pre-school children with the reading performance of first grade children. However, no significant correlations were observed for the brain responses. Finally, derivational morphology (brain responses and behavioral performance) was correlated cross-sectionally to cognitive and reading measures and no significant correlations were observed. Our current findings together with our previous neuroimaging results (Louleli et al., 2020; Louleli et al., under review), show that children possess morphological skills for derived words and pseudowords, but this skill does not seem to be related with reading acquisition.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Committee of the University of Jyväskylä in accordance with the Declaration of Helsinki. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

NL, JH, and PL designed the study and analyzed the data. NL performed the MEG experiments. All authors discussed the results and contributed to the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2021.655402/full#supplementary-material

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