Highlights

- The dyslexic children improved in RAN and in reading accuracy following RAN training.
- Gains in RAN correlated with greater FA in the left anterior segment of the AF.
- RAN is associated with the AF segment sustaining articulation and speech fluency.
- First evidence of the efficacy of RAN training with cognitive and brain evidence.

Abstract

Currently, no study has demonstrated the efficacy of RAN training with both behavioral and brain-imaging evidence. Besides, the brain basis of RAN and its contribution to reading processes are still not well understood. This study aimed to address these gaps with a RAN-objects intervention, administered to children with dyslexia, and assessed by behavioral and brain measures. Trained children (n = 18) were compared to untrained normal-reading children (n = 13) on RAN, reading, and diffusion MRI measures, before and after the intervention. Results showed significant improvements in the trained children in RAN performance and in word reading accuracy. Importantly, gains in RAN observed in the dyslexic group were correlated with increased fractional anisotropy (FA) in the left anterior segment of the arcuate fasciculus (AF), which is primarily known to be involved in articulation and in speech fluency. Our findings open up new perspectives for remediation of dyslexia, and suggest that RAN essentially recruits a brain pathway involved in oral language production and reading.

Keywords: rapid automatized naming (RAN), intervention, children with dyslexia, diffusion tensor imaging (DTI), white matter, fractional anisotropy (FA), plasticity, reading network

Efficacy of RAN Training in Children with Dyslexia: Behavioral and Brain Correlates.

1. Introduction

Fluent reading development is a key foundation for ensuring later educational, social, and professional achievement. Nowadays, about 2.3 to 12 % of educated pupils experience severe and persistent difficulties in learning to read despite normal intelligence, adequate socio-cultural and educational opportunities, and the absence of sensory deficits (Inserm, 2007; World Health Organization, 2016). Differences between pupils are already noticeable at the beginning of the learning process, and partly explained by the level of development of some cognitive precursors. Combined with the familial risk status, phonological awareness, letter knowledge, rapid automatized naming (RAN) has been found to be one of the key cognitive predictors of reading disability, enabling children at risk of dyslexia to be identified at the age of 3.5 years (Puolakanaho et al., 2007). Although studies on RAN are abundant, the question of the efficacy of RAN training remains open. There is only one very recent study showing the efficacy of RAN training among children with dyslexia so far. Highlighting the efficacy of such an intervention is crucial to guide the development of a new kind of targeted intervention for reading difficulties. Moreover, RAN intervention studies are essential to provide a better understanding of the causal relation between RAN and reading. Finally, the brain basis of RAN is not well understood. Importantly, no study has demonstrated the efficacy of RAN training with both behavioral and brain evidence. Combining neuroimaging data with RAN training should provide a better understanding of the circumstances under which RAN training is effective. The present study aimed to fill these gaps by means of an intervention design, and the combination of behavioral and brain measures collected before and immediately after a RAN training program administered to children with dyslexia.

1.1. The RAN-Reading Relationship

RAN refers to the ability to name as quickly as possible an array of highly familiar visual stimuli (traditionally digits, letters, colors, or objects) arranged in a matrix. Performance in RAN has consistently been found to predict reading fluency across languages (Araújo, Reis, Petersson, & Faísca, 2015; Caravolas et al., 2012; Georgiou, Aro, Liao, & Parrila, 2016; Moll et al., 2014). RAN is therefore recognized as a universal marker of reading speed.

However, the precise explanation of the RAN-reading relationship is still debated. There is no consensus regarding which processes are driving the RAN-reading relationship. Involving the activation and the integration of many of the components implied in reading (e.g., attentional, visual, orthographic, phonological, semantic, memory, and articulatory systems), several theoretical accounts have been proposed to explain the RAN-reading relationship. Initially, RAN was alternatively hypothesized to sustain the speed of access to the phonological codes (Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner et al., 1997) or to subserve orthographic processing (Bowers, 1995; Bowers & Wolf, 1993; Sunseth & Greig Bowers, 2002). On the one hand, RAN has been shown to be a good predictor of word and nonword reading fluency (Araújo et al., 2015; Moll, Fussenegger, Willburger, & Landerl, 2009; Ziegler et al., 2010), and to be especially important during the first stages of learning to read acquired in Grades 1 and 2 (Araújo et al., 2015; Rodríguez, van den Boer, Jiménez, and de Jong (2015); Wagner et al., 1997; Authors, 2020). On the other hand, other studies have demonstrated the RAN-reading relationship was fairly weak at the start of primary school, whereas it clearly increased during schooling (Landerl & Wimmer, 2008; Vaessen & Blomert, 2010), and through adulthood (van den Bos, Zijlstra, & lutje Spelberg, 2002). Some authors also found that RAN predicted reading of irregular words (Clarke, Hulme, & Snowling, 2005; Kruk, Mayer, & Funk, 2014; Manis, Seidenberg, & Doi, 1999), and high-frequency words (Vaessen & Blomert, 2010). More recent studies (de Jong, 2011;

Logan, Schatschneider, & Wagner, 2011; Protopapas, Altani, & Georgiou, 2013) have suggested that the serial format of RAN tasks would be determining for the RAN-reading relationship. In first-grade readers, de Jong (2011) showed that serial RAN (i.e. several items presented simultaneously) was more strongly related to reading than discrete RAN (i.e. individual items presented in isolation), irrespective of the reading format (discrete or serial reading). But, in more advanced readers (Grades 2 and 4), serial RAN better predicted serial reading (i.e. word lists), and discrete RAN better predicted discrete reading (i.e. isolated words). The author suggested that in beginning readers, words are processed serially, letter by letter, whether they are presented in discrete or serial format (serial within-word processes). As a consequence, serial RAN could be a more powerful predictor at this acquisition stage. In more advanced readers, words are read by sight, explaining why similar formats of RAN and reading were more strongly related. At this acquisition stage, discrete RAN would underlie direct recognition of words presented individually, whereas serial RAN would measure the seriality present between words in serial word reading (serial between-word processes).

In the end, probably no specific individual processing is sufficient to fully explain the RAN-reading relationship. Phonological, orthographic, serial, but also articulatory processes (Georgiou & Parrila, 2013; Georgiou, Parrila, Cui, & Papadopoulos, 2013; Papadopoulos, Spanoudis, & Georgiou, 2016; Van den Boer, van Bergen, & de Jong, 2014) all seem to play a role. In a review, Norton and Wolf (2012) have suggested a move to a more integrative view considering the RAN-reading relationship as having multiple sources. They have also proposed that the reason why RAN consistently predicts reading lies in: “the ability to automate both the individual linguistic and perceptual components and the connections among them in visually presented serial tasks” (p. 430).

While authors mainly investigated RAN's predictive contribution to reading and its relevance as a diagnostic indicator of reading disabilities, only a few studies raised the question of the causal relationship between RAN and reading through interventions.

1.2. RAN Interventions

The development of targeted interventions, which best address the child's needs, has become a major concern of research on learning disabilities. Years of research have widely demonstrated that training phonological awareness simultaneously with letter-sound knowledge is an efficient remediation strategy for decoding and spelling deficits (for meta-analyses, see Bus & van Ijzendoorn, 1999; Ehri et al., 2001). Conversely, RAN training has received much less attention by the scientific community.

Among the few authors who have attempted to train RAN so far, only one team of researchers has succeeded in observing a beneficial effect of RAN in children with dyslexia. To the best of our knowledge, there have been five published studies of a RAN intervention. The first three studies focused on letter-naming speed and mainly failed to observe benefits in RAN or reading (Conrad & Levy, 2011; de Jong & Vrielink, 2004; Fugate, 1997). Training letter naming or letter-sound naming is closely associated with word decoding. In this sense, the association between the two abilities involves a certain circularity in the interpretation. Another limitation lies in the mixed findings from the three studies. Fugate (1997) found a significant effect of letter-naming speed training in Grade 1 children at post-test, with improvement of the letter-naming speed and a small subsequent increase in reading fluency. However, these effects were no longer significant at follow-up, and intervention transfer to reading was only shown for one of the four reading measures. In de Jong and Vrielink (2004), the children trained in letter-sound naming speed did not outperform the non-trained group on this measure or on reading following the intervention. Conrad and Levy (2011) conducted crossover interventions in orthographic pattern recognition and fast letter recognition with Grade 1 and Grade 2 children who had poor reading scores and slow naming speeds. Results showed that letter-naming training provided benefits in letter-naming speed, but only when it was preceded by the orthographic pattern recognition training. However, the combination of the two consecutive interventions could have led to confounding training effects. Another limitation of these studies is that the training did not always include matrices (serial RAN), but sometimes corresponded to a flashcard drill of individual letters (de Jong & Vrielink, 2004; Fugate, 1997). Yet, the literature shows that traditional serial RAN is more strongly associated with reading than discrete RAN is (Georgiou et al., 2013; Logan et al., 2011; Wolf & Bowers, 1999). Finally, it is worth mentioning that all those studies delivered relatively short training interventions. Their total duration varied between 1.5 and 5 hours, and were spread from over 6 days to 15 weeks. As suggested by Kirby, Georgiou, Martinussen and Parrila (2010), it is possible that more intensive lessons over longer periods may be more effective. A recent study aimed to specifically train RAN objects among Grade 2 normal readers (Authors, 2018). The choice to focus on RAN objects was guided by the fact that object naming requires the perception of the object and the activation of the semantic information, whereas letter or digit naming reflects the access to a code, without a semantic mediation (Liu & Georgiou, 2017). When naming an object, the child must recognize this object and activate its semantic representation in order to recover its phonological representation. Moreover, RAN objects is a purer measure than RAN letters because it does not confound naming speed and letter identification (Wagner & Torgesen, 1987; Ziegler et al., 2010). A recent study also highlighted that RAN objects was a better indicator of reading level variance than RAN letters (Cohen, Mahé, Laganaro, & Zesiger, 2018). The children received the RAN intervention twice a week over a period of 2 months. The results demonstrated the efficacy of this RAN object intervention with specific transfer effects on reading speed in normal-reading second graders. Finally, a very recent study conducted by

Pecini et al. (2019) showed the effects of a RAN-objects intervention in children with dyslexia. They asked them to use software at home that gradually reduced the stimulus presentation time. They found that children improved in RAN and in reading following the intervention. It would be informative to be able to replicate these kind of effects by combining behavioral and brain measures to provide a better understanding of the circumstances under which RAN training is effective for children with reading disabilities.

1.3. RAN in The Brain

Only a handful of studies have explored the neural correlates of RAN, and their results are inconsistent. To our knowledge, only three studies have investigated the neural circuitry of RAN with fMRI and in-scanner RAN tasks. They all found a quite diffuse network of regions over the brain including and going beyond the dorsal and ventral routes of the reading network (Cummine, Chouinard, Szepesvari, & Georgiou, 2015; Cummine, Szepesvari, Chouinard, Hanif, & Georgiou, 2014; Misra, Katzir, Wolf, & Poldrack, 2004). More specifically, RAN tasks (objects, digits, letters) administered to normal adult readers produced a left-dominant activation pattern including regions related to visual processing (occipital gyri), phoneme-grapheme mapping (left supramarginal gyrus), semantic and orthographic processing (left middle/inferior temporal gyrus), motor planning (bilateral cerebellum), and articulation (left motor areas; Cummine et al., 2015; Cummine et al., 2014).

The dorsal and ventral routes of the reading network are identified in the left hemisphere of the brain. The dorsal route corresponds to left temporo-parietal regions (including the superior temporal and supramarginal gyri), and inferior frontal regions in and around Broca's area (Jobard, Crivello, & Tzourio-Mazoyer, 2003; Pugh et al., 2010). The ventral route is located in the left occipito-temporal region, at the junction between the inferior and middle temporal gyri, and the fusiform gyrus (Jobard et al., 2003; Pugh et al., 2010), also referred to as the visual word form area (i.e., the VWFA; Cohen et al., 2000;

Dehaene & Cohen, 2011). Connecting the inferior frontal regions, this route also promotes lexico-semantic processing (Jobard et al., 2003; Taylor, Rastle, & Davis, 2012; Specht et al., 2009; Rapp & Lipka, 2011). Some studies have supported the idea that RAN was mainly sustained by the dorsal route. fMRI studies showed that individual differences in RAN (measured outside the scanner) positively correlated with the strength of functional connectivity within the left dorsal regions (Boets et al., 2013; Qian, Bi, Wang, Zhang, & Bi, 2016).

Diffusion tensor imaging (DTI) by providing an index of connections between brain regions is a complementary imaging technique to MRI. DTI is an MRI sequence, which allows us to study the *in vivo* anatomy of white matter tracts (Catani & Thiebaut de Schotten, 2012). DTI studies reported correlations between RAN performance and the fractional anisotropy (FA) in the left AF segment (Deutsch et al., 2005; Gullick & Booth, 2015). Fractional anisotropy (FA) is a DTI-derived measure corresponding to the degree to which water molecules diffuse in a single predominant orientation (i.e., the degree of anisotropy; Jeurissen, Descoteaux, Mori, & Leemans, 2017; Soares, Marques, Alves, & Sousa, 2013). The FA provides information on the organization and the integrity of the neural tracts, and is one of the most reported indices in DTI (Catani & Thiebaut de Schotten, 2012). According to a review of DTI studies on reading (Vandermosten, Boets, Wouters, & Ghesquière, 2012), the two aforementioned neural routes would be sustained by white matter pathways enabling adequate communication between these cortical regions. On the one hand, the arcuate fasciculus (AF), which connects the temporo-parietal and frontal regions, is composed of three subcomponents (a direct long segment, an anterior segment, and a posterior segment; Catani, Jones, & Ffytche, 2005), and has been related to the phonological reading route (Steinbrink et al., 2008), as well as other phonology-related processes such as speech perception, phonological awareness, phonological short term memory, and articulation

(Duffau, 2008; Vandermosten, Boets, Wouters, et al., 2012; Thiebaut de Schotten, Cohen, Amemiya, Braga, & Dehaene, 2014). On the other hand, two white matter tracts have been suggested to subserve the ventral route: the left inferior fronto-occipital fasciculus (IFOF), connecting occipital and frontal lobes, has been related to the semantic system (Duffau, 2008), and to the orthographic processes of reading (Vandermosten, Boets, Poelmans, et al., 2012; Vanderauwera et al., 2018); and the left inferior longitudinal fasciculus (ILF), connecting occipital and temporal lobes, has been suggested to serve as a route to transfer visual input to the VWFA (Vandermosten, Boets, Wouters, et al., 2012).

Importantly, the aforementioned studies used a RAN composite score including different types of items (objects, colors, digits, and letters). Studies especially assessing RAN objects, found another pattern of results: RAN objects would recruit more ventral areas. Two fMRI studies using in-scanner RAN tasks found an activation specific to RAN objects in the left and right fusiform gyrus located on the ventral stream (Misra, Katzir, Wolf, & Poldrack, 2004; Cummine et al., 2014). Schurz et al. (2015) also reported correlations between RAN objects and the functional connectivity between ventral (left occipitotemporal) and frontal (left inferior frontal) areas. With DTI, RAN objects has recently been found to be associated with FA in right IFOF across pre-readers (Vandermosten et al., 2015), or in bilateral IFOF among adult normal readers (Rollans, Cheema, Georgiou, & Cummine, 2017). Those findings are not surprising in as far as we know that these occipitotemporal regions, including the VWFA in the left hemisphere, are not only implied in reading processing, but also in object recognition and naming (Rossion, Joyce, Cottrell, & Tarr, 2003; McCrory, Mechelli, Frith, & Price, 2005; Price & Devlin, 2011;Taylor, Rastle, & Davis, 2014). Previous studies have also shown that the left IFOF connecting these regions was involved in object naming (Gil-Robles et al., 2013; Shinoura et al., 2013).

To sum-up, studies in neuroimaging show that RAN is associated with a diffuse network of regions over the brain. None of them has explored the specific structural changes that could occur after RAN training. However, providing evidence of neuroplastic changes following the intervention would lead to a stronger understanding of the RAN neural substrate, and would add powerful support to the behavioral evidence of the efficacy of RAN training.

1.4. The Present Study

Altogether, behavioral and neuroimaging studies have not disentangled the question of the causal relationship RAN has with reading. Therefore, the present study aimed to address this question within an intervention design, combining cognitive measures, as well as DTI connectivity measures. The first objective was to demonstrate the efficacy of a RAN intervention among children with dyslexia and, in doing so, to replicate the results obtained by Pecini et al. (2019). Precisely, we wanted to investigate whether it is possible to enhance naming speed through RAN-objects training, and whether this training can provide benefits in reading. We chose to train RAN objects and not RAN letters to avoid the similarity issue with reading. We also wanted to use RAN objects and not RAN digits in order to examine the RAN-reading relationship including a semantic mediation. Indeed, while RAN letters or digits reflect access to a code with a direct access to the phonological representation, objects RAN requires the recognition of the concept – a semantic mediation – before retrieving the lexical unit (Protopapas, Katopodi, Altani, & Georgiou, 2018). Moreover, in the intervention, RAN objects tasks consisted of naming a wide variety of words in order to increase the resource demands of the task, with a larger number of tokens to retrieve in long-term memory (Araújo et al., 2015). This would not have been possible with a RAN-digits intervention for example. We anticipated that following the intervention, the children with dyslexia (i.e., the trained group) would have significantly enhanced their RAN performance compared to the control group. We also expected to show associated gains in reading speed especially since RAN generally predicts reading speed in particular.

The second objective was to provide complementary evidence of the benefits of RAN training by means of white matter connectivity measures. The observation of both cognitive and brain connectivity improvements following the intervention would add strong arguments in favor of RAN training to remediate reading disabilities. Similar to the main DTI findings, we would expect to observe associated FA changes in the left dorsal pathway (i.e., AF segments) or in the left IFOF which has previously been found to be specifically associated with RAN objects.

2. Materials and Methods

2.1. Participants

A total of 21 children with dyslexia and 21 TD children ($N = 42$) aged 8–12 years old participated in the study. Among them, the children included in our sample were selected based on inclusion and exclusion criteria. The inclusion criteria were normal nonverbal IQ as measured by the Matrix Reasoning Subtest of the WISC-IV (Wechsler, 2005); normal receptive vocabulary as assessed by the French adaptation of the Peabody Pictures Vocabulary Test (Dunn, Thériault-Whalen, & Dunn, 1993); and native French speaking. Exclusion criteria were history of brain damage, vision/hearing deficits or psychiatric disorder, usage of medication, and metal in the body. Two children from the initial sample were removed from the analyses because they did not meet one of these criteria. Four children were removed of the analyses because they withdrew from the study before the end of the trial, and another five due to inadequate MRI-data acquisition or motion artefacts in their scans.

The final studied sample consisted of 18 children with dyslexia (9 males; $M_{age} \pm SD$: 10.59 ± 0.96 years) and 13 TD children (5 males; $M_{age} \pm SD$: 10.47 ± 0.85 years). Although the analyses were run on this whole sample, it is worth noting that within it, 13 children with dyslexia and 13 TD children were matched pairwise based on gender, age, and handedness as assessed using the Edinburgh Handedness Inventory (Oldfield, 1971). No group differences were found on the matching variables (see Table 1). We also ensured that the 18 children with dyslexia and the 13 TD children did not differ in nonverbal IQ, vocabulary, and socio-economic status (SES) as measured by the ISCED-scale (International Standard Classification of Education; OECD, 1999). Every child with dyslexia had a formal diagnosis of developmental dyslexia and scored below the tenth percentile (based on age norms) regarding at least two reading and spelling measures from the BALE (Jacquier-Roux, Lequette, Guillemette, Valdois, & Zorman, 2010). Of the 18 individuals, 16 children scored below the third percentile regarding at least three measures. Moreover, independent *t* tests confirmed that the TD children significantly outperformed children with dyslexia on every reading and spelling measure (see Table 1). Children with dyslexia also had significantly poorer phonological abilities, as confirmed by their performance on a syllable and phoneme deletion task (Author, 2003). Those children came from six different schools, one of which was a special needs school. Importantly, none of them received or had received RAN training as part of their school curriculum or their speech therapy treatment.

The study was carried out in accordance with the ethical standards of the Declaration of Helsinki. We collected written informed consent from all participants and their parents. The children received a gift card following each MRI-scan session. All protocols were approved by the local Ethics Committee of the University Hospital of Saint-Luc (approval number B403201733750).

2.2. Procedure

All children with dyslexia received an 8-week RAN intervention over a 2-month period (March to April). There was a 2-week interruption after the sixth week due to the spring break. Forty-five-minute lessons took place twice a week at school for a total of 16 lessons (i.e., 12 hours). The children were trained by one of the three experimenters (the first author and two other researchers) in small subgroups of five children maximum. Precautions were taken to ensure that the interventions were delivered as planned by the three experimenters. For instance, a checklist containing step-by-step directions was checked off at each lesson, and the presence of each participant was noted. Over the 16 lessons, the experimenters completed 95.36% of the planned activities, and the children took part in 96.71% of them (for more details about fidelity treatment, see Authors, 2018). All participants (trained and untrained) received a cognitive and neuroimaging assessment before (T1; February) and immediately after (T2; May) the intervention. The cognitive testing was divided into two 40-minute sessions that took place at school. At the pre-test only, the tests of nonverbal IQ, vocabulary, and handedness were administered, and participants' SES were collected with a parental questionnaire. The MRI-scan sessions took place at the university hospital at weekends.

2.3. Intervention

The RAN intervention aimed at increasing the naming speed of objects. The intervention program was based on a previous study, in which authors demonstrated the efficacy of a RAN-objects training among Grade 2 normal readers (Authors, 2018). The same training program was implemented with some supplementary activities.

The material of 24-items RAN matrices was identical. Two types of RAN-objects' matrices were used: RAN-R matrices (RAN repeated) were composed of a few items that appeared several times (three items repeated eight times or six items repeated four times) while RAN-NR (RAN non-repeated) included 24 different items. The first eight lessons used RAN-R matrices. The last eight used RAN-NR ones. Two matrices were employed per lesson, resulting in a total of 16 RAN-R matrices and 16 RAN-NR matrices and a total of 192 items trained through the 16 lessons. Most of the 192 token items of the 32 matrices were objects, seven were colors (for further details on the items, see Authors, 2018). To this original material, we added 32 RAN strips of eight items (224 token items), 416 flash cards of discrete RAN, and eight sets of 14 real objects, especially designed for the present study. RAN strips were composed of items from the matrices and supplementary items arranged according to the semantic category (food and drinks, home objects, clothes, body parts, animals, music instruments, sports, action verbs…). They were arranged in one row. The flash cards were single cards presenting the RAN-matrices and the RAN-strips items in isolation. All items from the matrices, the strips, and the flash cards were color pictures of highly familiar objects. The nouns had a high frequency corresponding to the 75th percentile of the word-frequency distribution for Grade 1 children (SFI > 56 in MANULEX; Lété, Sprenger-Charolles, & Colé, 2004). Finally, the sets of real objects included items from the matrices. They were placed on a table and arranged in one row. In each condition (matrices, flash cards, strips, real objects), the objective always was to allow the child to name the set of items as precisely and as quickly as possible. Importantly, it should be noted that, except for four of the seven color names, none of the training items were used in the test matrices of our RAN measures. Hence, if we were to observe gains in naming speed of the untrained test items following the intervention, this would mean that RAN is a procedural skill, and not an item-specific skill.

Each lesson was constructed in the same way: (1) first, the children were asked to name as many flash cards as possible in one minute, then, (2) two RAN matrices were practiced with varied forms of activities (more details in Authors, 2018), and finally, (3) two RAN strips and one set of real objects were practiced. Those three sequences were formulated in order to diversify the activities and keep the children invested in the training. It is worth mentioning that the flash-card drill only lasted five minutes at the beginning of the lesson as a little warm-up, whereas serial RAN activities (RAN matrices, RAN strips, and real objects) were the core of the training lasting 25 minutes. The remaining 10 minutes were used to immerse the children in a story. To keep them motivated, they were told a story of travel through the solar system. They were astronaut in mission, and their rocket had the particularity to work with “word energy”. This encouraged them to name as many words as possible during each lesson to ensure the travel continued. They also received planet cards and stars to take home at the end of each lesson.

2.4. Cognitive Assessment

2.4.1. Rapid Automatized Naming

The RAN measures consisted of one matrix of objects and one matrix of colors. The RAN-objects matrix was adapted from the Battery for the Assessment of Phonological skills (Author, 2003). It was composed of three items repeated eight times and arranged semi-randomly in four rows of six, for a total of 24 stimuli. The items were highly familiar nouns with an age of acquisition (AoA) lower than six years, defined on the basis of AoA norms (Chalard, Bonin, Méot, Boyer, & Fayol, 2003; Ferrand et al., 2008). The word frequency corresponded to the 97th percentile of the word-frequency distribution of oral productions, defined on the basis of Lexique 3.80 (New, Pallier, Brysbaert, & Ferrand, 2004), and they had a two-to-three-syllable length. The words were illustrated by color photographs respecting the characteristics of the standardized images of Snodgrass and Vanderwart’s database (1980). The names in French were *guitare* /gitaʀ/ [guitar], *cheval* /ʃəval/ [horse], and *téléphone* /telefɔn/ [telephone]. The RAN-colors matrix came from the standardized battery DRA (Plaza & Robert-Jahier, 2006) and included four colors (blue, green, red, yellow) repeated 12 times and randomly arranged in six rows of eight, for a total of 48 stimuli. Both tasks were run on a portable computer, RAN objects with PsychoPy 1.82.01 software (Peirce, 2007, 2008), and RAN colors with Adeprio software (Adeprio logiciel, Paris), recording the total naming time of each screen. The material (15.6 inch-screen, headphones, software) was identical for the two testing sessions. Each test matrix was preceded by a training matrix. The training matrix of the RAN-objects task was composed of three objects which were different from the test matrix (i.e., skirt, paper, frog) and were repeated eight times. With regard to the RAN-colors task, the training matrix included the four colors of the test matrix arranged in a row of six items. Participants were instructed to name the items as quickly and accurately as possible from left to right and from top to bottom. In the analyses, we used the total naming time of each test matrix, as well as a composite score (RAN CS) that corresponded to the total naming time of both matrices (objects + colors). Reliability analyses performed in our previous intervention study (Authors, 2018), returned an alpha coefficient of 0.83 for the RAN object matrix.

2.4.2. Word Reading

The single word reading task was a standardized test from the BALE/Batterie Analytique du Langage Ecrit ([Analytic Battery of Written Language]; Jacquier-Roux et al., 2010). It consisted of three lists of printed words arranged in columns: 20 regular words, 20 irregular words matched on length, and 20 pseudowords, matched on length, phonemic and orthographic structure with the regular words (Bosse & Valdois, 2009). The children were asked to read the items aloud as quickly and accurately as possible. Regarding the pseudowords, they were informed that they were not real words, and that the purpose was to read them without trying to understand them. Speed (reading time in seconds) and accuracy (number of items correctly read) were recorded for each list. Reliability analyses performed in our previous intervention study (Authors, 2018) on the accuracy scores, returned an alpha coefficient of 0.90.

2.5. Neuroimaging Assessment

2.5.1. Data Acquisition

Given the young age of the participants, a detailed "rocket protocol" inspired by the submarine protocol (Theys, Wouters, & Ghesquiere, 2014) was used to prepare the children for their MRI scan (see the details of the procedure in Appendix A). The MRI-scan session lasted half an hour. All children underwent two MRI-scan session (T1 and T2), using a 3T (Achieva, Philips Healthcare, Eindhoven, The Netherlands) with a 32-channel phased array head coil. The anatomical 3D sequence consisted of a gradient-echo sequence with an inversion prepulse (Turbo Field Echo, TFE) acquired in the sagittal plane using the following parameters: repetition time (TR) = 9.1 ms, echo time (TE) = 4.6 ms, flip angle = 8°, number of slices = 150, slice thickness = 1 mm, in-plane resolution = 0.81×0.95 mm^2 (acquisition) reconstructed in 0.75×0.75 mm^2, field of view (FOV) = 220×197 mm^2, acquisition matrix = 296×247 (reconstruction 320^2), sensitivity encoding (SENSE) factor =1.5 (parallel imaging). DTI images were acquired using the following sequence: spin-echo planar imaging, TE = 83 ms, TR = 6422 ms, Bandwidth = 2790hz/pixel, number of slices = 70, slice thickness = 2mm, in-plane resolution = 2×2 mm^2, matrix size = 112×112, FOV = 224×224 mm^2, 55 directions, b = 800 s/mm^2.

2.5.2. Data Preprocessing

Preprocessing of the DTI-data was performed using BrainVoyager (Version 20.6, Brain Innovation, Maastricht, The Netherlands). The diffusion data were first corrected for eddy current-induced distortions and motion-induced artefacts, and then coregistred with the 3D anatomy of the participants to create volume diffusion weighted (vdw) data. All coregistrations were visually inspected, and possibly corrected manually if necessary. Given that children with dyslexia do not display a clear left-lateralized reading network (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Wang et al., 2016), we examined the tracts of interests in both left and right hemispheres. The selected tracts were chosen on an a priori basis because of their known role in RAN and reading processes: long AF segment, anterior

AF segment, posterior AF segment, IFOF, and ILF (see Figure 1). To construct the mask images of the tracts, we used a DTI-derived atlas (https://www.natbrainlab.co.uk/atlas-maps/) normalized in Talairach space. Fractional anisotropy (FA) maps were extracted from the vdw and normalized in Talairach space to obtain mean FA value in each tract of interest for each participant, in each hemisphere, and at each testing time (T1 and T2). Precisely, we calculated the mean FA changes from pre-test to post-test (T2 values – T1 values).

2.6. Statistical Analyses

Statistical analyses were performed using SPSS 26 (SPSS, Chicago, IL). Prior to all analyses, we observed the degree of skewness and kurtosis to ensure that the data met standard criteria of normality. Their values revealed no distributional problems except for response time (RT) in RAN and in reading. Inspection of the shape of the distributions revealed that RT variables tended to be asymmetric. For these reasons, and because it is recommended with speed measures, RAN and reading RTs were 1/RT transformed in order to reach distributions within acceptable levels of symmetry and peakedness.

We first analyzed the effect of the RAN intervention using two-way repeated measures ANOVAs with group as a between-participant factor and testing time as a within-participants factor. The assumption of sphericity was verified with Mauchly's test. We applied Greenhouse-Geisser corrections for data violating this assumption. Having four RAN measures, we further examined Group × Testing Time interactions that survived the correction for multiple comparisons with the Holm-Bonferroni Method (Holm, 1979).

Second, we analyzed the transfer effects of RAN training on the reading and on the MRI measures. Firstly, we performed repeated measures ANOVAs with a third within-participants factor (three-way repeated measures ANOVAs): word type for reading measures (i.e., irregular words, regular words, and pseudowords) and white matter tract for FA measures (i.e., the five tracts of interest). Next, we examined the correlations between RAN changes and other T1 to T2 change measures using Spearman correlation analyses performed in each group separately. More specifically, we wanted to examine whether reading or white matter (FA in the tracts of interest) changes (T2 – T1) in the dyslexic group were specifically associated with their RAN improvement (T2 – T1). For these analyses, we used a single RAN measure (i.e., the composite score). The reason for performing these correlational analyses in addition to group comparisons is that the two groups are not matched for literacy or for FA measures. Indeed, TD children are expected to naturally progress in word reading better than the children with dyslexia. Consequently, the group comparison could prevent the capture of literacy improvements in the dyslexic group that could be directly related to the RAN intervention. Along the same lines, TD children are also expected to show neuroplastic changes in the language tract because of their normal development, and schooling, and because those children are more often exposed to reading experiences than children with dyslexia. Therefore, comparing FA changes between groups would probably not be sufficient to highlight an intervention effect in the dyslexic group.

The alpha level was set at .05 for all the analyses. We reported significant interactions and correlations. When necessary, we also reported those that survived the correction for multiple comparisons (Holm-Bonferroni-adjusted *p*-values).

3. Results

3.1. Cognitive Results

3.1.1. Efficacy of the Intervention

The efficacy of the RAN intervention was analyzed with the two-way repeated measures ANOVAs conducted on the four RAN measures. The 2 × 2 ANOVAs showed significant Group × Testing Time interactions on each RAN variable: RAN CS (composite score), $F(1,29) = 10.94$, $p = .003$, $\eta^2_p = 0.27$, RAN Colors (seconds), $F(1,29) = 7.36$, $p = .011$, $\eta^2_p = 0.20$, RAN Colors (standardized score), $F(1,29) = 6.79$, $p = .014$, $\eta^2_p = 0.19$, and

RAN Objects, $F(1,29) = 5.41$, $p = .027$, $\eta^2_p = 0.16$. All interactions survived at the Holm-Bonferroni-adjusted *p*-values (respectively .013, .017, .025, .05 for four comparisons). As confirmed by the means and the paired samples *t*-tests (Appendix B), these results indicate that the children with dyslexia significantly improved in RAN from pre-test to post-test, compared to the untrained TD children who did not gain in naming speed between both time points (all *p*s > .46). Figure 2 displays this interaction with the RAN CS outcomes presented by group and testing time. Appendix B reports RAN performance scores by testing time and group, as well as paired samples *t*-tests comparing performance scores obtained at T1 and T2 for each RAN measure in each group separately.

Additionally, when looking at group differences at T1 and T2 separately, we found group differences for the two RAN measures at T1 with clear advantage for TD children (see Table 1), while no group differences were noticed at T2 (*p*s > .16). These results suggest that the children with dyslexia normalized their performances. Indeed, the average standardized score of RAN colors changed from being impaired at T1 (-1.46 σ = percentile 7) to within the average norms at T2 (-0.79 σ = percentile 20).

3.1.2. Reading Changes Associated with RAN Improvement

Firstly, we analyzed Group × Testing Time × Word Type interactions with three-way repeated measures ANOVAs conducted on word reading accuracy and on reading speed. Models were run separately for accuracy and speed as the values are different in nature (number of correct responses *vs*. response times in seconds). The 2 × 2 × 3 ANOVAs revealed significant Group × Testing Time interactions on word reading accuracy, $F(1,29) = 4.39$, $p = .04$, $\eta^2_p = 0.13$, and on word reading speed, $F(1,29) = 5.30$, $p = .03$, $\eta^2_p = 0.15$. The means suggest that children with dyslexia improved more than the TD children in word reading accuracy between T1 and T2, whereas the TD children enhanced word reading speed during this training period (Figure 3). No significant three-way interactions (Group × Testing

Time × Word Type) were found (*p*s > .05). Appendix C displays reading performances by testing time and group, as well as paired samples *t*-tests comparing performance scores obtained at T1 and T2 for each reading measure in each group separately.

Secondly, Spearman bivariate correlations were run in each group in order to examine whether the RAN improvement observed in the trained dyslexic group was specifically associated with word reading gains. We found a significant positive correlation between RAN changes and changes in regular word reading accuracy ($r = .52$; $p = .026$) and in regular word reading speed ($r = .52$; $p = .028$), suggesting that enhancement in naming speed (decrease of the naming times) was associated with enhanced regular word reading accuracy and speed (decrease of the reading times). However, these correlations did not survive Holm-Bonferroni correction for multiple comparisons (respectively .008 and .01 for six comparisons). As expected, no significant correlation was found between RAN changes and word reading changes in the TD group (*p*s > .15). Correlational analyses are provided in Appendix D.

3.2. DTI Results

3.2.1. Brain Changes Associated with RAN Improvement

We first analyzed the Group × Testing Time × White Matter Tract interaction with a three-way repeated measures ANOVA conducted on the FA values. The 2 × 2 × 10 ANOVAs revealed no significant two-way (Group × Testing Time) or three-way (Group × Testing Time × White Matter Tract) interactions (*p*s > .10). Appendix E shows FA values by testing time and group, as well as paired samples *t*-tests comparing FA values obtained at T1 and T2 for each tract in each group separately.

Then, Spearman bivariate correlations were conducted in each group in order to assess the relationship between the evidenced RAN improvement observed in the trained dyslexic group and FA changes that could have occurred in the 10 tracts of interest. Gains in RAN correlated with FA changes in three tracts: the left anterior AF segment (r = -.65, p = .004), the left long AF segment (r = -.59, p = .009), and the right posterior AF segment (r = -.48, p = .044). Hence, decrease in the naming times was associated with increases in FA in those tracts. However, only the correlation between RAN changes and FA changes in the left anterior AF segment remained significant after controlling for multiple comparisons across the 10 tracts (Holm-Bonferroni-adjusted p-value of .005; Figure 4). In the TD group, results showed one significant correlation between RAN changes and FA changes in the left IFOF (r = -.65, p = .015), but this correlation did not survive the Holm-Bonferroni correction. Correlational analyses are presented in Appendix F.

4. Discussion

The present study was motivated by two main observations. First, no study has demonstrated the efficacy of RAN training in children with dyslexia with both behavioral and brain evidence so far. Second, the brain bases of RAN and its contribution to reading processes of written words are still not well understood. This study aimed to address these gaps with a RAN-objects intervention administered to children with dyslexia, and assessed by behavioral and brain measures. Compared to the untrained children, the children with dyslexia significantly improved in RAN performance and in word reading accuracy following the intervention. Moreover, their RAN improvements were associated with white matter changes: enhanced naming speed correlated with increased FA in the left anterior AF segment. The results are discussed below.

4.1. RAN Can Be Improved

Because of the lack of strong evidence, most researchers in cognitive science and psycholinguistics have thought for a long time that RAN was impossible to improve by training. Avoiding the biases of the studies aiming at improving RAN, our previous study showed the efficacy of a specific RAN-objects program among Grade 2 normal readers

(Authors, 2018). More recently, Pecini et al. (2019) also demonstrated the efficacy of RAN-objects training in Italian dyslexic children. In the present study, we were able to replicate these results with French-speaking dyslexic children. Compared to the untrained children, the children with dyslexia significantly improved their performance in RAN objects and colors. Moreover, compared to their particularly low scores at pre-test, they showed RAN scores in the average norms following the intervention. It is worth noting that these results cannot be explained by some schooling or teaching/remediation effect, because the untrained children did not show any gains in RAN after the two-month period. Indeed, RAN is not a skill trained by teachers or by speech therapists. Practitioners have a generally poor understanding about the task and its clinical use (Norton & Wolf, 2012). Currently, RAN is only considered as a screening tool to identify risk of reading disabilities, and as an indicator supporting the diagnosis of dyslexia (Petscher et al., 2019). The evidenced efficacy of this RAN intervention could change this perspective.

With regard to the impact of RAN on literacy skills, our results revealed that the reading accuracy scores significantly increased in the trained children with dyslexia, compared to the untrained TD children. This result is similar to those observed by Pecini and colleagues (2019) since dyslexic children also improved in reading accuracy, as well as in reading speed. The improvement in reading accuracy can be related to the observation of an association between RAN and reading accuracy in the early stages of learning, whereas the RAN - reading speed association is stable over time (Araújo et al., 2015). The association between RAN and reading accuracy present in children in the early stages of learning may be similar to the one we make with children with difficulties. Overall, our findings of an enhancement of reading accuracy in the trained children compared to the control children open new hopes for remediation of reading disabilities. Providing RAN training could be one new key to addressing the needs of a child who would face reading accuracy deficits.

Besides, knowing that disabled readers often develop an aversion to reading, the present RAN-objects intervention would be an innovative alternative way to enhance reading, with attractive materials, and without making the child read.

How can it be understood that the RAN intervention was effective, as was that of Pecini and colleagues (2019), when previous interventions were not? A first reason that could explain the efficacy of these interventions is the type of stimuli. Indeed, previous studies in which children did not improve mainly trained RAN letters (Conrad & Levy, 2011; de Jong & Vrielink, 2004; Fugate, 1997). In the present study, as well as in Pecini and colleagues (2019), children were trained with RAN-objects matrices. As explained earlier, a difference between naming letters/digits *vs*. objects lies in the use of semantic mediation (Liu & Georgiou, 2017). When naming an object, the child must recognize this object and activate its semantic representation in order to recover its phonological representation. According to this analysis, a component that seems important to better understand the relation between RAN and reading would be the use of semantic mediation. In order to confirm this hypothesis, it could be interesting to compare the benefits of a RAN-objects intervention and a RAN-digits intervention. If the importance of the semantic mediation is confirmed, a RAN-digits intervention (which only requires the activation of the code) should be less beneficial than a RAN-objects intervention. However, this option raises a practical issue for children. Would they be motivated to name a large quantity of digits for several hours? A second reason for the effects of our RAN intervention could also be that the children had to name matrices and not isolated pictures. Indeed, the three interventions which appear to help children to improve their RAN performance involved the naming of matrices rather than isolated-pictures (Authors, 2018; Pecini et al. 2019). Although difficulties with isolated naming were also observed in children with dyslexia (Swan & Goswami, 1997), the serial format of the RAN material seems to be an important dimension of the intervention. This observation is clearly in line with the serial hypothesis (e.g. Logan et al., 2011; Pennington, Cardoso-Martins, Green, & Lefly, 2001; Georgiou et al., 2013; Wagner, Torgesen, & Rashotte, 1994). Finally, the question also arises as to whether proposing an intervention including RAN with repeated and unrepeated items was a relevant consideration. In our study, we proposed the two types of RAN matrices. We included matrices of non-repeated items in order to increase resource demands since there are more items to retrieve in long-term memory (Araújo et al., 2015). In comparison, the children in Pecini and colleagues (2019)'s study had to name only matrices of repeated items (i.e., five randomly repeated stimuli in a matrix ranging from 20 to 50 stimuli). Since both interventions appear to be effective, varying the number of repetitions does not appear to influence the benefits of the intervention. This observation is consistent with the meta-analysis conducted on the data from 137 studies (Araújo et al., 2015) showing that varying the number of repetitions of the token items does not significantly influence the RAN-reading relationship.

4.2. Brain Correlates of RAN

Importantly, this is the first study combining a RAN intervention with DTI-data. Beyond the intervention’s efficacy on naming speed and reading accuracy, the results showed that increased naming speed was associated with higher FA values in the arcuate fasciculus forming the dorsal pathway (i.e., the left anterior AF segment, the left long AF segment, and the right posterior AF segment). This finding is in line with two previous MRI studies demonstrating that RAN performance correlates with the FA in the AF (Deutsch et al., 2005; Gullick & Booth, 2015), and with functional connectivity between left frontal and temporal regions which are connected by the AF (Boets et al., 2013). The fine neuroplastic changes, already observable after 12 hours of training, support the behavioral findings and the efficacy of the training. Moreover, these changes in brain connectivity occurred in one white matter pathway, which is known to sustain reading skills, and for which anomalies have been

615 reported in developmental dyslexia. Indeed, reading difficulties have been consistently
616 associated with reduced FA values in the arcuate fasciculus (AF), in adults (Boets et al.,
617 2013; Klingberg et al., 2000; Vandermosten, Boets, Poelmans, et al., 2012), in children
618 (Deutsch et al., 2005; Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010), and in
619 children at risk of dyslexia (Wang et al., 2016; Langer et al., 2015; Vanderauwera, Wouters,
620 Vandermosten, & Ghesquière, 2017). Furthermore, the left AF would be a unique predictor
621 of who will develop dyslexia, above and beyond the familial risk and cognitive predictors
622 (Vanderauwera et al., 2017). Our findings of higher FA values associated with RAN
623 improvement in the AF, suggest that training RAN-objects stimulate efficient and fast
624 communication within a typical neural pathway of reading, and provide a new kind of causal
625 evidence of the RAN-reading relationship.

626 Of importance, the most powerful associated FA change (i.e., the only one to survive
627 the correction for multiple comparisons), was the correlation between increased naming
628 speed and greater FA in the left anterior segment of the AF. This segment would mainly be
629 involved in articulation and speech fluency (Duffau, 2008; Fridriksson, Guo, Fillmore,
630 Holland, & Rorden, 2013). Therefore, our result showing that naming speed gains are
631 primarily associated with increased FA values in the left anterior AF suggests that RAN
632 would be primarily determined, in the brain, by articulation and speech fluency processes.
633 Interestingly, articulation and fluency processes are implied in oral language, but also in
634 reading. Together with our results of a relationship between RAN and reading accuracy, this
635 suggests that RAN could underly the ability to produce words accurately when reading aloud.
636 This is in line with some studies showing that RAN was a better predictor of oral reading
637 than silent reading (Georgiou et al., 2013; Papadopoulos et al., 2016; Van den Boer et al.,
638 2014).

639 **4.3. Limitations and Future Directions**

Our study has several important limitations. First, our control group (i.e., the typically-reading children) was not equivalent to the intervention group (i.e., children with dyslexia) regarding literacy skills. An untrained group of children with dyslexia would have been more appropriate to measure the intervention effect. Aware of this limitation, we adapted our statistics to prevent potential confounds of the intervention effect, but future studies including equivalent groups are required to support our findings.

Second, there could have been one bias related to the assessment conditions. Indeed, for practical reasons, a small proportion of the children with dyslexia (i.e. 5/18) were trained and tested by the same experimenter. Therefore, this is possible that at post-test, those children were implicitly more incited to perform the RAN task quickly than the control children.

Third, our final sample size is rather small, because the experimental design imposed substantial efforts on the participants, and was very demanding in terms of practical and financial resources. In addition, we had to remove some children from the analyses due to inadequate MRI-data acquisition or motion artefacts in their scans. Consequently, our small sample size might have affected our ability to detect changes associated with the RAN intervention. This small sample size also limits the extent to which the results can be generalized. Furthermore, although Holm-Bonferroni correction is a conservative method that significantly reduces statistical power, some findings should be interpreted with caution, and should be replicated with the same RAN intervention on a greater sample. Future studies on a larger dataset could also enable experimenters to better account for environmental differences known to have an influence on oral and written language (bilingualism, home literacy practices, method of reading instruction). Besides, adding a third testing time to measure the intervention effects in the long run could also help to capture more changes. Indeed, the induced cognitive and neuroplastic changes might not necessarily occur exactly during the treatment. In our previous RAN intervention study, a follow-up conducted six months after the intervention enabled us to reveal more effects of the intervention.

Finally, we can point two limitations related to the MRI data preprocessing. First, it has to be mentioned that for practical reasons (i.e., 10 tracts of interest), we did not perform whole-brain tractography of each individual DTI dataset and manual delineation of the specific tracts in native space. We rather used a standard template of an adult brain to construct the mask images of the tracts. This has the advantage to be fast and to enable the observation of a great number of tracts at a time. This does not undermine the observed effects, because our participants were tested twice, and exactly the same procedure was applied to the preprocessing of both testing times. For that purpose, we used an adult atlas because there is currently no child atlas available. We considered that this was more appropriate than comparing our participants to the template of an infant (i.e., 0-2 years old) brain (De Macedo Rodrigues et al., 2015). Second, the biological interpretation of FA values is challenging and remains speculative. Indeed, FA can be modulated by many complex processes such as changes in myelin, axon diameter, or axonal density (Sampaio-Baptista & Johansen-Berg, 2017). Yet, FA remains a useful measure of white matter microstructure, consistently reported in studies examining white matter plasticity.

4.4. Conclusion

The present study is the first to demonstrate the efficacy of a RAN intervention with both behavioral and brain evidence. Contrary to what has been believed for a long time, it is possible to train RAN. Together, the cognitive and neuroplastic gains associated with the training's efficacy revealed the potential of this kind of behavioral remediation program for children with dyslexia. This study also showed significant improvements of the trained children in word reading accuracy, and revealed that RAN objects was mainly associated with the left anterior AF segment which is part of the dorsal white matter pathway involved in oral language production and reading. This suggests RAN as primarily determined, in the brain, by the automatization of articulation and speech fluency processes. Overall, our results demonstrate how cognitive sciences and neurosciences can complement each other. Future studies are needed to further investigate the benefits of RAN training, and to better understand its neural basis.

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Table 1

Table 1

Participant Characteristics by Group at pre-test (T1)

Characteristic	DYS (n = 18) *M*	DYS (n = 18) *SD*	TD (n = 13) *M*	TD (n = 13) *SD*	Range	Test statistics
General characteristics						
Gender (boy/girl)	9/9		5/8			$\chi^2(1) = 0.41, p = .52$
SES (level 1/2/3)	0/4/14		0/1/12		2–3	$\chi^2(1) = 1.18, p = .28$
Handedness (left/right)	2/16		1/12			$\chi^2(1) = 0.10, p = .75$
Age in years	10.59	0.96	10.47	0.85	8.5–12	$t(29) = -0.34, p = .74$
Nonverbal IQ [a]	9.50	3.25	11.08	2.72	5–17	$t(29) = 1.42, p = .17$
Receptive vocabulary [b]	121.33	10.45	123.08	8.08	96–141	$t(29) = 0.50, p = .62$
RAN						
Objects (seconds)	24.54	5.43	20.30	3.13	16–36	$t(29) = -2.74, p = .01^*$
Colors [c]	-1.46	1.12	-0.25	0.79	-4–1	$t(29) = 3.32, p < .01^*$
Phonological awareness						
Accuracy (max = 30)	20.89	5.68	26.15	3.34	11–30	$t(29) = 3.24, p < .01^*$
Response time (seconds/item)	4.16	1.40	2.65	0.75	2-7	$t(29) = -4.10, p < .001^*$
Word reading accuracy						
Regular words [c]	-2.01	1.31	0.17	0.62	-5–1	$t(29) = 6.13, p < .001^*$
Irregular words [c]	-1.57	1.09	0.44	0.52	-3–1.5	$t(29) = 6.81, p < .001^*$
Pseudowords [c]	-2.54	1.51	-0.05	0.76	-6–1	$t(29) = 6.02, p < .001^*$
Word reading speed						
Regular words [c]	-2.15	1.74	-0.06	0.98	-6–1	$t(29) = 3.89, p = .001^*$
Irregular words [c]	-1.59	1.93	0.08	1.21	-6–3	$t(29) = 2.76, p = .01^*$
Pseudowords [c]	-0.81	1.04	-0.02	0.88	-3–1	$t(29) = 2.23, p = .03$
Word spelling						
Regular words [c]	-4.36	2.17	-0.61	1.19	-7.5–1	$t(29) = 6.16, p < .001^*$
Irregular words [c]	-3.29	1.25	-0.80	0.92	-6–1	$t(29) = 6.09, p < .001^*$
Pseudowords [c]	-0.79	1.43	0.33	0.47	-3–1	$t(29) = 2.72, p = .01^*$

Note. SES = socio-economic status, measured with the seven-point scale classification of the OECD (ISCED-scale; International Standard Classification of Education; OECD, 1999), and converted into a three-point scale classification, like in Boets, Wouters, Van Wieringen, and Ghesquière (2006); Group means were compared by independent *t* test, except for gender, socio-economic status (SES), and handedness, which were analyzed by a Chi-square test. Those scores are standardized, based on age norms: [a] Wechsler subtest scaled score (M = 10, SD = 3). [b] standard scores (M = 100, SD = 15). [c] z-scores (M = 0, SD = 1).

* Remains significant after Bonferroni correction for multiple comparisons (two comparisons regarding phonological awareness and RAN; three comparisons regarding word reading accuracy, word reading speed, and word spelling).

Figure 1
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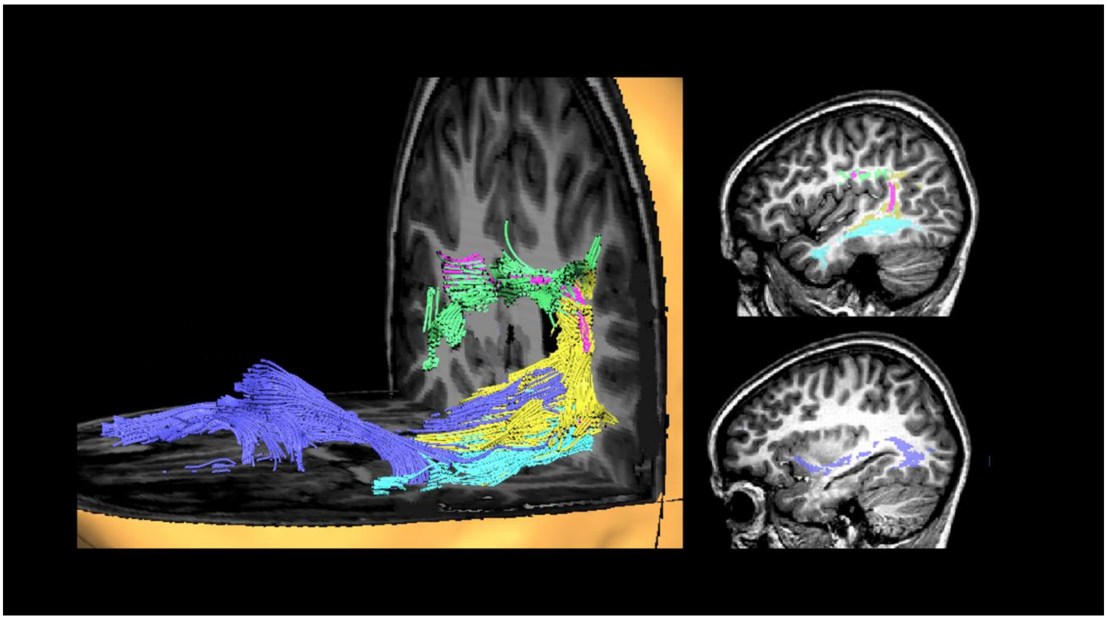

Figure 1. Sagittal views of the left tracts of interest from a single participant: (1) long segment of the arcuate fasciculus (AF) depicted in pink; (2) anterior AF segment depicted in light green; (3) posterior AF segment depicted in yellow; (4) inferior fronto-occipital fasciculus (IFOF) depicted in dark blue; (5) inferior longitudinal fasciculus (ILF) depicted in light blue. Right homologues are not presented in the figure but were included in the analyses.

Figure 2
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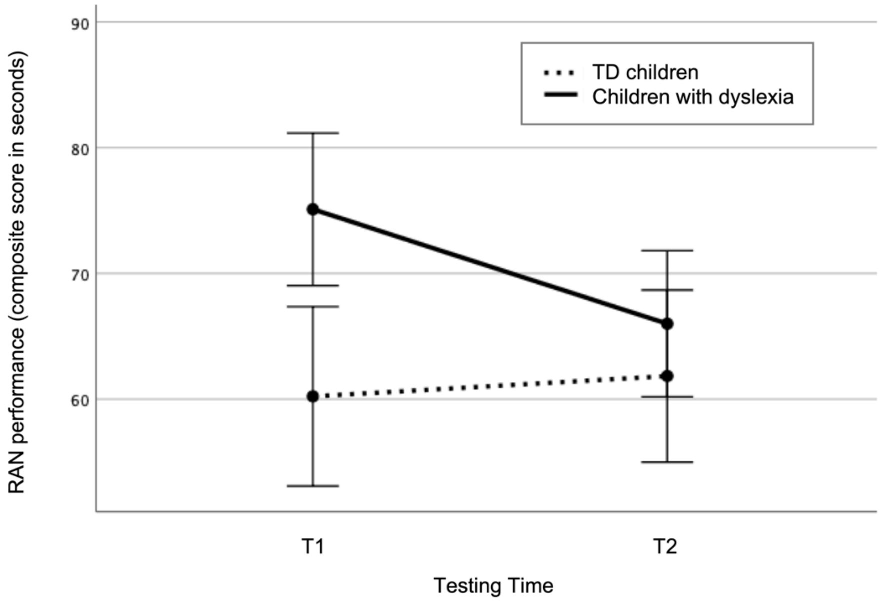

Figure 2. Group × Testing Time interaction on RAN performance. Error bars represents the 95% confidence interval.

Figure 3
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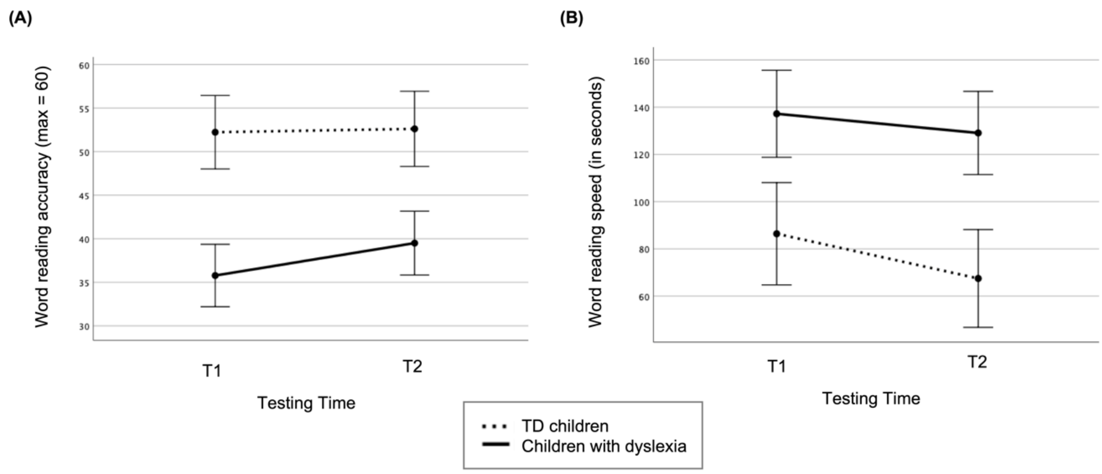

Figure 3. Group × Testing Time interactions on reading performance. (A) Word reading accuracy outcomes by group and testing time. (B) Word reading speed by group and testing time. Error bars represents the 95% confidence interval.

Figure 4
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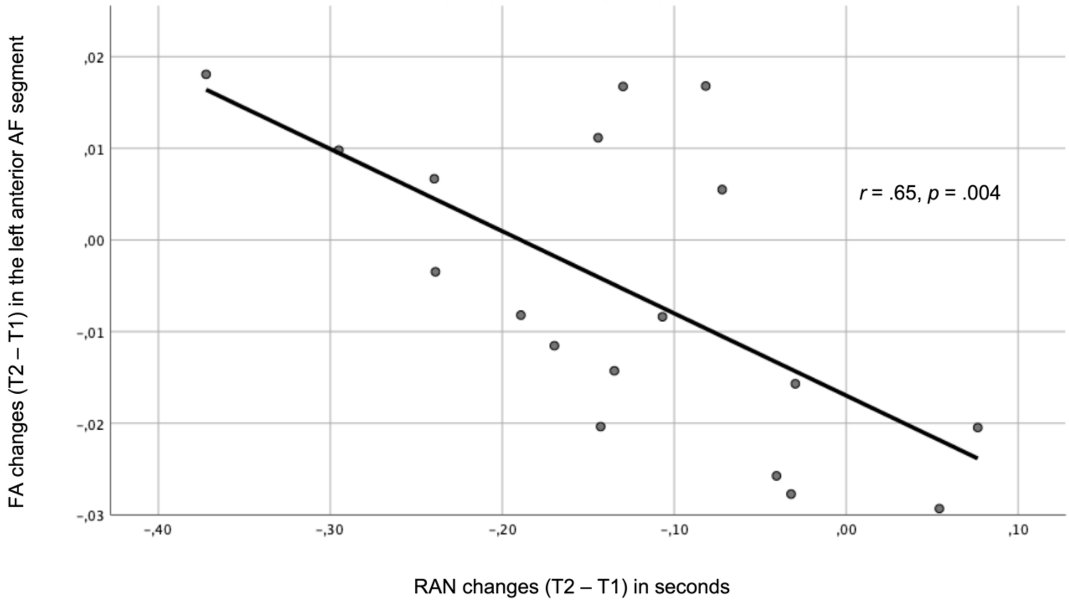

Figure 4. Significant Correlation between RAN change and FA Change in the Left Anterior AF Segment Found in the Dyslexic Group.

Appendix A

Description of the rocket protocol

Theys, Wouters, and Ghesquiere (2014) demonstrated that preparing the child to the MRI-scan session in a playful manner, enables to acquire good quality DTI images among young children in an efficient time. Inspired by this research using a submarine protocol, the MRI scans of the present study were conducted using a rocket protocol.

In a first step, parents and children were invited to an information meeting. The entire study was presented (goals, design, practical aspects…), with a particular focus on the MRI-scan session. We already immersed the participants in an exciting story about a spatial mission adventure. By playing MRI-sound recordings, we also prepared them to the noises of the rocket (i.e., the MRI scanner) that can be impressive. This meeting was an occasion to fully inform the parents and their children about the MRI technique, to reassure them, and to provide them sufficient time to ask any questions they may have.

Second, a pre-scanning preparation phase was proposed the day of the MRI-scan session, before entering the scanner room. During 20 minutes, five games were played together with the child, explaining every aspect of MRI scanning, and teaching adequate within-scanner behavior.

1. Familiarization: The goal of this task was to make the child feel at ease with the researcher. We welcomed the child dressed up in astronauts, and we explain him/her the objective of his/her spatial mission, which was to take new pictures of our solar system. The child was in turn dressed up in astronaut. This moment gave the opportunity to have an informal conversation with the child and his/her parents. When the child was ready, a picture of the spatial crew was taken.
2. Good and blurry pictures: The researcher explained that the rocket was equipped with a giant photo camera, which will take pictures of the planets during the spatial journey

(i.e., the scanning session). As in Theys et al. (2014), we ask the child to sort sharp and blurry pictures to make him/her aware that the pictures taken by the rocket will be blurry if he/she moves during the journey.

3. Candy on nose: The purpose was to check if the child was able to lie still. The child was invited to lay down on a bed. Then, the right astronaut's position (on the back with arms along the body) was taught to him/her. As in Theys et al. (2014), he/she was trained to lie still as a statue, while balancing a candy on his/her nose. He/she had to try to answer some questions without moving, keeping the candy suspended on his/her nose. The child was allowed to eat the candy if it did not fall off during the conversation.
4. Space helmet: A non-working MRI head coil was placed over the child's head to help him/her get used to the feeling of wearing a "space helmet". The researcher asked some questions to the child, reminding him/her not to move his/her head.
5. Hearing protections: The researcher explained to the child that the rocket can make a lot of noise, like an airplane. To prepare the child to the various noises, recordings of different MRI sounds were presented. This preparation allowed the child to be prepared to the noise changes, and to perceive them as a normal part of the process. Then, we explained to him/her that he/she will wear earplugs to protect his/her ears, and headphones to ensure good communication with the control tower. We finally explained to the child that he/she will always be in contact with the control tower, and that each step of the spatial mission will be recalled during the journey.

Third, we finished the preparation in the scanner room. The room was decorated in the spatial theme (rockets, stars, planets…). We began by introducing the child to the rocket (i.e., MRI scanner), and we gave him the necessary time to explore the room and to examine the rocket. The child was then installed in the MRI scanner. We remind him/her what will happen during the mission, and we wished him/her a good journey. After the first MRI-sequence acquisition, we reassured the child by congratulating him/her for the successful taking off of the rocket. Between each scan sequence, the researcher talked to the child to keep him/her motivated, and to inform the child again of the step about to occur. For example, we said that the rocket was about to "go through a black hole", implying that the rocket noise will change.

At the end of the MRI-scan session, the researcher expressed that she was very proud of the child. At pre-test, we gave him/her a "first flight diploma", and at post-test, a "diploma of astronaut" with the picture of him/her dressed up in astronaut. We also delivered a gift card (usable in a shop of books, music and games for kids) at each MRI-scan session as a compensation for the travelling and the participation. As recommended by Theys et al. (2014), the same researcher (the first author in the present study) was involved in the three phases of the protocol (parents' meeting, pre-scanning preparation, communication with the child during the scanning).

Reference

Theys, C., Wouters, J., & Ghesquiere, 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), e94019.

Appendix B

Descriptive Statistics and Paired Samples t Tests on RAN Performance Scores by Group

	T1			T2			Test statistics		
Measure	*M*	*SD*	Range	*M*	*SD*	Range	*t*	*p*	*d*
DYS children (n = 18)									
RAN Objects (seconds)	24.54	5.43	17.1 – 35.8	21.40	4.79	16.1 – 36.2	3.88	.001*	0.86
RAN Colors (seconds)	50.56	10.29	34.5 – 71.3	44.59	8.99	29.3 – 66.2	3.61	.002*	0.83
RAN Colors [a]	-1.46	1.12	-3.9 – 0.42	-0.79	1.03	-3.4 – 1	-3.23	.005*	0.76
RAN SC	75.10	14.59	51.6 – 105	66.00	12.18	46.4 – 92.9	4.68	<.001*	1.06
TD children (n = 13)									
RAN Objects (seconds)	20.30	3.13	16.3 – 27.6	20.11	3.18	14.4 – 25.7	0.28	.79	0.07
RAN Colors (seconds)	39.92	6.42	31.8 – 53.1	41.73	9.70	31.9 – 66.8	-0.68	.51	0.23
RAN Colors [a]	-0.25	0.79	-1.9 – 0.95	-0.46	1.14	-3.4 – 0.58	0.75	.47	0.22
RAN CS	60.22	8.97	48.8 – 80.7	61.84	11.88	49.7 –92.5	-0.57	.58	0.18

Note. T1 = pre-test; T2 = post-test; CS = composite score corresponding to the total naming time of both matrices (objects and colors). [a] Those scores are standardized, based on age norms (M = 0, SD = 1); * p-values that survive Holm-Bonferroni correction for multiple comparisons.

Appendix C

Descriptive Statistics and Paired Samples t Tests on Reading Performances by Group

	T1			T2			Test statistics		
Measure	*M*	*SD*	Range	*M*	*SD*	Range	*t*	*p*	*d*
DYS children (*n* = 18)									
Regular word reading AC	15.22	2.51	9 – 19	15.67	2.70	12 – 20	-0.97	.35	0.23
Irregular word reading AC	8.83	4.66	2 – 18	10.22	4.91	2 – 19	-2.01	.06	0.47
Pseudoword reading AC	11.56	3.24	5 – 16	13.61	3.15	9 – 19	-2.91	.01	0.68
Regular word reading RT	44.72	16.16	23 – 77.6	39.54	15.43	22 – 72.8	2.24	.04	0.48
Irregular word reading RT	49.52	17.25	24 – 87.9	44.57	18.02	21.8 – 83.9	2.53	.02	0.53
Pseudoword reading RT	42.98	11.81	27 – 70.6	44.97	15.39	25.3 – 70.6	-0.403	.69	0.17
TD children (*n* = 13)									
Regular word reading AC	19.00	1.22	17 – 20	19.00	1.47	15 – 20	0.00	1.00	0.00
Irregular word reading AC	16.31	2.81	9 – 19	17.23	2.52	10 – 19	-2.80	.02	0.79
Pseudoword reading AC	17.00	1.68	14 – 20	16.31	2.39	11 – 20	1.09	.30	0.30
Regular word reading RT	25.87	8.98	13.5 – 44	19.90	6.34	11.6 – 33.6	4.64	.001*	1.19
Irregular word reading RT	28.46	13.70	12.9 – 60	20.37	5.60	12.9 – 32.7	3.10	.009*	0.81
Pseudoword reading RT	32.08	9.01	20.4 – 52	27.20	5.52	19 – 38	2.64	.02	0.72

Note. T1 = pre-test; T2 = post-test; AC = accuracy; RT = response time (speed); * p-values that survive Holm-Bonferroni correction for multiple comparisons.

Appendix D

Spearman Bivariate Correlations between RAN Changes and Reading Changes

	RAN CS (T2 – T1)			
	DYS (n = 18)		TD (n = 13)	
Measure (T2 – T1)	*r*	*p*	*r*	*p*
1. Regular word reading AC	.52	.03	-.41	.16
2. Irregular word reading AC	.32	.19	.12	.73
3. Pseudoword reading AC	-.17	.50	.39	.19
4. Regular word reading RT	.52	.03	.21	.48
5. Irregular word reading RT	-.11	.66	.18	.55
6. Pseudoword reading RT	.47	.05	.34	.26

Note. CS = composite score; AC = accuracy; RT = response time (speed). No correlations survive Holm-Bonferroni correction for multiple comparisons.

Appendix E

Descriptive Statistics and Paired Samples t Tests on Fractional Anisotropy Values by Group

	T1			T2			Test statistics		
Measure	*M*	*SD*	Range	*M*	*SD*	Range	*t*	*p*	*d*
DYS children (*n* = 18)									
Left hemisphere									
Long AF seg	0.430	0.026	0.377 – 0.465	0.428	0.023	0.385 – 0.458	0.50	.63	0.12
Ant AF seg	0.364	0.032	0.298 – 0.450	0.358	0.029	0.315 – 0.446	1.46	.16	0.38
Post AF seg	0.402	0.033	0.317 – 0.457	0.410	0.025	0.378 – 0.457	-1.66	.11	0.36
IFOF	0.376	0.032	0.322 – 0.450	0.370	0.026	0.329 – 0.444	0.85	.41	0.22
ILF	0.414	0.025	0.364 – 0.462	0.417	0.026	0.362 – 0.459	-0.76	.46	0.17
Right hemisphere									
Long AF seg	0.409	0.040	0.312 – 0.468	0.401	0.032	0.302 – 0.433	0.98	.34	0.23
Ant AF seg	0.342	0.038	0.270 – 0.429	0.329	0.031	0.269 – 0.377	2.17	.044	0.52
Post AF seg	0.332	0.037	0.256 – 0.399	0.325	0.028	0.285 – 0.371	1.07	.30	0.26
IFOF	0.374	0.015	0.351 – 0.400	0.372	0.016	0.353 – 0.410	0.68	.50	0.14
ILF	0.362	0.031	0.315 – 0.427	0.359	0.024	0.326 – 0.410	0.59	.56	0.15
TD children (*n* = 13)									
Left hemisphere									
Long AF seg	0.420	0.034	0.351 – 0.493	0.414	0.039	0.335 – 0.475	0.84	.42	0.23
Ant AF seg	0.356	0.041	0.259 – 0.414	0.356	0.040	0.268 – 0.415	-0.02	.99	0.00
Post AF seg	0.404	0.028	0.355 – 0.447	0.401	0.024	0.359 – 0.441	0.39	.71	0.12
IFOF	0.388	0.026	0.351 – 0.430	0.383	0.029	0.350 – 0.431	1.22	.25	0.38
ILF	0.417	0.017	0.384 – 0.438	0.411	0.018	0.364 – 0.433	0.80	.44	0.26
Right hemisphere									
Long AF seg	0.385	0.052	0.291 – 0.452	0.372	0.051	0.281 – 0.446	1.62	.13	0.45
Ant AF seg	0.322	0.039	0.268 – 0.386	0.321	0.037	0.267 – 0.395	0.41	.69	0.06
Post AF seg	0.321	0.024	0.279 – 0.363	0.325	0.025	0.268 – 0.355	-1.06	.31	0.31
IFOF	0.376	0.028	0.325 – 0.425	0.382	0.025	0.334 – 0.417	-3.66	.003*	0.99
ILF	0.353	0.017	0.326 – 0.384	0.360	0.014	0.338 – 0.387	-3.47	.005*	0.89

Note. T1 = pre-test; T2 = post-test; ant = anterior; post = posterior; seg = segment; AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; ICP = inferior cerebellar peduncle; SCP = superior cerebellar peduncle; * p-values that survive Holm-Bonferroni correction for multiple comparisons.

Appendix F

Spearman Bivariate Correlations between RAN Changes and Fractional Anisotropy Changes

	RAN CS (T2 – T1)			
	DYS (n = 18)		TD (n = 13)	
Measure (T2 – T1)	*r*	*p*	*r*	*p*
1. Left long AF seg	-.59	.009	.05	.05
2. Left ant AF seg	-.65	.003*	.17	.58
3. Left post AF seg	-.44	.07	.27	.37
4. Left IFOF	-.27	.28	.65	.02
5. Left ILF	-.39	.11	.53	.06
6. Right long AF seg	-.37	.14	.48	.09
7. Right ant AF seg	-.34	.16	.10	.73
8. Right post AF seg	-.48	.04	-.24	.44
9. Right IFOF	-.36	.14	.02	.94
10. Right ILF	-.32	.20	.17	.58

Note. CS = composite score; ant = anterior; post = posterior; seg = segment; AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; ILF = inferior longitudinal fasciculus; ICP = inferior cerebellar peduncle; SCP = superior cerebellar peduncle.

*p-value that survives Holm-Bonferroni correction for multiple comparisons.