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PEDAGOGISCHE WETENSCHAPPEN

Onderzoekseenheid Gezins- en Orthopedagogiek

THE LINK BETWEEN PARENTAL READING SKILLS AND COGNITIVE AND NEUROANATOMICAL MEASURES IN PRE-READERS

Master's thesis submitted for the
degree of Master of Science in de
Pedagogische Wetenschappen by
Lieselore Cuynen

Supervisor: Dr. Maaike Vandermosten
Co-supervisor: Prof. Dr. Pol Ghesquière
With the collaboration of:
Jolijn Vanderauwera

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Summary

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In this study we examined whether a family risk for dyslexia, a behavioural risk or an interaction of both is associated with the neuroanatomical pathways for reading in children. Previous studies investigated family risk only based on a dyslexia diagnosis within the family, without taking into account the individual variability within parents' reading skills. In addition, previous neuroimaging studies were based on findings in school-aged children and adults. Hence, in this study we applied a dimensional approach by investigating reading skills of the affected and unaffected parent and investigated whether they could be associated with children's reading skills and their neural reading-related pathways.

This study included behavioural and magnetic resonance imaging (MRI) data of 71 children of whom 36 have a family risk for dyslexia (i.e. having at least one first-degree relative with dyslexia). Diffusion MRI and pre-literacy skills were assessed in the last year of kindergarten and reading was assessed in third grade. In addition, reading measures in parents were collected. With regard to the neuroanatomical data, for each child the arcuate fasciculus (AF) and the inferior fronto-occipital fasciculus (IFOF) were delineated for both the left and right hemisphere. We used fractional anisotropy (FA) as the index for the connections between brain regions and of the white matter properties of these connections. We will examine family and behavioural risk as a dimensional factor to take into account individual differences. Correlational and regression analyses were performed to analyse the data gathered.

A first aim of this study is to investigate the relation between parental reading skills and children's pre-literacy and reading skills. Our results show that there is a relation between parental reading skills and children's pre-literacy and reading skills. Reading experience of parents predicts a unique part of children's reading ability. No relation was found between home literacy and children's pre-literacy and reading skills. A second aim is to examine the relation between parental reading skills and the neural reading network of pre-readers. Our results show that phonological skills and parental reading data are related with bilateral AF and IFOF. However, parental reading data do not predict uniquely beyond phonological skills. We can conclude that there is a direct link between familial risk and later reading skills of children. In addition, there is an indirect link between familial risk and children's white matter connections via behavioural risk.

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Writing this article has been a challenging and valuable experience. I want to thank a few people. Without their assistance and support, I would not be able to present this article.

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Approach

This master thesis is part of a longitudinal study. The subject overlaps with the master thesis of Frauke Moerenhout, with whom I collaborated for literature study, DTI data collection and DTI data processing. In consultation with my supervisor the subject of my master thesis was further specified. To start, my supervisor provided me with some articles. Based on these scientific articles I have written down the structure of this master thesis. I searched for more articles, to complete the literature. This search was done in scientific databases such as LIMO and Web of Science. The participants for the study were already contacted, as they participated in the longitudinal study. The first data collection of this longitudinal study took place in June-September 2012. During the first data collection (wave 1) the 'submarine' protocol was used to prepare the children for the MRI scan (Theys, Wouters & Ghesquière, 2014). The second data collection (wave 2) took place in June-September 2014. In this master thesis, we will use the data from wave 1, given the time intensiveness of data processing. But myself and a fellow student have been working out the data collection protocol for the second wave that includes a story which is designed in a castle theme. The goal of this protocol is to prepare children on a MRI scan in a child-friendly way. During this second data collection, me and a fellow student prepared the children for the MRI scan using the 'castle' protocol. I conducted the statistical analysis of the data (wave 1 and 2) in SPSS. During the data-analysis, I have also delineated the most important white matter tracts which were involved in reading (wave 2). After performing these analyses, I worked out the results and interpreted the data to write the discussion.

I opted for a research article because writing an article is related to the work of a researcher and thus to what I wanted to experience. I strive for a publication of this article in Brain & Language. This journal focuses on articles about neurobiological mechanisms underlying human language. This study is in line with previous research published in this journal.

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Introduction

Research shows that 5-7% of the population develops dyslexia (Peterson & Pennington, 2012; Ramus, 2001; Ramus et al., 2003), a specific learning disorder characterized by severe and resistant reading and spelling difficulties (Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Dyslexia is considered as a multifactorial disorder, meaning that it is not caused by one etiological factor, but rather by an interaction of cognitive, neural and etiological factors (Pennington, 2006). Moreover, several studies have shown that dyslexia is highly familial, with a heredity level of about 50% (Scerri & Schulte-Körne, 2010). Dyslexia may be further associated with neuroanatomical peculiarities (Vandermosten, Boets, Wouters, & Ghesquière, 2012b). A large number of studies in adults and school-aged children demonstrates that reading involves a left lateralised neural network. Abnormalities in that network are considered to be the basis of the severe and resistant reading and spelling difficulties persons with dyslexia are struggling with (Vandermosten et al., 2012b).

Based on these findings, in this study we will investigate the relation between parental reading skills and cognitive and neuroanatomical measures in pre-readers. Adding to previous studies, the familial risk in the current study is not only determined based on diagnosis of the parent with reading difficulties but also based on the reading scores of the unaffected parent. Further, previous neuroimaging studies were based on findings in school-aged children and adults. Hence in this study, we investigate white matter pathways of pre-reading children. It is important to investigate the neural reading circuit of children at this young age, in order to know the characteristics of these brain areas before being influenced by reading instruction or reading experience. In this study we examine whether the familial risk for dyslexia, or the behavioural risk, or an interaction of both, is associated with the white matter properties of the neuroanatomical pathways of the reading network in children. In the first part of this study, we will investigate the relation between parental reading skills and children's pre-literacy and reading skills. In the second part we will examine the relation between parental reading skills and the white matter properties of the neural reading network of beginning readers.

Theoretical background

Reading and dyslexia

Reading is a cognitive skill that is not rapidly accomplished, but results from an enduring process that requires explicit instruction.

In a first stage, the logographic phase, children recognise words based on the visual features of words, similar to the recognition of visual objects. The logographic phase is rather preparatory and the 'reading' in this stage is of a primitive form. In a next stage, children learn that each grapheme is linked to a corresponding phoneme. More specifically they will apply a set of learned correspondence rules to link graphemes to phonemes and assemble them into a word (Coltheart, 2005; Geijsel & Aarnoutse, 2006). This limited set of rules allows children to get access to the meaning of thousands of newly encountered written words. This reading strategy is also called the sublexical phonological route. Through repeated exposure to patterned orthographic information, children develop a second reading strategy, i.e. the direct lexical reading route. Here children do not apply grapheme-phoneme correspondence rules, but directly recognise the words (or chunks of words) based on their visual word form (Geijsel & Aarnoutse, 2006). Whenever the child decodes an unfamiliar word, it will acquire orthographic information about this word at the same time. This can be seen as a bootstrapping mechanism, wherein the sublexical phonological route stimulates the lexical reading route (Ziegler, Perry, & Zorzi, 2014). The sublexical phonological route has to be used in new and infrequent words, while frequent words can be more easily processed by the direct lexical reading route. It has been argued that the sublexical phonological route and the direct lexical reading route supplement each other in skilled readers (Barron, 1986; Coltheart, 2005).

Although most of the children learn to read fluently, 5-7% of the population develops dyslexia (Peterson & Pennington, 2012; Ramus, 2001; Ramus et al., 2003). Dyslexia is a disorder characterized by severe reading and spelling difficulties. The difficulties persist despite intensive remediation and are not due to factors such as lack of motivation, a sensory deficit or inadequate schooling (Snowling, 2000; Vellutino et al., 2004). It is generally accepted that dyslexia derives from a phonological deficit. The phonological deficit concerns problems with the representation and processing of speech sounds, and can be expressed in three subskills, i.e. phonological awareness (PA), rapid automatized naming (RAN) and verbal short-term memory (VSTM) (Snowling, 2000). Both PA and RAN are considered as good predictors for reading (Boets et al., 2010; Caravolas, Hulme, & Snowling, 2001; Parilla, Kirby, & Mcquarrie, 2004; Wagner, Torgesen, & Rashotte, 1994). Besides these skills, also letter knowledge (LK) is often considered as a good predictor for reading (Boets et al., 2010; Puolakanaho et al., 2007).

VSTM also has a predictive value, but is less strongly associated with reading development as opposed to PA and RAN (Dandache, Wouters, & Ghesquière, 2014; Smans & Boets, 2009). Children with dyslexia perform poorly on the phonological tasks (Wagner & Torgesen, 1987) and the phonological deficit is manifest before the onset of reading instruction starts (Boets, Wouters, van Wieringen, & Ghesquière, 2007; Elbro, Borstrøm, & Petersen, 1998; Pennington & Lefly, 2001; Snowling, Gallagher, & Frith, 2003). Not only phonological skills, but also orthographic skills play an important role in the development of reading. Orthographic skills concern the representation and processing of the written form of letters and words, and can be related to the lexical reading route (Furnes & Samuelsson, 2011; Smans & Boets, 2009). Orthographic problems may be the result of the phonological problems or can be seen as an independent cause of dyslexia (Bekebrede, van der Leij, & Share, 2009; Share, 1995).

Furthermore, a reciprocal relationship between phonological skills and reading skills has been established (Bentin & Leshem, 1993; Castles & Coltheart, 2004). The phonological skills affect the reading development, but learning to read also affects the development of the phonological skills. Given that there is a reciprocal relationship it can be stated that the phonological deficit can be both cause and consequence of the reading difficulties (Castles & Coltheart, 2004; Smans & Boets, 2009). However, the phonological deficit doesn't explain all the variance in reading. Hence, researchers encourage to consider dyslexia as a multifactorial disorder.

Family risk

Dyslexia can be seen as a multifactorial disorder in which, besides cognitive skills, genetic and environmental factors are also considered as influencing factors. The multiple deficit model of Pennington (2006) also assumes that dyslexia is not caused by a single etiological factor, but rather an interaction of several risk and protective factors. This model consists of four levels namely behavioural disorders, cognitive processes, neural systems and etiological factors. For the case of dyslexia, the cognitive level includes the phonological deficit. The neural level consists of the brain networks, where the etiological level includes the genetic effects such as family risk. In addition to poor phonological skills, also family risk can be considered as an important predictor for dyslexia. Children with a family risk for dyslexia (FRD^+, i.e. having a first degree relative diagnosed with dyslexia) have a chance of 40 to 60% to ultimately develop dyslexia (Scerri & Schulte-Körne, 2010). Children without a family risk (FRD^-, i.e. no first degree relative with reading problems) have a 5 to 7% chance to develop dyslexia (Peterson & Pennington, 2012; Ramus, 2001; Ramus et al., 2003).

Genetic factors

Normal reading FRD^+ children perform weaker on reading and spelling compared to normal reading FRD^- children (Naples, Chang, Katz, & Grigorenko, 2009; Petrill, Deater-Deckard, Thompson, De Thorne, & Schatschneider, 2006). Normal reading FRD^+ children perform better on reading related tasks than dyslexic reading FRD^+ children. However, the normal reading FRD^+ children perform more poorly on PA and literacy compared to FRD^- children (Boets et al., 2010; Elbro et al., 1998; Snowling et al., 2003; van Bergen, de Jong, Plakas, Maassen, & van der Leij, 2012). In contrast, a study of Pennington & Lefly (2001) demonstrated that normal reading FRD^+ children were comparable to FRD^- children on PA, but show impairments for VSTM and RAN.

Besides the differences between FRD^+ children, the relation between behavioural aspects of the parents and the children is relevant as well. Dyslexic parents of a dyslexic reading FRD^+ child experience more problems on RAN and reading compared with dyslexic parents of a normal reading FRD^+ child (van Bergen et al., 2011; van Bergen et al., 2012). A study by van Bergen, de Jong, Maassen, & van der Leij (2014a) shows that even for the unaffected parent a difference could be determined. Parents of a dyslexic reading FRD^+ child perform more slowly on RAN tasks than parents of a normal reading FRD^+ child. No differences were found for parental non-word reading, spelling and non-word repetition between these two groups. Children of dyslexic parents with a RAN deficit are more likely to develop dyslexia than children of parents without this deficiency (van Bergen et al., 2012).

Environmental factors

Besides parental influences via genetic factors, reading environment can also be included as a factor influencing the reading process in children. A study by Niklas & Schneider (2013) shows that socio-economic status, migration background and home literacy environment (HLE) are also relevant aspects in reading development. Shared parent-child reading appeared to be related to better results on word reading in kindergarten (Sénéchal & Lefevre, 2002; Silinskas et al., 2012; Torppa, Poikkeus, Laakso, Eklund, & Lyytinen, 2006). A longitudinal study of Molfese, Modglin & Molfese (2003) shows that HLE can be related to later reading skills. However, in a study of van Bergen, van der Leij, & de Jong (2014b) the environmental factor is disproved. It states there is no difference between normal reading FRD^+ children and dyslexic reading FRD^+ children.

Furthermore it shows no group difference between the FRD^+ and FRD^- groups in terms of cognitive stimulation by parents, which is in line with a study of Hosseini et al. (2013). In addition, several studies demonstrate there is no effect of HLE on the reading outcomes of children (Elbro et al., 1998; Snowling, Muter, & Carroll, 2007; Torppa et al., 2007; van Bergen et al., 2011; van Bergen et al., 2014b).

Neural correlates involved in reading

Reading requires the collaboration of different cortical regions. Several functional magnetic resonance imaging (fMRI) studies show that three brain regions are particularly active while reading, the inferior frontal gyrus, the temporoparietal and occipitotemporal regions in the left hemisphere (Jobard, Crivello, & Tzourio-Mazoyer, 2003; Pugh et al., 2000; Schlaggar & McCandliss, 2007). In a recent meta-analysis of Martin, Schurz, Kronbichler, & Richlan (2015) in which they discuss twenty fMRI studies in normal reading adults, activation in occipitotemporal and inferior frontal regions was confirmed, yet activation in the left superior temporal gyrus was not determined. The left inferior frontal gyrus is associated with articulation, subvocal rehearsal, memory and high-order phonological processes (Fiez & Peterson, 1998; Gandour et al., 2002; Murphy et al., 1997; Smith & Jonides, 1999). The left temporoparietal area is responsible for phonological processing and grapheme-to-phoneme mapping (Becker, MacAndrew, & Fiez, 1999; Démonet, Thierry, & Cardebat, 2005; Jobard et al., 2003; Simos et al., 2002; van Atteveldt, Formisano, Goebel, & Blomert, 2004). The left occipitotemporal area is related to the automatic processing of visual word form perception and is also called the Visual Word Form Area (Dehaene, 2014; Jobard et al., 2003). Based on the distinct activation patterns of dorsal versus ventral regions during reading-related fMRI-tasks, it is generally assumed that two distinct neural routes seem to be involved in reading. The dorsal route, comprising left temporoparietal and inferior frontal regions, would be related to the sublexical phonological route, whereas the ventral route would be related to the direct lexical reading route (Jobard et al., 2003; Schlaggar & McCandliss, 2007).

Not only the brain regions are interesting, the connections between these brain regions play an important role as well. Using diffusion tensor imaging (DTI) tractography we can delineate white matter tracts such as the arcuate fasciculus (AF), the inferior fronto-occipital fasciculus (IFOF) and the inferior longitudinal fasciculus (ILF) that all connect reading-related areas (Catani, Howard, Pajevic, & Jones, 2002).

The AF is a dorsal white matter tract between the posterior inferior frontal cortex and the temporal cortex. A recent DTI-study in adults shows that this tract is important for PA, an essential component of reading development (Vandermosten et al., 2012a). In addition, fractional anisotropy (FA) in the left AF is also correlated with PA in pre-reading children (Saygin et al., 2013; Vandermosten et al., submitted). RAN is related to FA in the left temporoparietal regions, while VSTM is associated with FA in the frontal regions (Deutsch et al., 2005). The ILF is a ventral white matter tract, which transmits signals between the occipital lobe and the anterior and inferior temporal lobe. Studies in adults, adolescents as well as children show that these signals can be important for the reading process (Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012). The IFOF is another ventral white matter tract. The occipital component of this tract runs parallel to the ILF but connects to the orbitofrontal and dorsolateral prefrontal areas involved in the semantic system (Duffau et al., 2005). The IFOF in adults is related to orthographic processing. This tract could be responsible for the direct lexical reading route (Vandermosten et al., 2012a).

Neural correlates of reading in adults with dyslexia

The above cited neuroimaging studies demonstrate that reading requires an activation of brain regions in the left hemisphere as well as a good cooperation between the different brain regions. The activation of these brain regions seems to fail in individuals with dyslexia. First the findings of adults with dyslexia will be discussed. A meta-analysis of Richlan, Kronbichler, & Wimmer (2011) discusses nine fMRI studies which demonstrate the brain activity in adults with dyslexia while reading. Underactivation was observed in the left occipitotemporal area and the left inferior frontal gyrus. Underactivation was also determined in the left temporo-parietal area, more specifically in the superior temporal gyrus. Underactivation in the left temporoparietal area may reflect the phonological impairment. These findings can be integrated in a neuroanatomical model of developmental dyslexia, postulating a primary dysfunction of the left temporoparietal area and a secondary dysfunction of the left occipitotemporal area (Richlan, 2012).

In addition to the activation of the brain regions, the cooperation between the different brain regions seems to fail in individuals with dyslexia. A review study of Vandermosten et al. (2012b) shows that ten studies observe a lower FA in the left temporo-parietal region in adults with dyslexia. Five studies found a lower FA in the left frontal cortex in adults with dyslexia.

A lower FA was also revealed in the bilateral fronto-temporal and left occipital regions. In addition, a decreased FA was observed in the left AF, particularly in the area that connects the posterior temporal and inferior frontal regions. Two studies reported a higher FA in the posterior part of the corpus callosum in adults with dyslexia (Frye et al., 2008; Odegard, Farris, Ring, McColl, & Black, 2009). A lower FA in the left temporoparietal and frontal areas indicates poor reading skills. However, a lower FA in the posterior part of the corpus callosum indicates good reading skills. No group difference was found in the FA in the left IFOF and the right AF in adults with dyslexia (Vandermosten et al., 2012a).

Neural correlates of reading in children.

First we will discuss the findings of brain activity in school-aged reading children, followed by findings at the onset of reading (i.e. in pre- to beginning readers). A meta-analysis of Martin et al. (2015) including 40 fMRI studies in normal readers shows overlap as well as activation differences between children (7–12 years old) and adults. Activation in the left occipitotemporal area and the left inferior frontal gyrus was identified both in children and adults. Activation in the left superior temporal gyrus and the bilateral supplementary motor area was only found in children. In contrast, activation in the bilateral posterior occipitotemporal area was only identified in adults.

Given the described neuroanatomical model of developmental dyslexia, we would expect a dysfunction in both areas in older children because they already are advanced in the reading process. Findings of fMRI studies in children with dyslexia (9-11 years old) observe underactivation in the left temporoparietal area compared to their normal reading peers. Underactivation was also found in the left anterior occipitotemporal area (Richlan et al., 2011). More specifically, when contrasting adults and children fMRI-studies, it is observed that children also show underactivation in the bilateral inferior parietal area, which is not the case for adult dyslexics. Adults on the other hand show more underactivation in the occipito-temporal area than children. Underactivation in the anterior part of the occipitotemporal cortex is observed both in children and adults (Richlan et al., 2011).

For pre- to beginning readers we would expect a dysfunction of the temporoparietal area according to the neuroanatomical model of developmental dyslexia. In order to investigate the neural reading circuit of pre-reading children, it is recommend to use specific protocols to prepare the children for a MRI scan.

For research objectives, however, it is not ethical to sedate children. Hence, specific protocols were developed for this purpose (Barnea-Goraly et al., 2014; Byars et al., 2002; de Bie et al., 2010; Raschle et al., 2012b; Theys, Wouters, & Ghesqhuière, 2014). Pre-reading children and beginning readers with a family risk for dyslexia show underactivation in bilateral temporoparietal regions (Raschle, Chang, & Gaab, 2011). Also pre- to beginning readers with a behavioural risk for dyslexia show underactivation in these regions (Yamada et al., 2011). A study in pre-reading children with a family risk for dyslexia shows underactivation in the occipitotemporal area (Raschle et al., 2011). Underactivation in the bilateral inferior parietal cluster is observed in beginning readers with a family risk for dyslexia (Specht et al., 2009). A study of Brem et al. (2010) also shows underactivation in bilateral inferior parietal regions in beginning readers without family risk for dyslexia. Underactivation is also noted in the frontal regions in beginning readers with a behavioural risk for dyslexia (Specht et al., 2009; Yamada et al., 2011). These findings are contrary to what we expected based on the neuroanatomical model of developmental dyslexia.

Now the findings from DTI-studies in children with dyslexia or children at risk for dyslexia are being discussed. A significant group difference was observed in FA in the left IFOF between pre-reading children with and without a family risk. No group difference in these children was found in FA in the left AF as was observed in adults with dyslexia (Vandermosten et al., 2012a). A study by Vandermosten et al. (submitted) shows a correlation between PA and FA in bilateral AF in pre-reading children and beginning readers. This finding is in line with a study of Saygin et al. (2013) which also shows that FA in the left AF correlates with PA. However, LK and RAN do not correlate with FA in the left AF (Saygin et al., 2013; Vandermosten et al., submitted). A study of Myers et al. (2014) also shows that the development of PA involves the temporoparietal and inferior frontal regions and this in the early stages of reading acquisition.

The present study

The present study aims to investigate the relation between parental reading skills and cognitive and neuroanatomical measures in pre-readers. The research question we try to answer in this study examines whether the family risk for dyslexia, or the behavioural risk or an interaction of both, is associated with the neuroanatomical pathways of the reading network in children.

We will examine behavioural risk and family risk as dimensional factors. A first objective is to assess the relation between parental reading skills (representing the familial risk) and children's pre-literacy skills (representing the behavioural risk). We propose that when parents perform weak on reading scores, we will also encounter weaker scores on reading and pre-literacy skills in children. A study by van Bergen et al. (2012) observes a correlation between performances in parents and children on word-reading fluency. Given that we test children's pre-reading skills as well as their later reading skills (beginning readers), we can determine whether the familial risk and behavioural risk each uniquely predict a child's later reading skills. Adding to previous studies, the familial risk in the current study is not only determined based on the parent with reading problems but also based on the unaffected parent. In addition, as the familial risk might be driven by both genetic and environmental factors, the latter was taken into account by assessing the home literacy environment of the child. Given that a maternal history of reading difficulties correlates with neuroanatomical structures of pre-reading children (Hosseini et al., 2013), we will also investigate the relation between behavioural measures of the parents and the neural reading network of beginning readers.

Participants

This study is part of a longitudinal project. In total, 87 Dutch-speaking children were selected for this project. We are using data collected in the last year of kindergarten and in third grade. At the first measurement, participants underwent behavioural and MRI assessments (wave 1). In the total sample of 87 children, behavioural data such as RAN and PA were measured at the beginning of the last year of kindergarten. At the end of the last year of kindergarten a MRI-scan and a LK task were administered in a subsample of 75 children for whom parents gave informed consent to participate in the MRI-session. Due to unsuccessful DTI-acquisition, four children had to be excluded from the DTI-analyses (N = 71). At the beginning of the third grade (wave 2), reading ability was measured.

The data presented in this study are pre-literacy skills and MRI from wave 1 and the reading data from wave 2. In this sample, a distinction was made between children with and without a family risk for dyslexia. Children with a family risk belong to the FRD^+ group and children without a family risk belong to the FRD^- group. A family risk for dyslexia is defined as having at least one first-degree relative with dyslexia.

The FRD$^+$ group was matched with the FRD$^-$ group, based on five criteria: (1) educational environment, i.e. same class, (2) gender, (3) age, (4) non-verbal IQ and (5) socio-economic status (SES), using the Family Affluence Scale (Boudreau & Poulin, 2009; Boyce, Torsheim, Currie, & Zambon, 2006). Non-verbal IQ was measured with Raven's Coloured Progressive Matrices (Raven, Court, & Raven, 1984). In addition, five exclusion criteria were taken into consideration: (1) a non-verbal IQ below 80, (2) a hearing loss, (3) multilingualism, (4) a history of brain damage, vision deficits, or articulatory problems, and (5) a high risk for developing ADHD, based on the Strengths and Difficulties Questionnaire (Goodman, 1997; Widenfelt, Goedhart, Treffers, & Goodman, 2003).

The results reported in the present study include data of 71 children, of whom 36 belong to the FRD$^+$ group and 17 children can be considered as dyslexics (Moerenhout, 2015). This study was approved by the local Ethical Board. The parents of all children gave their written consent so the children could participate in this study.

Behavioural measures in children

Table 1 provides descriptive statistics of children's and parental cognitive and reading skills. To evaluate phonological skills, children were measured on PA and RAN at the beginning of the last year of kindergarten. PA in children was assessed by an end phoneme and end rhyme identification task (de Jong, Seveke, & van Veen, 2000). These tasks consisted of high frequent one-syllabe Dutch words and each item included a row of five pictures. The first picture represented the given word and was separated from the other pictures. All items were named for the child. The child responded by naming or by pointing to the corresponding alternative. Performance on both tasks was assessed by the number of correct answers (Boets et al., 2010). These scores were converted into z-scores and averaged to obtain a composite score for PA.

Naming speed in children was assessed by RAN tasks requiring children to sequentially name lists of objects and colours as quickly as possible. The objects represented five high frequent one-syllable words. The colours were represented by small rectangles in five colours. Each list of stimuli is displayed on a card consisting of 50 symbols in a random order. The child was asked to name the symbols of the last column of a card to determine whether the child was familiar with all the presented symbols (Boets et al., 2010; van den Bos, Zijlstra, & Spelberg, 2002). Performance on these tasks was assessed by the number of correct answers per second. These scores were also converted into z-scores and averaged to obtain a composite score for naming speed.

LK of the children was measured at the end of the last year of kindergarten and was assessed by both a receptive and productive task (Boets et al., 2010; Verhoeven, 2002). In the receptive task, children had to choose the letter which matched with the corresponding sound from six alternatives. In the productive task, children had to name the 16 most frequently used letters in Dutch books. These scores were also converted into z-scores and averaged to obtain a composite score for LK.

To evaluate reading ability, word and pseudo-word reading tests were administered at the beginning of the third grade. Word reading fluency was assessed by the One-Minute-Test (Brus & Voeten, 1973) and the Three-Minutes-Test (Verhoeven, 1995). The One-Minute-Test consists of a list of 116 words of increasing difficulty. The Three-Minutes-Test comprises three different lists. The first and second list consisted of 150 monosyllabic words. The first list includes words with a consonant vowel, vowel consonant or consonant vowel consonant pattern. The second list consists of words with at least one consonant cluster. The third list consists of 120 polysyllabic words. Non-word reading fluency was measured with the Klepel (van den Bos, Spelberg, Scheepstra, & de Vries, 1994). This test consists of a list of 116 pseudo-words of increasing difficulty. The number of words read correctly was converted into z-scores and averaged to obtain a composite score for reading ability.

Behavioural measures in parents

Information about reading experience was assessed by an adult reading history questionnaire (Lefly & Pennington, 2000; Nuytten, 2005). This questionnaire was completed by both mother (n = 64) and father (n = 60). The items were scored on a five-point scale. This questionnaire measures both the childhood and current reading experiences. A cut-off score of 0.35 was used to determine the existence of family risk for dyslexia. A higher score represents more reading impairment during childhood (Black et al., 2012; Hosseini et al., 2013; Lefly & Pennington, 2000).

To evaluate reading ability, the same word and pseudo-word reading tests as in children were administered in parents except for the Three-Minutes-Test. The One-Minute-Test (Father: n = 32; Mother: n = 57) and the Klepel (Father: n = 31; Mother: n = 56) were used (Brus & Voeten, 1973; van den Bos et al., 1994). These tests required the speeded reading of lists of words/pseudo-words at increasing difficulty. The number of words read correctly was converted into z-scores and averaged to obtain a composite score for reading ability.

Home literacy environment

Information about home literacy was assessed by a questionnaire (Torppa et al., 2007; van Bergen et al., 2014a). The parents were asked to estimate the reading frequency of the child and the time they spent reading together. Three of the items were scored on a five-point scale. This scale had a range from “never” to “several times a day”. Four of the items were scored on a three-point scale. This scale had a range from “less than 15 minutes a day” to “more than 45 minutes a day”. 62 of the 71 questionnaires were completed.

Table 1

Descriptive statistics of children’s and parental cognitive and reading skills

	N	Minimum	Maximum	Mean	Std. Deviation
One-Minute-Test_Child	71	7,00	77,00	39,23	15,97
Klepel_Child	71	3,00	77,00	33,34	15,00
Three-Minutes-Test_Child	71	-6,47	6,01	,00	2,95
Phonological Awareness	71	-1,84	1,75	,00	,79
Rapid Automatized Naming	71	-2,00	2,29	,00	,94
Letter Knowledge	71	-2,21	1,57	,00	,97
One-Minute-Test_Mother	56	51,00	116,00	88,59	14,38
Klepel_mother	56	20,00	115,00	86,32	20,32
One-Minute-Test_Father	32	63,00	116,00	96,78	16,47
Klepel_Father	31	53,00	113,00	90,16	18,58
Home literacy environment	62	,27	,90	,49	,13

Neuroanatomical measures

Data acquisition

All participants underwent MRI examination on a 3T scanner (Philips) with a 32-channel head coil. The MRI data were acquired using a single shot echo planar imaging (EPI) with SENSE (parallel) acquisition. DTI sagittal slices were acquired with the following parameters: repetition time 7600 ms, echo time 65 ms, flip angle 90°, voxel size 2.5 x 2.5 x 2.5 mm, 60 non-collinear directions, b-value 1300 s/mm^2, 6 non-diffusion-weighted images.

To prepare the children for the MRI-scan, the ‘submarine’ protocol was used. This protocol consisted of three phases. In the first stage, all participants received two movies to watch at home. The first movie described the scanning procedure. The second movie was directed to the child and includes a child-friendly introduction to the MRI-scanning procedure. In the second stage, the child was prepared for the actual scan. During this preparation, the child had to complete six tasks. Each task familiarized the child with the different aspects of an MRI scan. The final stage was the actual MRI scan. The child had the chance to explore the scanner room, which was decorated in the abovementioned theme (for a comparable approach see Theys et al., 2014).

Data processing

Raw data were transferred to an offline workstation. Pre-processing was done using ExploreDTI (Leemans & Jones, 2009). The data were corrected for eddy current distortions and subject motion. The software TrackVis was applied to perform tractography. This software is using regions of interest (ROI). ROI's are defined based on anatomical landmarks in colour-coded maps. In these colour-coded maps, the colour indicates the direction of the stream of the fibers. On the basis of these ROI's the white matter tracts can be delineated.

In this study, for each individual the AF direct (see Figure 1) and the IFOF (see Figure 1) were delineated for both the left and right hemisphere according to the Wakana protocol (Wakana et al., 2007). We were able to delineate the IFOF and the AFdirect in all children, except for the right AFdirect which was only found in 50 of the 71 subjects (70%). An average FA-value along each tract was calculated. All white matter tracts were manually delineated. To assess the reproducibility of the obtained results, each tract in the left hemisphere was delineated by two raters. Concordance Correlation Coefficients (CCC) were also calculated for the extracted FA-values (Crawford, Kosinski, Lin, Williamson, & Barnhart, 2007). For each of the left hemispheric tracts the correspondence between the two raters was very high, with CCC equal to .981 and .977 for IFOF and AF direct.

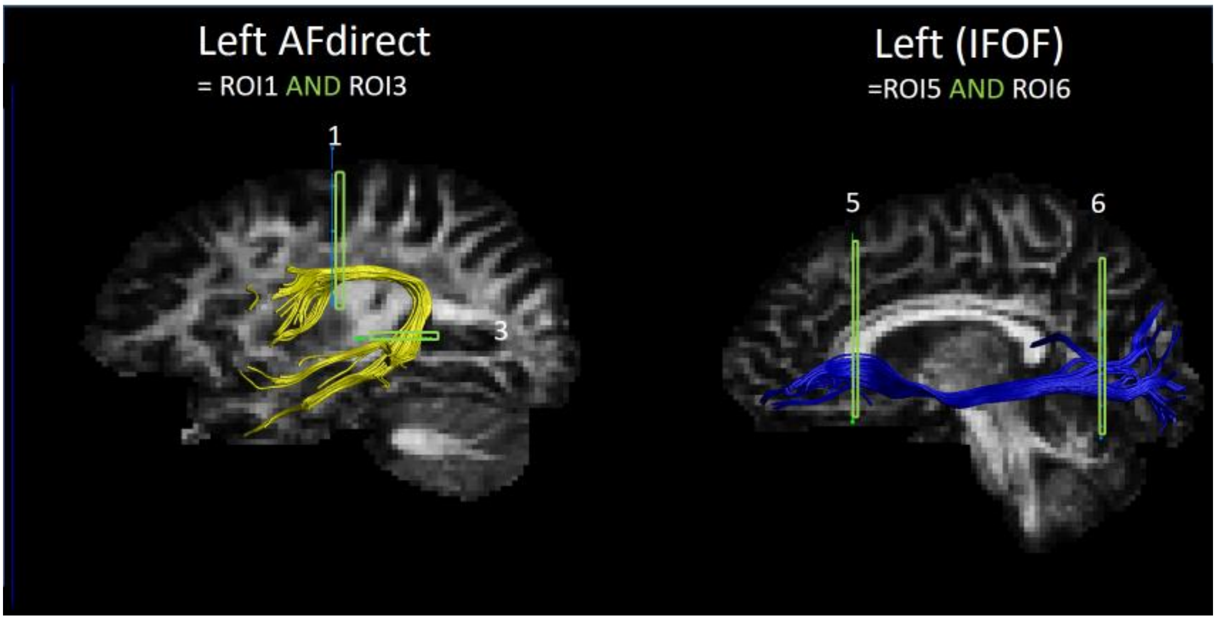

Figure 1. DTI tractography of the left arcuate fasciculus (AF) direct and the left inferior fronto-occipital fasciculus (IFOF)

Analyses

Statistical analyses were conducted in SPSS. In order to determine the correlation of behavioural measures in parents with behavioural measures in children and the relation between behavioural measures and diffusion measures, Pearson correlations were calculated. Reading ability of mother, reading ability of father, LK, reading experience of father, reading experience of the affected parent and home literacy were not normally distributed. For these variables Spearman's rho were reported. In addition, regression analyses were performed to explore the role of parental reading skills as early predictors of children's reading skills and children's white matter connections in the brain. The residuals of the right IFOF (model 1) and of the right IFOF within the FRD^+ group (model 1) were not normally distributed. Results were considered significant only if they passed $p < 0.05$.

Results

Effect of parents' reading skills on children's phonological and reading skills

Table 2 provides Pearson and Spearman correlation coefficients between parental reading skills and children's pre-literacy and reading skills. In general, reading ability of parents correlated with children's pre-literacy skills, namely with RAN, LK, and to a smaller extent also with PA. Contrary, home literacy environment did not show clear relations with pre-literacy skills of the child. More specifically, performance of a child on PA correlated with reading ability, as measured with the One-Minute-Test and Klepel, of fathers (n = 32, r = 0.427, p = 0.015) but not with reading ability of mothers (n = 56, r = 0.481, p = 0.096). No significant correlation was found with reading experience, as measured with a reading history questionnaire, and with home literacy. Performance of a child on RAN correlated with the reading tests of mothers (n = 56, r = 0.384, p = 0.003) and of fathers (n = 32, r = 0.409, p = 0.020). In addition, RAN correlated with the reading questionnaire of mothers (n = 64, r = -0.396, p = 0.001). RAN was only marginally correlated with the reading questionnaire of fathers (n = 60, r = -0.234, p = 0.072). No significant correlation was found between RAN and home literacy. LK correlated with reading tests of mothers (n = 56, r = 0.450, p = 0.001) but not with fathers (n = 32, r = 0.294, p = 0.103). Furthermore, LK correlated with the reading questionnaire of mothers (n = 64, r = -0.404, p = 0.001). LK was marginally correlated with the reading questionnaire of fathers (n = 60, r = -0.231, p = 0.076). In addition, LK was marginally correlated with home literacy (n = 62, r = 0.228, p = 0.074).

In addition, reading skills of parents correlated with reading ability of children. Reading ability of children, indexed by a composite score of the One-Minute-Test, Klepel and Three-Minutes-test, correlated with reading tests of mothers (n = 56, r = 0.635, p < 0.001) and of fathers (n = 32, r = 0.457, p = 0.008). Reading tests of children also correlated with the reading questionnaire of mothers (n = 64, r = -0.300, p = 0.016) and of fathers (n = 60, r = -0.347, p = 0.007). No significant correlation was found between reading skills of children and home literacy.

Table 2

*Pearson and Spearman (**bold**) correlations between parental reading skills and children's pre-literacy and reading skills*

	Reading ability_mother	Reading ability_father	Reading experience_mother	Reading experience_father	Home literacy
PA	**,096**	**,427***	-,038	**-,211**	**-,022**
RAN	**,384****	**,409***	-,396**	**-,234**	**-,022**
LK	**,450****	**,294**	**-,404****	**-,231**	**,228**
Reading ability_child	**,635****	**,457****	-,300*	**-,347****	**,153**

*. $p < 0.05$

**. $p < 0.01$

Since a child's later reading performance was correlated with (1) parents' reading skills, as well as with (2) a child's pre-reading cognitive skills (see Supplementary Information (SI) Table 1), we performed hierarchical regression analyses to explore the unique contribution of each. In the first step of the regression we added each of the three pre-literacy skills as independent variables and used children's reading ability as dependent variable. 26.3% of the variance in reading ability could be explained by pre-literacy skills. Results indicated that LK (β = 0.265, p = 0.047) predicted a significant amount of variance in children's reading ability. RAN (β = 0.244, p = 0.052) was also marginally significant associated with children's reading ability. In a second step, reading experience in parents was added to the model (model R^2 = 27.9%). Reading experience of father (β = -1.697, p = 0.045) predicted a significant amount of variance in children's reading ability beyond the pre-literacy skills. Reading experience of mother (β = -1.455, p = 0.123) wasn't associated with children's reading ability. Note however that after adding reading experience of parents to the model, none of the pre-literacy skills remained a significant predictor of children's reading ability (PA: p = 0.275; RAN: p = 0.504; LK: p = 0.457).

In a final step, we examined the role of home literacy in predicting children's reading ability (model R^2 = 30.9%). Reading experience of mother (β = -1.889, p = 0.057) was marginally associated with children's reading ability. Reading experience of father (β = -2.772, p = 0.006) remained a significant predictor and explained unique variance.

Effect of parents' reading skills on children's white matter connections in the brain

Since children's pre-literacy skills correlate with their white matter connections (see SI Table 1; see also Vandermosten et al., 2012b), we also investigated whether parental reading skills related to children's white matter connections. There was no significant correlation found between reading experience of mother and children's white matter connections (see Table 3), but reading experience of father correlated with FA in the left IFOF (n = 60, r = -0.258, p = 0.047). Home literacy significantly correlated with the FA in the right AF (n = 43, r = 0.385, p = 0.011) and the left IFOF (n = 62, r = 0.292, p = 0.021). Note, however, that none of the correlations was corrected for multiple comparisons.

Table 3

*Pearson and Spearman (**bold**) correlations between parents' reading-related behavioural measures and children's white matter connections*

	Right AF	Left AF	Right IFOF	Left IFOF
Reading ability_mother	**,120**	**-,005**	**-,009**	**-,010**
Reading ability_father	**,102**	**,125**	**,005**	**,038**
Reading experience_mother	-,028	,155	-,013	,035
Reading experience_father	**-,204**	**-,060**	**-,017**	**-,258***
Home literacy	**,385***	**,052**	**,060**	**,292***

*. $p < 0.05$

To explore the role of parental reading skills as early predictors of the properties of children's white matter connections in the brain, beyond a child's pre-literacy skills, we also performed hierarchical regression analyses. We ran regressions in which FA in each tract was predicted on the basis of the three pre-literacy skills (PA, RAN, LK). The first multiple regression showed that 9.4% of the variance in the left AF could be explained by children's pre-literacy skills, with PA as strongest predictor (β = 0.009, p = 0.063). In a next step, reading experience in parents was added to the model (model R^2 = 15.2%). No significant association was found with FA in the left AF. Also after adding home literacy (model R^2 = 18.1%), there was no significant association found with FA in the left AF.

When we performed regression analyses for the right AF, significant results were found only after adding home literacy. PA (β = 0.013, p = 0.017) was significantly associated with FA in the right AF. Also home literacy (β = 0.067, p = 0.047) predicted a significant amount of variance in FA in the right AF.

In the left IFOF, 13.9% of the variance could be explained by children's pre-literacy skills. PA (β = 0.009, p = 0.026) was significantly associated with FA in the left IFOF. When reading experience in parents was added to the model (model R^2 = 13.2%), no significant association was found with FA in the left IFOF. In a final step, home literacy was added to the model (model R^2 = 25.7%). Home literacy (β = 0.056, p = 0.038) predicted a significant amount of variance in FA in the left IFOF.

Finally, we examined the role of children's pre-literacy skills and parents' reading skills as early predictors of the right IFOF in children. The results of model 1 should be interpreted with some caution, because this model is not normally distributed. 17.6% of the variance in the right IFOF could be explained by children's pre-literacy skills. PA (β = 0.008, p = 0.026) was significantly associated with FA in the right IFOF. In a next step reading experience of parents was added to the model (model R^2 = 20%). Results indicated that RAN (β = 0.007, p = 0.024) was significantly associated with FA in the right IFOF. No significant association was found with reading experience of parent. After adding home literacy (model R^2 = 19%), no significant association was found with FA in the right IFOF.

The effect of the (un)affected parent on children's pre-literacy skills and white matter connections

Given the theory of the multiple deficit model of Pennington (2006), it is relevant to investigate the relation between the reading experience of the affected and unaffected parent and children's pre-literacy skills. These analyses are only performed within the FRD^+ group, because by definition only at-risk children have an affected parent. This is a small subsample, because not every FRD^+ child has an affected parent. Since children's pre-literacy skills as well as children's white matter connections correlated with parental reading skills of the (un)affected parent (see SI Table 2), we performed hierarchical regression analyses to explore the unique contribution of each. In the first step, children's pre-literacy skills were added as independent variables and children's reading ability was used as dependent variable. 31.8% of the variance in children's reading ability could be explained by children's pre-literacy skills.

Results indicated that LK (β = 0.419, $p = 0.040$) predicted a significant amount of variance in children's reading ability. In the second step of the regression we added reading experience of the affected and unaffected parent (model R^2 = 28.7%). No significant association was found with children's reading ability. In a third step home literacy was added to the model (model R^2 = 29.1%), but no significant association was found.

We also performed hierarchical regression analyses to explore the role of parents' reading skills as early predictors of the properties of children's white matter connections in the brain. We ran regressions in which FA in each of the significant tracts was predicted on children's pre-literacy skills and parental reading skills. The first multiple regression showed that 27% of the variance in the left AF could be explained by children's pre-literacy skills. PA (β = 0.015, $p = 0.014$) was significantly associated with FA in the left AF. In a next step, reading experience of the affected and unaffected parent was added to the model (model R^2 = 31.6%). No significant association was found between reading experience of the affected and unaffected parent with FA in the left AF. Also after adding home literacy (model R^2 = 38.1%), there was no significant association found with FA in the left AF.

When we perform regression analyses for the right AF, only after adding home literacy significant results were found. RAN (β = 0.021, $p = 0.028$) predicted a significant amount of variance in FA in the right AF. Home literacy (β = 0.103, $p = 0.065$) was marginally significantly associated with FA in the right AF.

In the left IFOF, 27.7% of the variance could be explained by children's pre-literacy skills. PA (β = 0.015, $p = 0.004$) was significantly associated with FA in the left IFOF. When reading experience in the affected and unaffected parent was added to the model (model R^2 = 48.1%), reading experience of the affected parent (β = 0.084, $p = 0.013$) was significantly associated with FA in the left IFOF. After adding home literacy (model R^2 = 49.1%), no significant association was found with FA in the left IFOF.

Finally, 23.5% of the variance in the right IFOF could be explained by children's pre-literacy skills. The results of model 1 should be interpreted with some caution, because this model is not normally distributed. Results indicated that PA (β = 0.009, $p = 0.038$) predicted a significant amount of variance in FA in the right IFOF. When reading experience was added to the model (model R^2 = 63%), PA (β = 0.009, $p = 0.044$) remained a significant predictor of FA in the right IFOF. LK (β = - 0.008, $p = 0.041$) was significantly associated with FA in the right IFOF.

Reading experience of the affected parent (β = 0.055, p = 0.006) was also associated with FA in the right IFOF as well. Reading experience of the unaffected parent (β = -0.056, p = 0.069) was marginally associated with FA in the right IFOF. After adding home literacy (model R^2 = 58.9%), significant results were found as well. LK (β = - 0.009, p = 0.038) predicted a significant amount of variance in the right IFOF, which remained a significant predictor and thereby explained unique variance. PA (β =0.009, p = 0.055) was marginally associated with FA in the right IFOF.

Discussion

The purpose of this study was to investigate the relation between parental reading skills and cognitive and neuroanatomical measures in pre-readers. More specifically, we examined whether the family risk for dyslexia, or the behavioural risk or an interaction of both, is associated with reading and the white matter properties of the neuroanatomical pathways of the reading network in children. First we will discuss the findings of the cognitive part of the study, followed by a discussion of the neuroanatomical results.

Regarding the cognitive data, we investigated the relation between parents' reading skills, children's pre-literacy skills and reading outcome. Our results indicated that familial risk correlated with children's pre-literacy and reading skills. In addition, familial risk had a unique contribution to the prediction of children's reading ability beyond the child behavioural measures.

Regression analyses were performed to explore the role of parental reading skills as early predictors of children's reading skills. The first model shows that LK and RAN contributed to the prediction of children's reading skills. However, after adding reading experience of parents none of the pre-literacy skills remained a significant predictor of children's reading ability. Only the reading experience of parents has a unique contribution to the prediction of children's reading ability. If this finding would be consistently confirmed in future studies, this could have implications for clinical practice. Given that reading experience of parents predicts children's reading ability, it can be appropriate to use this information in educational settings to predict dyslexia in young children and/or start up preventive actions.

Next, we wanted to explore whether a similar pattern can be found between reading tests and reading experience of parents and their relation with children's pre-literacy skills. Reading tests of parents are correlated with the three pre-literacy skills of children.

However, reading experience of parents is only related to RAN and LK. More specifically, we wanted to compare the use of reading tests and the use of a reading questionnaire. Reading tests are prepared in accordance with psychometric requirements and are thus also standardized. In addition, they include a reference group with which the scores can be compared. The completion of these tests is the same for all respondents because of the standardized procedure. Questionnaires with scaled questions can be misinterpreted by the respondents and the answer of the respondent does not always coincide with the proposed choices. The weakness of questionnaires is that respondents try to give socially desirable answers. In this way it is possible they forget some relevant information. Questionnaires will not always match the abilities of the respondent while this is so in psychometric testing (Stone et al., 1999). Questionnaires are more subjective than psychometric tests, which could explain the differences between these two research methods. Another interpretation that could explain the differences between reading tests and reading experience, is the fact that not every parent has carried out both reading tests and the reading experience questionnaire. When we run a correlational analysis only for parents who completed the reading tests, we determine an opposite pattern. More specifically, reading tests correlated with RAN and LK, while reading experience correlated with the three pre-literacy skills.

No correlations were found between home literacy and children's pre-literacy skills and reading ability. However, a trend with LK was found. This finding is in line with a study of Torppa et al. (2007) in which also no association was found between home literacy environment and beginning reading development. Also in a study of van Bergen et al. (2014b) no link was found between children's home literacy environment and children's reading outcome. In addition, different studies show that there are no differences between at-risk groups and normal reading children for home literacy environment (Elbro et al., 1998; Snowling et al., 2007; Van Bergen et al., 2011). We can assume that the link between familial risk and later reading skills is not driven by home literacy environment. Although we have no genetic data available, the relation between familial risk and later reading skills might be more genetically driven. Different event-related potential (ERP) measures show evidence for a genetic influence. Differences in brain response measures were found between new-borns with and without family risk. In addition, it was shown that these differences persist to school-aged children (Guttorm, Leppänen, Richardson, & Tolvanen, 2001; Hämäläinen, Leppänen, Guttorm, & Lyytinen, 2007; Hämäläinen, Leppänen, Guttorm, & Lyytinen, 2008; Leppänen et al., 2002).

An ERP study of Leppänen et al. (2010) also found differences between new-borns who later became dyslexic and new-borns who later became typical readers on processing of non-speech sounds. These ERP measures are predictive for later reading skills (Guttorm et al., 2010; Leppänen et al., 2010). In future research it would be interesting to investigate whether home literacy environment of the FRD^+ group is equal to the FRD^- group due to stimulation of the unaffected parent or rather of the affected parent.

Now we will discuss the findings of the neuroanatomical part. The second aim of our study was to explore the relation between parental reading skills and the white matter properties of the neural reading network of beginning readers. Results indicated that both familial risk and behavioural risk correlated with the properties of children's white matter connections. However, regression analyses indicated that familial risk predicts not uniquely the properties of children's white matter connections beyond cognitive measures.

Results showed that FA in the left AF was correlated with PA. However, no correlation was found between FA in the left AF and RAN and LK (for more details see SI table 1 and Vandermosten et al., submitted). A study of Saygin et al. (2013) also observed a relation between PA and FA in the left AF in pre-readers. In addition, the relation between PA and the left AF was observed in adults (Vandermosten et al., 2012a). Based on these findings we can suggest that the relation between PA and the left AF is present throughout reading development. Each of the three pre-literacy skills of children was related to the IFOF. PA and LK correlated with bilateral IFOF and RAN only correlated with the right IFOF. These findings suggests that the right hemisphere plays an important role in early reading development. A bilateral pattern can be determined by children (Shaywitz et al., 2002; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003), while adults establish a dominance of the left hemisphere (Fiez & Petersen, 1998; Jobard et al., 2003; Turkeltaub, Eden, Jones, & Zeffiro, 2002). We can assume that the role of the right hemisphere changes throughout reading development. Abovementioned correlations between pre-literacy skills and children's white matter connections suggest both a dorsal and ventral involvement in pre-reading children. This ventral involvement in phonological aspects of reading has also been found in previous studies (Brem et al., 2010; Raschle, Zuk & Gaab, 2012a; Vandermosten et al., submitted; Yamada et al., 2011).

A correlation was found between reading experience of father and the left IFOF. However, after adding cognitive measures to the model, reading experience of father did not remain a significant predictor of FA in the left IFOF. No correlation was found between reading experience of mother and the properties of children's white matter connections.

In contrast, a study of Black et al. (2012) does show a relation between parental reading skills and children's brain structures, beyond cognitive measures. More specifically, they found a relation between maternal reading history and children's grey matter volume. This relation is only found for bilateral prefrontal regions and the parietotemporal region. For white matter volume, only a trend with maternal reading history was observed. The more problematic the maternal reading history, the lower the grey matter volume of children. No relation was found between paternal reading history and children's grey and white matter volume. More specifically, grey matter volume was more strongly influenced by maternal rather than paternal reading history. The study of Black et al. (2012) indicates that maternal reading history is associated with dorsal regions, while our study suggests that paternal reading history is associated with ventral regions. Further research is needed to determine whether there is an interaction between maternal versus paternal influences and the locations in the brain.

Several limitations of the present study should be acknowledged. There are three main limitations in this study. First, no corrections for multiple comparisons were performed in the analyses. This results in an increased risk on type 1 errors. However, the relation we found between cognitive measures and reading outcome and the relation between cognitive measures and the left AF, are consistent with previous studies (Saygin et al., 2013; Vandermosten et al., 2012a; Vandermosten et al., submitted; Yeatman et al., 2012). Based on these findings, type 1 errors are less plausible. The second limitation is that the questionnaire which assessed home literacy was completed by only one of the two parents. 40 questionnaires were completed by mothers, while 22 questionnaires were completed by fathers. There could be a difference depending on the fact that one of the parents spent more time on reading-related activities with their child(ren) than the other. In addition, there could be a difference in the FRD^+ group when the questionnaire is completed by the affected parent rather than the unaffected parent. Finally, there are also some limitations to the use of DTI. More specifically, with DTI only one direction per voxel can be estimated (Wiegell, Larsson, & Wedeen, 2000). Given that not all fibers are oriented in the same direction, DTI is not enable to precisely estimate the orientation of crossing fibers (Alexander, Barker, & Arridge, 2002; Tuch et al., 2002). Based on these findings, it is appropriate to use Spherical Deconvolution (SD) in future research. SD is a technique that addresses the shortcomings of DTI. This technique is able to make an accurate estimation of multiple fiber directions in crossing fiber regions (Vanderauwera, Vandermosten, Dell'Acqua, Wouters, & Ghesquière, submitted).

Conclusion

The purpose of this study was to examine the relation between parental reading skills and cognitive and neuroanatomical measures in pre-readers. This study presents DTI data collected before reading onset. Hereby we can investigate the properties of the white matter connections before neural reorganisation in the brain has taken place due to reading instruction and reading experience. In addition, we consider dyslexia as a multifactorial disorder which can be situated in the multiple cognitive deficit model of Pennington (2006). In this way we can explore whether the reading skills of the affected and unaffected parent are associated with pre-readers' cognitive and neuroanatomical profile. Our findings indicate that there is a direct link between familial risk and later reading skills of children, beyond cognitive measures. In addition, both familial risk and behavioural risk are related with the properties of children's white matter connections, but familial risk has no predictive value on these connections beyond cognitive measures. We suggest that there is rather an indirect link between both familial risk and behavioural risk and the properties of children's white matter connections.

References

Alexander, D.C., Barker, G.J., & Arridge, S.R. (2002). Detection and modelling of non-Gaussian apparent diffusion coefficient profiles in human brain data. *Magnetic Resonance in Medicine, 48*(2), 331-340. doi: 10.1002/mrm.10209

Barnea-Goraly, N., Weinzimer, S.A., Ruedy, K.J., Mauras, N., Beck, R.W., Marzelli, M.J., Mazaika, P.K., Aye, T., White, N.H., Tsalikian, E., Fox, L., Kollman, C., Cheng, P., & Reiss, A.L. (2014). High success rates of sedation-free brain MRI scanning in young children using simple subject preparation protocols with and without a commercial mock scanner. *Pediatric Radiology, 44*(2), 181-186. doi: 10.1007/s00247-013-2798-7

Barron, R.W. (1986). Word recognition in early reading: A review of the direct and indirect access hypotheses. *Cognition, 24*(1), 93-119. doi: 10.1016/0010-0277(86)90006-5

Becker, J., MacAndrew, D., & Fiez, J. (1999). A comment on the functional localization of the phonological storage subsystem of working memory. *Brain and Cognition, 41*(1), 27-38. doi: 10.1006/brcg.1999.1094

Bekebrede, J., van der Leij, A., & Share, D. (2009). Dutch dyslexic adolescents: phonological core variable-orthographic differences. *Reading and Writing, 22*(2), 133-165. doi: 10.1007/s11145-007-9105-7

Bentin, S., & Leshem, H. (1993). On the interaction of phonological awareness and reading acquisition: It's a two way street. *Annals of Dyslexia, 43*, 125-148.

Black, J. M., Tanaka, H., Stanley, L., Nagamine, M., Zakerani, N., Thurston, A., Kesler, S., Hulme, C., Lyytinen, H., Glover, G.H., Serrone, C., Raman, M.M., Reiss, A.L., & Hoeft, F. (2012). Maternal history of reading difficulty is associated with reduced language-related gray matter in beginning readers. *NeuroImage, 59*(3), 3021-3032. doi: 10.1016/j.neuroimage.2011.10.024

Boets, B., De Smedt, B., Cleuren, L., Vandewalle, E., Wouters, J., & Ghesquière, P. (2010). Towards a further characterization of phonological and literacy problems in Dutch speaking children with dyslexia. *British Journal of Developmental Psychology, 28*(1), 5-31. doi: 10.1348/026151010X485223

Boets, B., Wouters, J., van Wieringen, A., & Ghesquière, P. (2007). Auditory processing, speech perception and phonological ability in pre-school children at high-risk for dyslexia: A longitudinal study of the auditory temporal processing theory. *Neuropsychologia, 45*(8), 1608-1620. doi: 10.1016/j.neuropsychologia.2007.01.009

Boudreau, B., & Poulin, C. (2009). An examination of the validity of the Family Affluence Scale II (FAS II) in a general adolescent population of Canada. *Social Indicators Research, 94*(1), 29-42. doi: 10.1007/s11205-008-9334-4

Boyce, W., Torsheim, T., Currie, C., & Zambon, A. (2006). The family affluence scale as a measure of national wealth: Validation of an adolescent self-report measure. *Social Indicators Research, 78*(3), 473-487. doi: 10.1007/s11205-005-1607-6

Brem, S., Bach, S., Kucian, K., Guttorm, T.K., Martin, E., Lyytinen, H., Brandeis, D., & Richardson, U. (2010). Brain sensitivity to print emerges when children learn letter speech sound correspondences. *Proceedings of the National Academy of Sciences of the United States of America, 107*(17), 7939-7944. doi: 10.5167/uzh-34590

Brus, B.T., & Voeten, M.J. (1973). *Eén Minuut Test: verantwoording en handleiding* [One Minute Test: Manual]. Nijmegen: Berkhout.

Byars, A.W., Holland, S.K., Strawsburg, R.H., Bommer, W., Dunn, R.S., Schmithorst, V.J., & Plante, E. (2002). Practical aspects of conducting large-scale functional magnetic resonance imaging studies in children. *Journal of Child Neurology, 17*(12), 885-890.

Caravolas, M., Hulme, C., & Snowling, M.J. (2001). The foundations of spelling ability: Evidence from a 3-year longitudinal study. *Journal of Memory and Language, 45*(4), 751-774. doi: 10.1006/jmla.2000.2785

Castles, A., & Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read. *Cognition, 91*(1), 77-111. doi: 10.1016/S0010-0277(03)00164-1

Catani, M., Howard, R.J., Pajevic, S., & Jones, D.K. (2002). Virtual in vivo interactive dissection of white matter fasciculi in the human brain. *NeuroImage, 17*(1), 77-94. doi: 10.1006/nimg.2002.1136

Coltheart, M. (2005). Modeling reading: The dual-route approach. In M.J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp.6-23). Oxford OX: Blackwell.

Crawford, S.B., Kosinski, A.S., Lin, H.M., Williamson, J.M., & Barnhart, H.X. (2007). Computer programs for the concordance correlation coefficient. *Computer Methods and Programs in Biomedicine, 88*(1), 62-74. doi: 10.1016/j.cmpb.2007.07.003

Dandache, S., Wouters, J., & Ghesquière, P. (2014). Development of reading and phonological skills of children at family risk for dyslexia: A longitudinal analysis from kindergarten to sixth grade. *Dyslexia, 20*(4), 305-329. doi: 10.1002/dys.1482

de Bie, H.M.A., Boersma, M., Wattjes, M., Adriaanse, S., Vermeulen, R., Oostrom, K., Huisman, J., Veltman, D., & Delemarre-Van de Waal, H. (2010). Preparing children with a mock scanner training protocol results in high quality structural and functional MRI scans. *European Journal of Pediatrics, 169*(9), 1079-1085. doi: 10.1007/s00431-010-1181-z

Dehaene, S. (2014). Reading in the brain revised and extended: Response to comments. *Mind and language, 29*(3), 320-335. doi: 10.1111/mila.12053

de Jong, P.F., Seveke, M.J., & van Veen, M. (2000). Phonological sensitivity and the acquisition of new words in children. *Journal of Experimental Child Psychology, 76*(4), 275-301. doi: 10.1006/jecp.1999.2549

Démonet, J., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiology Review, 85*(1), 49-95.

Deutsch, G.K., Dougherty, R.F., Bammer, R., Siok, W.T., Gabrieli, J.D.E., & Wandell, B. (2005). Children's reading performance is correlated with white matter structure measured by diffusion tensor imaging. *Cortex, 41*(3), 354-363. doi: 10.1016/S0010-9452(08)70272-7

Duffau, H., Gatignol, P., Mandonnet, E., Peruzzi, P., Tzourio-Mazoyer, N., & Capelle, L. (2005). New insights into the anatomo-functional connectivity of the semantic system: a study using cortico-subcortical electrostimulations. *Brain, 128*(4), 797-810. doi: 10. 1093/brain/awh423

Elbro, C., Borstrøm, I., & Petersen, D. K. (1998). Predicting dyslexia from kindergarten: The importance of distinctness of phonological representations of lexical items. *Reading Research Quarterly, 33*(1), 36–60.

Fiez, J.A., & Peterson, S.E. (1998). Neuroimaging studies of word reading. *Proceedings of the National Academy of Sciences of the United States of America, 95*(3), 914-921.

Frye, R.E., Hasan, K., Xue, L., Strickland, D., Malmberg, B., Liederman, J., & Papanicolaou, A. (2008). Splenium microstructure is related to two dimensions of reading skill. *Neuroreport, 19*(16), 1627-1631. doi: 10.1097/WNR.0b013e328314b8ee

Furnes, B., & Samuelsson, S. (2011). Phonological awareness and rapid automatized naming predicting early development in reading and spelling: Results from a cross-linguistic longitudinal study. *Learning and Individual differences, 21*(1), 85-95. doi: 10.1016/j.lindif.2010.10.005

Gandour, J., Wong, D., Lowe, M., Dzemidzic, M., Satthamnuwong, N.Y., & Li, X. (2002). A cross-linguistic fMRI study of spectral and temporal cues underlying phonological processing. *Journal of Cognitive Neuroscience, 14*(7), 1076-1087. doi: 10.1162/089892902320474526

Geijsel, M., & Aarnoutse, C. (2006). De ontwikkeling van het fonemisch bewustzijn in de eerste weken van het formele leesonderwijs. *Pedagogiek*, *26*(2), 172-191.

Goodman, R. (1997). The Strenghts and Difficulties Questionnaire: A research note. *Journal of Child Psychology and Psychiatry, 38*(5), 581-586. doi: 10.1111/j.1469-7610.1997.tb01545.x

Guttorm, T., Leppänen, P., Richardson, U., & Tolvanen, A. (2001). Event-related potentials and consonant differentiation in newborns with familial risk for dyslexia. *Journal of Learning Disabilities, 34*(6), 534-544.

Hämäläinen, J., Leppänen, P., Guttorm, T., & Lyytinen, H. (2007). N1 and P2 components of auditory event-related potentials in children with and without reading disabilities. *Clinical Neurophysiology, 118*(10), 2263-2275. doi: 10.1016/j.clinph.2007.07.007

Hämäläinen, J., Leppänen, P., Guttorm, T., & Lyytinen, H. (2008). Event-related potentials to pitch and rise time change in children with reading disabilities and typically reading children. *Clinical Neurophysiology, 119*(1), 100-115. doi: 10.1016/j.clinph.2007.09.064

Hosseini, S. M. H., Black, J. M., Soriano, T., Bugescu, N., Martinez, R., Raman, M.M., Kesler, S.R., & Hoeft, F. (2013). Topological properties of large-scale structural brain networks in children with familial risk for reading difficulties. *NeuroImage, 71*, 260-274. doi: 10.1016/j.neuroimage.2013.01.013

Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual route theory of reading: A metanalysis of 35 neuroimaging studies. *NeuroImage, 20*(2), 693-712. doi: 10.1016/S1053-8119(03)00343-4

Leemans, A., & Jones, D.K. (2009). The B-matrix must be rotated when correcting for subject motion in DTI data. *Magnetic Resonance in Medicine, 61*(6), 1336-1349. doi: 10.1002/mrm.21890

Lefly, D.L., & Pennington, B.F. (2000). Reliability and validity of the adult reading history questionnaire. *Journal of Learning Disabilities, 33*(3), 286-296.

Leppänen, P.H.T., Hämäläinen, J.A., Salminen, H.K., Eklund, K.M., Guttorm, T.K., Lohvansuu, K., Puolakanaho, A., & Lyytinen, H. (2010). Newborn brain event-related potentials revealing atypical processing of sound frequency and the subsequent association with later literacy skills in children with familial dyslexia. *Cortex, 46*(10), 1362-1376. doi: 10.1016/j.cortex.2010.06.003

Leppänen, P.H.T., Richardson, U., Pihko, E., Eklund, K.M., Guttorm, T.K., Aro, M., & Lyytinen, H. (2002). Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. *Developmental Neuropsychology, 22*(1), 407-422. doi: 10.1207/S15326942dn2201_4

Martin, A., Schurz, M., Kronbichler, M., & Richlan, F. (2015). Reading in the brain of children and adults: A meta-analysis of 40 functional magnetic resonance imaging studies. *Human brain mapping*. doi: 10.1002/hbm.22749

Moerenhout, F. (2015). *Een longitudinale studie naar de invloed van ouderlijke leesvaardigheid en leesomgeving op fonologische en neuroanatomische markers van dyslexie* (Unpublished master's thesis). Katholieke Universiteit Leuven, Faculteit Psychologie en Pedagogische Wetenschappen.

Molfese, V.J., Modglin, A., & Molfese, D.L. (2003). The role of environment in the development of reading skills: A longitudinal study of preschool and school-age measures. *Journal of Learning Disabilities, 36*(1), 59-67.

Murhpy, K., Corfield, D.R., Guz, A., Fink, G.R., Wise, R.J., Harrison, J., & Adams, L. (1997). Cerebral areas associated with motor control of speech in humans. *Journal of applied physiology, 83*(5), 1438-1447.

Myers, C.A., Vandermosten, M., Farris, E.A., Hancock, R., Gimenez, P., Black, J.M., Casto, B., Drahos, M., Tumber, M., Hendren, R.L., Hulme, C., & Hoeft, F. (2014). White matter morphometric changes uniquely predict children's reading acquisition. *Psychological Science, 25*(10), 1870-1883. doi: 10.1177/0956797614544511

Naples, A.J., Chang, J.T., Katz, L., & Grigorenko, E.L. (2009). Same or different? Insights into the etiology of phonological awareness and rapid naming. *Biological Psychology, 80*(2), 226-239. doi: 10.1016/j.biopsycho.2008.10.002

Niklas, F., & Schneider, W. (2013). Home literacy environment and the beginning of reading and spelling. *Contemporary Educational Psychology, 38*(1), 40-50. doi: 10.1016/j.cedpsych.2012.10.001

Nuytten, S. (2005). *Vragenlijst leeservaring van volwassenen: een vertaling van de 'Adult Reading History Questionnaire'* (Unpublished master's thesis). Katholieke Universiteit Leuven, Faculteit Psychologie en Pedagogische Wetenschappen.

Odegard, T.N., Farris, E.A., Ring, J., McColl, R., & Black, J. (2009). Brain connectivity in non-reading impaired children and children diagnosed with developmental dyslexia. *Neuropsychologia, 47*(8-9), 1972-1977. doi: 10.1016/j.neuropsychologia.2009.03.009

Parilla, R., Kirby, J.R., & Mcquarrie, L. (2004). Articulation rate, naming speed, verbal short term memory, and phonological awareness: longitudinal predictors of early reading development. *Scientific Studies of Reading, 8*(1), 3-26. doi: 10.1207/s1532799xssr0801_2

Pennington, B.F. (2006). From single to multiple deficit models of developmental disorders. *Cognition, 101*(2), 385-413. doi: 10.1016/j.cognition.2006.04.008

Pennington, B. F., & Lefly, D. L. (2001). Early reading development in children at family risk for dyslexia. *Child Development, 72*(3), 816-833. doi: 10.1111/1467-8624.00317

Peterson, R.L., & Pennington, B.F. (2012). Developmental dyslexia. *The Lancet, 379*(9830), 1997-2007. doi: 10.1016/S0140-6736(12)60198-6

Petrill, S.A., Deater-Deckard, K., Thompson, L.A., De Thorne, L.S., & Schatschneider, C. (2006). Reading skills in early readers: genetic and shared environmental influences. *Journal of Learning Disabilities, 39*(1), 48-55.

Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., Shaywitz, S.E., & Shaywitz, B.E. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews, 6*, 207-213.

Puolakanaho, A., Ahonen, T., Aro, M., Eklund, K., Leppänen, P.H.T., Poikkeus, A.-M., Tolvanen, A., Torppa, M., & Lyytinen, H. (2007). Very early phonological and language skills: estimating individual risk of reading disability. *Journal of Child Psychology and Psychiatry, 48*(9), 923-931.

Ramus, F. (2001). Dyslexia: Talk of two theories. *Nature, 412*(6845), 393-395. doi: 10.1038/35086683

Ramus, F., Rosen, S., Dakin, S.C., Day, B.L., Castellote, J.M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126*(4), 841-865. doi: 10.1093/brain/awg076

Raschle, N.M., Chang, M., & Gaab, N. (2011). Structural brain alterations associated with dyslexia predate reading onset. *NeuroImage, 57*(3), 742-749. doi: 10.1016/j.neuroimage.2010.09.055

Raschle, N.M., Zuk, J., & Gaab, N. (2012a). Functional characteristics of developmental dyslexia in left-hemispheric posterior brain regions predate reading onset. *Proceedings of the National Academy of Sciences of the United States, 109*(6), 2156-2161. doi: 10.1073/pnas.1107721109

Raschle, N., Zuk, J., Ortiz-Mantilla, S., Sliva, D.D., Franceschi, A., Grant, P.E., Benasich, A.A., & Gaab, N. (2012b). Pediatric neuroimaging in early childhood and infancy: Challenges and practical guidelines. *Annals of the New York Academy of Sciences*, *12521*(1), 43-50. doi: 10.1111/j.1749-6632.2012.06457.x

Raven, J.C., Court, J.H., & Raven, J. (1984). *Manual for Raven's progressive matrices and vocabulary scales*. London, UK: Lewis.

Richlan, F. (2012). Developmental dyslexia: Dysfunction of a left hemisphere reading network. *Frontiers in Human Neuroscience, 6*, 1-5. doi:10.3389/fnhum.2012.00120

Richlan, F., Kronbichler, M., & Wimmer, H. (2011). Meta-analyzing brain dysfunctions in dyslexic children and adults. *NeuroImage, 56*(3), 1735-1742. doi: 10.1016/j.neuroimage.2011.02.040

Saygin, Z.M., Norton, E.S., Osher, D.E., Beach, S.D., Cyr, A.B., Ozernov-Palchik, O., Yendiki, A., Fischl, B., Gaab, N., & Gabrieli, J.D.E. (2013). Tracking the roots of reading ability: white matter volume and integrity correlate with phonological awareness in prereading and early-reading kindergarten children. *The Journal of neuroscience, 33*(33), 13251-13258. doi: 10.1523/JNEUROSCI.4383-12.2013

Scerri, T.S., & Schulte-Körne, G. (2010). Genetics of developmental dyslexia. *European Child and Adolescent Psychiatry, 19*(3), 179-197. doi: 10.1007/s00787-009-0081-0

Schlaggar, B.L., & McCandliss, B.D. (2007). Development of neural systems for reading. *Annual review of neuroscience, 30*, 475-503. doi: 10.1146/annurev.neuro.28.061604.135645

Sénéchal, M., & Lefevre, J.-A. (2002). Parental involvement in the development of children's reading skill: A five-year longitudinal study. *Child Development, 73*(2), 445-460. doi: 10.1111/1467-8624.00417

Share, D.L. (1995). Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition, 55*(2), 151-218. doi: 10.1016/0010-0277(94)00645-2

Shaywitz, B.A., Shaywitz, S.E., Pugh, K.R., Mencl, W.E., Fulbright, R.K., Skudlarski, P., Constable, R.T., Marchione, K.E., Fletcher, J.M., Lyon, G.R., & Gore, J.C. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry, 52*(2), 101-110. doi: 10.1016/S0006-3223(02)01365-3

Silinskas, G., Lerkkanen, M.-K., Tolvanen, A., Niemi, P., Poikkeus, A.-M., & Nurmi, J.-E. (2012). The frequency of parents' reading-related activities at home and children's reading skills during kindergarten and Grade 1. *Journal of Applied Developmental Psychology, 33*(6), 302-310. doi: 10.1016/j.appdev.2012.07.004

Simos, P.G., Breier, J.I., Fletcher, J.M., Foorman, B.R., Castillo, E.M., & Papanicolaou, A.C. (2002). Brain mechanisms for reading words and pseudowords: An integrated approach. *Cerebral Cortex, 12*(3), 297-305.

Smans, V., & Boets, B. (2009). Het belang van fonologische vaardigheden in de vroege leesontwikkeling: een prospectieve longitudinale studie bij kinderen met familiaal risico op dyslexie. In A. Desoete, C. Andries & P. Ghesquière (Eds.), *Leerproblemen evidence-based voorspellen, onderkennen en aanpakken: bijdragen uit onderzoek* (pp.127-150). Leuven: Acco.

Smith, E.E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*(5408), 1657-1661.

Snowling, M.J. (2000). Dyslexia (2nd ed.). Oxford: Blackwell Publishers.

Snowling, M.J., Gallagher, A., & Frith, U. (2003). Family risk of dyslexia is continuous: Individual differences in the precursors of reading skill. *Child Development, 74*(2), 358-373. doi: 10.1111/1467-8624.7402003

Snowling, M. J., Muter, V., & Carroll, J. (2007). Children at family risk of dyslexia: A follow-up in early adolescence. *Journal of Child Psychology and Psychiatry*, *48*(6), 609-618. doi: 10.1111/j.1469-7610.2006.01725.x

Specht, K., Hugdahl, K., Ofte, S., Nygård, M., Bjørnerud, A., Plante, E., & Helland, T. (2009). Brain activation on pre-reading tasks reveals at-risk status for dyslexia in 6-year-old children. *Scandinavian Journal of Psychology, 50*(1), 79-91. doi: 10.1111/j.1467-9450.2008.00688.x

Stone, A.A., Turkkan, J.S., Bachrach, C.A., Jobe, J.B., Kurtzman, H.S., & Cain, V. (1999). *The science of self-report: Implications for research and practice*. New Jersey, NJ: Lawrence Erlbaum Associates.

Theys, C., Wouters, J., & Ghesquière, P. (2014). Diffusion tensor imaging and resting-state functional MRI-scanning in 5- and 6-year old children: Training protocol and motion assessment. *PLoS One, 9*(4), art.nr. e94019, 1-7.

Torppa, M., Poikkeus, A.-M., Laakso, M.-L., Eklund, K., & Lyytinen, H. (2006). Predicting delayed letter knowledge development and its relation to grade 1 reading achievement among children with and without familial risk for dyslexia. *Developmental Psychology, 42*(6), 1128-1142. doi: 10.1037/0012-1649.42.6.1128

Torppa, M., Poikkeus, A.-M., Laakso, M.-L., Tolvanen, A., Leskinen, E., Leppänen, P.H.T., Puolakanaho, A., & Lyytinen, H. (2007). Modeling the early paths of phonological awareness and factors supporting its development in children with and without familial risk of dyslexia. *Scientific Studies of Reading, 11*(2), 73-103. doi: 10.1080/10888430709336554

Tuch, D.S., Reese, T.G., Wiegell, M.R, Makris, N., Belliveau, J.W., & Wedeen, V.J. (2002). High angular resolution diffusion imaging reveals intravoxel white matter fiber heterogeneity. *Magnetic Resonance in Medicine, 48*(4), 577-582. doi: 10.1002/mrm.10268

Turkeltaub, P.E., Eden, G.F., Jones, K.M., & Zeffiro, T.A. (2002). Meta-analysis of the functional neuroanatomy of single-word reading: method and validation. *NeuroImage, 16*(3), 765-780. doi: 10.1006/nimg.2002.1131

Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., & Eden, G.F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience, 6*(7), 767-773. doi: 10.1038/nn1065

van Atteveldt, N., Formisano, E., Goebel, R., & Blomert, L. (2004). Integration of letters and speech sounds in the human brain. *Neuron, 43*(2), 271-282. doi: 10.1016/j.neuron.2004.06.025

van Bergen, E., de Jong, P.F., Maassen, B., & van der Leij, A. (2014a). The effect of parents' literacy skills and children's preliteracy skills on the risk of dyslexia. *Journal of Abnormal Child Psychology, 42*(7), 1187-1200. doi: 10.1007/s10802-014-9858-9

van Bergen, E., de Jong, P.F., Plakas, A., Maassen, B., & van der Leij, A. (2012). Child and parental literacy levels within families with a history of dyslexia. *Journal of Child Psychology and Psychiatry, 53*(1), 28-36. doi: 10.1111/j.1469-7610.2011.02418.x van Bergen, E., de Jong, P.F., Regtvoort, A., Oort, F., van Otterloo, S., & van der Leij, A. (2011). Dutch children at family risk of dyslexia: precursors, reading development and parental effects. *Dyslexia, 17*(1), 2-18. doi: 10.1002/dys.423

van Bergen, E., van der Leij, A., & de Jong, P. (2014b). The intergenerational multiple deficit model and the case of dyslexia. *Frontiers in Human Neuroscience, 8*. doi: 10.3389/fnhum.2014.00346

van den Bos, K.P., Spelberg, H.C.L., Scheepstra, A.J.M., & de Vries, J.R. (1994). De Klepel. Vorm A en B. Een test voor de leesvaardigheid van pseudowoorden. Verantwoording, handleiding, diagnostiek en behandeling [Word and non word reading test A & B manual]. Nijmegen: Berkhout.

van den Bos, K.P., Zijlstra, B.J.H., & Spelberg, H.C.L. (2002). Life-span data on continuous naming speeds of numbers, letters, colors, and pictured objects, and word-reading speed. *Scientific Studies of Reading, 6*(1), 25-49. doi: 10.1207/S1532799XSSR0601_02

Vanderauwera, J., Vandermosten, M., Dell'Acqua, F., Wouters, J., & Ghesquière, P. (submitted). Disentangling the relation between left temporoparietal white matter and reading: A Sphercial Deconvolution tractography study.

Vandermosten, M., Boets, B., Poelmans, H., Sunaert, S., Wouters, J., & Ghesquiere, P. (2012a). A tractography study in dyslexia: Neuroanatomic correlates of orthographic, phonological and speech processing. *Brain, 135*(3), 935-948. doi: 10.1093/brain/awr363

Vandermosten, M., Boets, B., Wouters, J., & Ghesquière, P. (2012b). A qualitative and quantitative review of diffusion tensor imaging studies in reading and dyslexia. *Neuroscience and Biobehavioral Reviews, 36*(6), 1532-1552. doi: 10.1016/j.neubiorev.2012.04.002

Vandermosten, M., Vanderauwera, J., Theys, C., De Vos, A., Vanvooren, S., Sunaert, S., Wouters, J., & Ghesquière, P. (submitted). A DTI tractography study in pre-readers at risk for dyslexia.

Vellutino, F.R., Fletcher, J.M., Snowling, M.J., & Scanlon, D.M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades. *Journal of Child Psychology and Psychiatry, 45*(1), 2-40. doi: 10.1046/j.0021-9630.2003.00305.x

Verhoeven, L. (1995). Drie-Minuten-Toets. Verantwoording. [Three-Minute Reading test. Manual]. Arnhem: Cito.

Verhoeven, L. (2002). *Passieve letterkennis* [*Receptive letter knowledge*]. Arnhem: Cito.

Wagner, R.K., & Torgesen, J.K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*(2), 192-212. doi: 10.1037/0033-2909.101.2.192

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology, 30*(1), 73-87.

Wakana, S., Caprihan, A., Panzenboeck, M.M., Fallon, J.H., Perry, M., Gollub, R.L., Hua, K., Zhang, J., Jiang, H., Dubey, P., Blitz, A., van Zijl, P., & Mori, S. (2007). Reproducibility of quantitative tractography methods applied to cerebral white matter. *NeuroImage, 36*(3), 630-644. doi: 10.1016/j.neuroimage.2007.02.049

Widenfelt, B., Goedhart, A., Treffers, P., & Goodman, R. (2003). Dutch version of the Strenghts and Difficulties Questionnaire (SDQ). *European Child & Adolescent Psychiatry, 12*(6), 281-289. doi: 10.1007/s00787-003-0341-3

Wiegell, M.R., Larsson, H.B., & Wedeen, V.J. (2000). Fiber crossing in human brain depicted with diffusion tensor MR imaging. *Radiology, 217*(3), 897-903.

Yamada, Y., Stevens, C., Dow, M., Harn, B.A., Chard, D.J., & Neville, H.J. (2011). Emergence of the neural network for reading in five-year-old beginning readers of different levels of pre-literacy abilities: An fMRI study. *NeuroImage, 57*(3), 704-713. doi: 10.1016/j.neuroimage.2010.10.057

Yeatman, J.D., Dougherty, R.F., Ben-Shachar, M., & Wandell, B.A. (2012). Development of white matter and reading skills. *Proceedings of the National Academy of Sciences, 109*(44), 3045-3053. doi: 10.1073/pnas.1206.1206792109

Ziegler, J.C., Perry, C., & Zorzi, M. (2014). Modelling reading development through phonological decoding and self-teaching: implications for dyslexia. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 369*(1634), 20120397. doi: 10.1098/rstb.2012.0397

Supplementary information

Table 1

*Pearson and Spearman (**bold**) correlations between familial risk, behavioural risk and children's white matter connections*

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Behavioural risk	1. PA (wave 1)	1,000												
		.												
		71												
	2. RAN (wave 1)	,357**	1,000											
		,002	.											
		71	71											
	3. LK (wave 1)	**,439****	**,492****	1,000										
		,000	**,000**	.										
		71	**71**	71										
	4. Reading ability_child (wave 2)	,351**	,413**	**,435****	1,000									
		,003	,000	**,000**	.									
		71	71	**71**	71									
children's white matter connections	5. Right AF	,253	,105	**,235**	,277	1,000								
		,077	,468	**,100**	,051	.								
		50	50	**50**	50	50								
	6. Left AF	,296*	,178	**,203**	,075	,504**	1,000							
		,012	,138	**,090**	,537	,000	.							
		71	71	**71**	71	50	71							
	7. Right IFOF	,375**	,311**	**,276***	,083	,393**	,454**	1,000						
		,001	,008	**,020**	,489	,005	,000	.						
		71	71	**71**	71	50	71	71						
	8. Left IFOF	,362**	,189	**,263***	,200	,556**	,479**	,659**	1,000					
		,002	,114	**,026**	,095	,000	,000	,000	.					
		71	71	**71**	71	50	71	71	71					
Familial risk	9. Reading ability_mother	**,096**	**,384****	**,450****	**,635****	**,120**	**-,005**	**-,009**	**-,010**	1,000				
		,481	**,003**	**,001**	**,000**	**,466**	**,968**	**,950**	**,941**	.				
		56	**56**	**56**	**56**	**39**	**56**	**56**	**56**	56				
	10. Reading experience_mother	-,038	-,396**	**-,404****	-,300*	-,028	,155	-,013	,035	**-,416****	1,000			
		,763	,001	**,001**	,016	,857	,222	,916	,782	**,002**	.			
		64	64	**64**	64	45	64	64	64	**52**	64			
	11. Reading ability_father	**,427***	**,409***	**,294**	**,457****	**,102**	**,125**	**,005**	**,038**	**,272**	**-,097**	1,000		
		,015	**,020**	**,103**	**,008**	**,629**	**,497**	**,977**	**,835**	**,247**	**,609**	.		
		32	**32**	**32**	**32**	**25**	**32**	**32**	**32**	**20**	**30**	32		
	12. Reading experience_father	**-,211**	**-,234**	**-,231**	**-,347****	**-,204**	**-,060**	**-,017**	**-,258***	**-,024**	**-,185**	**-,609****	1,000	
		,106	**,072**	**,076**	**,007**	**,190**	**,651**	**,900**	**,047**	**,875**	**,172**	**,000**	.	
		60	**60**	**60**	**60**	**43**	**60**	**60**	**60**	**46**	**56**	**31**	60	
	13. Home literacy	**-,022**	**-,022**	**,228**	**,153**	**,385***	**,052**	**,060**	**,292***	**,300***	**-,208**	**-,207**	**-,021**	1,000
		,865	**,865**	**,074**	**,234**	**,011**	**,686**	**,642**	**,021**	**,034**	**,124**	**,281**	**,880**	.
		62	**62**	**62**	**62**	**43**	**62**	**62**	**62**	**50**	**56**	**29**	**53**	62

*. $p < 0.05$

**. $p < 0.01$

Table 2

*Pearson and Spearman (**bold**) correlations between familial risk, behavioural risk and children's white matter connections within the FRD$^+$ group*

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
Behavioural risk	1. PA (wave 1)	1,000														
		.														
		36														
	2. RAN (wave 1)	,450**	1,000													
		,006	.													
		36	36													
	3. LK (wave 1)	**,587****	**,611****	1,000												
		,000	**,000**	.												
		36	**36**	36												
	4. Reading ability_child (wave 2)	,446**	,331*	**,571****	1,000											
		,006	,049	**,000**	.											
		36	36	**36**	36											
Children's white matter connections	5. Right AF	,478*	,215	**,380**	,415	1,000										
		,024	,337	**,081**	,055	.										
		22	22	**22**	22	22										
	6. Left AF	,421*	,331*	**,145**	,168	,454*	1,000									
		,010	,049	**,399**	,329	,034	.									
		36	36	**36**	36	22	36									
	7. Right IFOF	,442**	,346*	**,301**	,070	,261	,378*	1,000								
		,007	,039	**,075**	,685	,241	,023	.								
		36	36	**36**	36	22	36	36								
	8. Left IFOF	,500**	,229	**,222**	,210	,447*	,456**	,690**	1,000							
		,002	,178	**,193**	,220	,037	,005	,000	.							
		36	36	**36**	36	22	36	36	36							
Familial risk	9. Reading ability_mother	**,262**	**,205**	**,622****	**,655****	**,297**	**-,038**	**,063**	**,103**	1,000						
		,147	**,260**	**,000**	**,000**	**,218**	**,838**	**,732**	**,575**	.						
		32	**32**	**32**	**32**	**19**	**32**	**32**	**32**	32						
	10. Reading experience_mother	,048	-,359*	**-,419***	-,247	-,049	,257	-,126	,162	**-,483****	1,000					
		,788	,037	**,014**	,158	,832	,142	,478	,359	**,006**	.					
		34	34	**34**	34	21	34	34	34	**31**	34					
	11. Reading ability_father	**,604***	**,442**	**,389**	**,442**	**,483**	**,345**	**,218**	**,174**	**,049**	**,210**	1,000				
		,022	**,114**	**,169**	**,114**	**,187**	**,227**	**,455**	**,553**	**,894**	**,491**	.				
		14	**14**	**14**	**14**	**9**	**14**	**14**	**14**	**10**	**13**	14				
	12. Reading experience_father	**-,279**	**-,154**	**-,239**	**-,211**	**-,102**	**-,117**	**,027**	**-,098**	**,065**	**-,522****	**-,713****	1,000			
		,122	**,400**	**,189**	**,247**	**,670**	**,523**	**,883**	**,595**	**,743**	**,003**	**,006**	.			
		32	**32**	**32**	**32**	**20**	**32**	**32**	**32**	**28**	**30**	**13**	32			
	13. Reading experience_affected parent	**-,177**	**-,087**	**-,099**	**-,067**	**,247**	**,272**	**,384***	**,312**	**-,237**	**,162**	**-,409**	**,460***	1,000		
		,349	**,646**	**,602**	**,724**	**,323**	**,146**	**,036**	**,093**	**,224**	**,392**	**,212**	**,018**	.		
		30	**30**	**30**	**30**	**18**	**30**	**30**	**30**	**28**	**30**	**11**	**26**	30		
	14. Reading experience_unaffected parent	,162	-,396*	**-,511****	-,234	,299	,170	-,237	-,035	**-,387**	,679**	**,150**	**-,135**	**-,155**	1,000	
		,410	,037	**,005**	,230	,244	,386	,225	,860	**,056**	,000	**,659**	**,492**	**,449**	.	
		28	28	**28**	28	17	28	28	28	**25**	26	**11**	**28**	**26**	28	
	15. Home literacy	**,160**	**-,013**	**,168**	**,197**	**,452***	**-,014**	**,079**	**,276**	**,415***	**-,258**	**-,253**	**,302**	**,147**	**-,010**	1,000
		,358	**,943**	**,334**	**,257**	**,040**	**,935**	**,653**	**,109**	**,020**	**,147**	**,382**	**,099**	**,448**	**,960**	.
		35	**35**	**35**	**35**	**21**	**35**	**35**	**35**	**31**	**33**	**14**	**31**	**29**	**27**	35

*. $p < 0.05$

**. $p < 0.01$