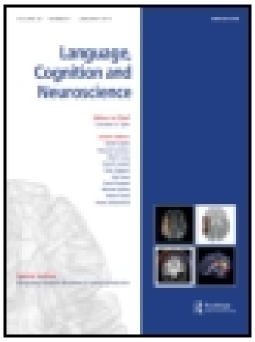

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Distinguishing cause from effect – many deficits associated with developmental dyslexia may be a consequence of reduced and suboptimal reading experience

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ABSTRACT
The cause of developmental dyslexia is still unknown despite decades of intense research. Many causal explanations have been proposed, based on the range of impairments displayed by affected individuals. Here we draw attention to the fact that many of these impairments are also shown by illiterate individuals who have not received any or very little reading instruction. We suggest that this fact may not be coincidental and that the performance differences of both illiterates and individuals with dyslexia compared to literate controls are, to a substantial extent, secondary consequences of either reduced or suboptimal reading experience or a combination of both. The search for the primary causes of reading impairments will make progress if the consequences of quantitative and qualitative differences in reading experience are better taken into account and not mistaken for the causes of reading disorders. We close by providing four recommendations for future research.

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Dyslexia; illiterates; literacy; phonological awareness; reading experience

1. Introduction

The specific reading disability known as developmental dyslexia is a burgeoning field of scientific inquiry. About 8500 studies in the Web of Science over the last two decades include the key word "dyslexia". Yet, despite frequent claims to the contrary, establishing a cause of developmental dyslexia remains as elusive as ever. This is evident from articles in high impact journals, which not infrequently arrive at contrary conclusions. To mention just a few, it has been argued that it is "widely agreed that developmental dyslexia is caused by a 'phonological core deficit'" (e.g. Goswami, 2003; and many others, see also Blomert, 2011; Olulade, Napoliello, & Eden, 2013; Saksida et al., 2016; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wimmer & Schurz, 2010, for recent discussions); that dyslexia is "a deficit in visuo-spatial attention, not in phonological processing" (Vidyasagar & Pammer, 2010); that "it is illogical to conclude that absence of evidence for some aspects of a magnocellular deficit in some dyslexics is evidence of its absence in all" (Stein, Talcott, & Walsh, 2000); that phonological and magnocellular deficit accounts both fail "to account for the full range of deficits established for dyslexic children … the full range of deficits might be accounted for in terms of a cerebellar deficit" (Nicolson, Fawcett, & Dean, 2001); and that "the cerebellum might stand unfairly accused, an innocent bystander in the processes responsible for disordered motor control in developmental dyslexia … the 'cerebellar' signs and symptoms associated with developmental dyslexia reflect a remote effect of neocortical perisylvian damage on cerebellar function" (Zeffiro & Eden, 2001). It has even been suggested that developmental dyslexia and specific language impairment are points on a continuum of learning disorders rather than distinct disabilities (Kamhi & Catts, 1986; cf. Tallal, Allard, Miller, & Curtiss, 1997; but see Bishop & Snowling, 2004; Norbury, 2014; Reilly, Bishop, & Tomblin, 2014).

In this opinion article, we conjecture that deficiencies in reading *experience* in individuals with dyslexia are a major reason for the disagreement among researchers about the causes of dyslexia and therefore the arguable lack of progress towards understanding the fundamental causes of the condition. First, we draw attention to the fact that most known deficits associated with these reading impairments also occur in "normal" illiterate or low literate adults who have received no reading instruction or very little. We argue that in a substantial number of individuals with dyslexia, many deficiencies are secondary consequences of a lack of (adequate) reading experience. There are of course many people with dyslexia who read as much or even more than people with no

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reading disorders. We suggest that in many of these cases the observed impairments are partly secondary consequences of *suboptimal* reading experience. In short, we suggest that many performance differences in individuals with dyslexia are effects of quantitatively and/or qualitatively different reading experience to an extent that has not been fully appreciated by the research community. In conclusion we argue that the search for the origins of reading impairments will make progress if the consequences of reading impairments are better taken into account and not mistaken for their causes. Finally, we provide four recommendations for future research.

2. A substantial number of dyslexia research findings are a proxy for a lack of (adequate) reading experience

Many experimental studies of the effect of literacy on cognitive processing have been carried out with illiterate and low literate participants across the world since the seminal study of deficits in phonemic awareness in illiterate adults by Morais and colleagues (Morais, Cary, Alegria, & Bertelson, 1979). Here, we review the most important research findings with regard to their relevance for dyslexia research. We will draw on evidence from studies with illiterate and low literate participants (see Dehaene, Cohen, Morais, & Kolinsky, 2015; Dehaene et al., 2010; Demoulin & Kolinsky, 2016; Huettig & Mishra, 2014), studies with pre-literate children, literate children, and adults as well as evidence from children and adults with dyslexia. We discuss experimental evidence from behavioural studies involving categorical perception, phonological awareness, verbal short-term memory, pseudoword repetition, rapid automatised naming (RAN), prediction in spoken language processing, and mirror invariance. We then turn to studies that have used structural and functional brain imaging techniques. We will illustrate how illiterate and low literate people produce the same or very similar experimental results as individuals with dyslexia in these tasks. We suggest that many performance similarities of illiterates and people with dyslexia are not a coincidence but likely reflect (at least in part) a common lack of adequate reading experience. Many conclusions from dyslexia research might therefore be misleading with respect to the underlying causes of dyslexia. Before we turn to the experimental evidence we will discuss what we mean by reduced reading experience.

2.1. What do we mean by a lack of (adequate) reading experience?

We consider reduced reading experience to be any reading experience that is below the average of a reader of the same age and educational background. Reading experience is thus operationalised as any experience with any reading materials including writing on social media and television programmes. Reading experience therefore also includes reading exposure in non-school settings such as home settings or exposure in pre-school nurseries. An important issue is that it is very difficult to quantify reading experience, especially reading exposure in non-school settings as well as exposure/training in the pre-cursors of reading (e.g. rhyme judgments and other phonological awareness tasks) in pre-school nurseries and home settings (but see Lefly & Pennington, 2000). We will return to this issue in the conclusion section of this article. Note that many individuals with dyslexia have (almost by definition) *qualitatively* different reading experience. As we draw attention to relevant research with illiterate individuals here in Section 2, we will primarily focus on quantitatively different reading experience before discussing qualitatively different experience in Sections 3 and 4. It is, however, important to keep in mind the strong interrelation between quantitative and qualitative reading experience.

2.2. Similarities in performance in behavioural studies

2.2.1. Categorical perception

In line with findings that individuals with dyslexia sometimes show less sharp category boundaries in the categorical perception task than individuals with no reading impairments, it has been suggested that a cause of dyslexia may be a low-level speech perception impairment (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Hurford & Sanders, 1990; Mody, Studdert-Kennedy, & Brady, 1997; Reed, 1989; Tallal, 1980). In the categorical perception task participants have to judge CV syllables from a continuum of speech sounds (e.g. /da/ … /ta/) and are asked to indicate which stimulus they heard. Typically, participants judge stimuli to be consistently either /da/ or /ta/ leading to a steep slope at the category boundary in identification curves (hence referred to as categorical perception). Serniclaes, Ventura, Morais, and Kolinsky (2005) conducted a study investigating categorical perception using this task in Portuguese illiterate participants. They found overall similar performances of illiterates and literates on /ba/-/da/ contrasts with this task but observed that illiterates (like participants with dyslexia) had a less sharp categorical boundary.

A difficult issue with research on categorical perception is that most of the studies (both with illiterates and individuals with dyslexia) have used synthetic speech. This has been criticised (Blomert & Mitterer,

2004) because there is evidence that performance on synthetic continua only weakly predicts comprehension of natural speech. Blomert and Mitterer (2004) demonstrated that when a stimulus continuum based on natural speech is used no perception deficits in participants with dyslexia are observed. Moreover, and perhaps more importantly, gating studies on speech perception have revealed that low-level speech perception is not (or only very slightly) impaired, both in individuals with dyslexia (Griffiths & Snowling, 2001; Metsala, 1997) and in illiterates (Ventura, Kolinsky, Fernandes, Querido, & Morais, 2007). Mendonça et al. (2003) assessed phonological sensitivity to different sub-lexical and lexical units in a syllable comparison task, where the sound difference between consonants was manipulated (i.e. voicing, place, and manner of articulation); and a minimal pair comparison task, where the consonants in stressed and unstressed syllables were manipulated. A comparison of results from 16 illiterates and 16 literates revealed small benefits of literacy for the discrimination of similar phonemes (consonant pairs differing in voicing), particularly when these phonemes appeared on unstressed syllables characterised by less prosodic prominence. Overall however, their results largely confirmed that low-level speech perception is hardly modulated by literacy. These findings, we suggest, are most compatible with the notion that extensive reading practice has little impact on fine discrimination of perceptual categories but may result in more fine grained phonological processing of spoken words (Smith, Monaghan, & Huettig, 2014; cf. Ziegler & Goswami, 2005), which we will discuss further in the next sections.

2.2.2. Phonological awareness

A dominant explanation of developmental dyslexia is that it reflects a phonological core deficit (e.g. Goswami, 2003; Stanovich, 1988). Indeed, one of the most consistent findings of research on *both* illiterates (with no known socio-cultural/economic, developmental, or acquired impairments; see Reis & Petersson, 2003; Reis, Guerreiro, & Petersson, 2003) and individuals with dyslexia is that they show poor awareness of the decompositional nature of speech units. Successful reading requires awareness that words can be decomposed into smaller segments because arbitrary characters must be mapped to corresponding units of spoken language. Without awareness that words (in alphabetic writing systems) can be decomposed, a reader cannot efficiently decode the orthography of her language. Phonemic awareness develops from larger to smaller units (Morais, Content, Cary, Mehler, & Segui, 1989). Children are typically-able to recognise and manipulate syllables before they can recognise and manipulate onsets and rhymes. Onset and rhyme awareness in turn develops before children detect and manipulate phonemes (see Anthony & Francis, 2005; Anthony, Lonigan, Driscoll, Phillips, & Burgess, 2003, for review). Early forms of phonological knowledge and segmental awareness (e.g. syllable, onset, and rhyme awareness) develop without teaching and before reading instruction. Such pre-literate development of phonological awareness is influenced by the properties of the particular language that is acquired (e.g. the salience of syllables and complexity of onsets; Caravolas & Bruck, 1993; Cossu, Shankweiler, Liberman, Katz, & Tola, 1988; Demont & Gombert, 1996; Durgunoğlu & Öney, 1999).

Morais and colleagues (Morais et al., 1979) asked illiterate Portuguese speakers to take part in a study to investigate whether phonemic awareness is acquired spontaneously during development or whether its occurrence requires some specific training. Thirty illiterates (aged 38–60 years) and 30 late literates (aged 26–60 years; individuals who had taken part in adult literacy programmes after the age of 15 years) were asked to add or delete one phoneme (e.g. "p") of an utterance (becoming another word or a nonword) produced by the experimenter (e.g. "alhaço" became "palhaço" or "purso" became "urso"). Note that in word trials the correct response could be found by searching memory for a similar sounding word and thus only nonword trials provide information about participants' segmentation abilities and phonological awareness. Mean correct responses on nonword trials were 19% for illiterates but 72% for late literates. Subsequent studies have replicated these results (e.g. Morais, Bertelson, Cary, & Alegria, 1986) but have shown that illiterates perform much better when tested on other meta-phonological abilities such as syllable detection (Morais et al., 1989) or rhyme awareness (Adrián, Alegria, & Morais, 1995; Morais et al., 1986). Read, Yun-Fei, Hong-Yin, and Bao-Qing (1986) demonstrated that it is not literacy per se (i.e. the ability to read and write) but alphabetic literacy (i.e. the knowledge of an alphabetic script), which causes differential performance on phonemic awareness tasks. Read and colleagues found that phonemic awareness of Chinese readers who had no alphabetic knowledge was similar to illiterates but phonemic awareness of Chinese readers who had alphabetic knowledge was similar to those of late literates.

Many studies have found that phonological awareness in pre-school children is an important predictor of early reading skills after schooling has started (e.g. Adams, 1990; Bryant, MacLean, & Bradley, 1990; Bryant, Bradley, Maclean, & Crossland, 1989; Byrne & Fielding-Barnsley, 1991; Cronin & Carver, 1998; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004; Stanovich, 1992; Tunmer, Herriman, & Nesdale, 1988; Vellutino & Scanlon, 2001; Wagner & Torgesen, 1987; and many others). Moreover, training pre-school children in phonological awareness before reading instruction has been found to facilitate subsequent reading acquisition (Lundberg, Frost, & Petersen, 1988; see also Ball & Blachman, 1991; Bradley, 1988; Bradley & Bryant, 1983; McGuinness, McGuinness, & Donohue, 1995). These studies show that phonological awareness is important for early reading acquisition in alphabetic writing systems. Indeed, training in phonological awareness tasks in the early school years also results in more rapid reading acquisition in children with no detectable signs of reading impairment.

Do these studies thus suggest that the phonological awareness deficits in individuals with dyslexia are a likely cause of developmental dyslexia? As for adult illiterates, there is evidence that many children need instruction for phonemic awareness (Ehri & Robbins, 1992; Masonheimer, Drum, & Ehri, 1984). Moreover, exposure to pre-school phonological awareness training (e.g. kindergarten or parental teaching) differs greatly and is often influenced by factors such as nursery access and the socioeconomic status (SES) of the children. Some children get a head start in phonological awareness training prior to school whereas others have a lot of catching up to do.

It is pertinent at this junction to further discuss the issue of SES. There is no doubt that dyslexia is a real phenomenon (see Stein, 2017, for further discussion) and has a partly biological origin. Twin studies estimate the heritability of the disorder to be between 0.50 and 0.60 (e.g. Grigorenko, 2001; see also Carrion-Castillo, Franke, & Fisher, 2013; Carrion-Castillo et al., 2017; Ramus, 2013). It has also been convincingly demonstrated that environmental factors, in particular SES, play a large role in reading skills (Bowey, 1995; Fluss et al., 2009). Indeed, SES has been found to systematically mediate the relationship between phonological awareness and reading ability (Noble, Farah, & McCandliss, 2006; Noble, Wolmetz, Ochs, Farah, & McCandliss, 2006). The study by Fluss et al. (2009) particularly demonstrates the influence of SES. They tested 1062 elementary school children from Paris and observed that children from areas with low neighbourhood SES were almost 10 times more likely to have a reading disorder than children from areas with high neighbourhood SES. Level of maternal education and father unemployment were the largest SES factors associated with poor phonological awareness and poor decoding skills. In short, differences in "reading-relevant" language experience emerge very early on and have a large influence on whether children develop dyslexia or not.

Finally, it is often overlooked that phonological awareness greatly supports vocabulary acquisition. There is much work that has demonstrated the reciprocal relationship between vocabulary acquisition and reading skills (e.g. Bishop & Adams, 1990; Butler, Marsh, Sheppard, & Sheppard, 1985; Catts, Fey, Zhang, & Tomblin, 1999; Chaney, 1998; Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003; Lonigan, Burgess, & Anthony, 2000; Scarborough, 1989; Shankweiler et al., 1999; Share, Jorm, Maclean, & Matthews, 1984; Stahl & Fairbanks, 1986; Tunmer et al., 1988; Vellutino & Scanlon, 2001; and many others). For example, children with good phonological awareness can draw on these abilities to decode words more rapidly and thus get a head start in figuring out the meaning of new words (cf. Beck, Perfetti, & McKeown, 1982) which in turn further increases their phonological awareness.

We do not deny the possibility that severe deficiencies in the acquisition of phonemic awareness may be causally related to the reading impairments in some individuals with dyslexia. We do however note that this has not been convincingly demonstrated to date. Indeed, deficiencies in phonological awareness are entirely consistent with the assumption that dyslexia is linked to suboptimal reading experience (which we will discuss later on in this article). Moreover, it is also feasible that deficiencies in the acquisition of phonemic awareness reflect comorbidity with the actual underlying cause of dyslexia (cf. Williams & Lind, 2013). In any case, there is no doubt that it is experience with alphabetic writing systems that radically improves phonological awareness.

It is important to note that it depends on the properties of the orthography acquired as to how quickly reading instruction improves phonological awareness (Ziegler et al., 2010). A useful way to describe the orthographic code of a particular language is in terms of transparency and granularity (Wydell & Butterworth, 1999; Ziegler & Goswami, 2005). Children learning to read a transparent (i.e. consistent print-to-sound mapping) orthography (e.g. Italian) learn to recode letter strings with 90% accuracy within a few months (Goswami, Porpodas, & Wheelwright, 1997; Seymour, Aro, & Erskine, 2003). Children learning to read a non-transparent orthography (e.g. English) acquire the same level of accuracy only after 3–4 years of reading instruction (Goswami et al., 1997). Moreover, there are suggestions that incidences of dyslexia in opaque languages (e.g. English) are considerably higher than in languages with more transparent print-to-sound mapping (e.g. Italian or Spanish; Castles & Coltheart, 1993; Jiménez & Ramírez, 2002) though there have been few systematic assessments of reported incidences of dyslexia across languages. What is clear is that the profile of individuals with dyslexia in transparent orthographies can be different. Dyslexia in opaque languages manifests itself in reading accuracy measures whereas in transparent languages is often only revealed by reading speed measures. This means that it is much easier to predict and assess dyslexia in opaque than in transparent languages (Moll et al., 2014). Relatedly, dyslexia appears to occur much less in orthographies with a coarse-grained granularity (e.g. Mandarin; Ho, Chan, Chung, Lee, & Tsang, 2007). It is therefore likely that lack of sufficient experience with consistent print-to-sound mapping is a main determinant of the phonological awareness deficits in people with dyslexia, and this is of course obviously the case for illiterates. This conclusion is also suggested by a study that showed that the phonological awareness deficits of children with dyslexia tend to disappear if they learn a consistent orthography (Dutch) but not if they learn an inconsistent orthography such as English (De Jong & van der Leij, 2003).

In summary, as adult illiterates learn to read a transparent and fine-grained orthography, their phonological awareness skills progressively reach close to normal levels. Similarly, as children get exposed to written language, their phonological awareness increases rapidly. Many children with dyslexia who learn a consistent orthography eventually develop normal levels of phonological awareness. There is little doubt that people struggling to acquire a new skill typically, and quickly, receive comparatively less experience in applying the skill. Thus, it is likely that children who struggle with reading acquisition quickly get a lot less adequate reading experience than children who excel. We therefore conjecture that phonological awareness deficits are largely a consequence of a lack of adequate experience with consistent print-to-sound mapping, and not a cause of dyslexia.

There is much experimental evidence that is consistent with the notion that developmental dyslexia involves a phonological core deficit (e.g. Goswami, 2003; Ramus, 2014; Stanovich, 1988). It is important to stress here that we do not argue that lack of reading experience explains all of the phonological deficits observed in people with dyslexia nor do we aim to provide a comprehensive discussion of phonological theories of dyslexia here (see Ahissar, 2007; Ramus, Marshall, Rosen, & van der Lely, 2013; Shaywitz & Shaywitz, 2008 for further discussion). What we do stress is that experimental studies need to tightly control the reading experience of participants. Studies with illiterate and ex-illiterate control groups offer one particularly useful way to achieve this. A recent study by Fernandes, Vale, Martins, Morais, and Kolinsky (2014) illustrates this point nicely. Using a paradigm introduced by Van Leeuwen and Lachmann (2004) they examined the influence of surrounding contours on letter and pseudo-letter processing by children with dyslexia and adult illiterates and ex-illiterates. All groups showed a congruency effect for pseudo-letters, namely better performance for targets surrounded by congruent shapes than for targets surrounded by incongruent shapes but only the children with dyslexia (but not the adult illiterates and ex-illiterates) showed a congruency effect for letters. Interestingly, the letter (but not the pseudo-letter) congruency effect of the children with dyslexia correlated strongly with measures assessing their phonological recoding abilities, consistent with the hypothesis that developmental dyslexia involves a phonological deficit.

2.2.3. Verbal short-term memory

Several studies have reported deficits of participants with dyslexia in verbal memory tasks including story recall (Felton, Wood, Brown, Campbell, & Harter, 1987; O'Neill & Douglas, 1991), list learning (Douglas & Benezra, 1990; Felton et al., 1987; Kinsbourne, Rufo, Gamzu, Palmer, & Berliner, 1991; McGee, Williams, Moffitt, & Anderson, 1989; Michaels, Lazar, & Risucci, 1997; Rudel & Helfgott, 1984), and paired associate learning (Helfgott, Rudel, & Kairam, 1986; Vellutino, Steger, Harding, & Phillips, 1975), suggesting that verbal memory deficits might be causally related to dyslexia. Note, however, that participants with dyslexia show comparable performance to controls on spatial/visual memory tasks (Fletcher, 1985; Liberman, Mann, Shankweiler, & Werfelman, 1982; Nelson & Warrington, 1980): the short-term memory deficit appears largely specific to verbal short-term memory.

Similar to people with dyslexia, memory deficits in illiterates appear to be related to verbal short-term memory rather than visual/spatial memory. A number of studies observed a difference on digit span tasks between illiterate and literate participants (Ardila, Rosselli, & Rosas, 1989; Reis, Guerreiro, Garcia, & Castro-Caldas, 1995; Reis et al., 2003). In digit span tasks participants are required to verbally repeat a list of digits forwards (or sometimes backwards). Reis et al. (2003) observed that number of years of formal education improved performance (mean digit span for illiterates was 4.1, for low literates with 4 years of education it was 5.2, and for high literates with 9 years of education: 7.0). Improvement contingent upon formal schooling thus appears to be graded, which suggests that performance on digit span tasks (and probably short-term memory tests in general) is at least partly a function of schooling/literacy. Petersson, Ingvar, and Reis (2009) found no significant difference between illiterates and low-level literates on the Wechsler spatial span task but replicated the significant difference on the Wechsler digit span (see also Silva, Faísca, Ingvar, Petersson, & Reis, 2012). These results are most compatible with the notion that verbal memory deficits both in illiterates and individuals with dyslexia are at least partly a secondary consequence of reading practice leading to the development of more fine-grained phonological representations (cf. Demoulin & Kolinsky, 2016; Smith et al., 2014; Ziegler & Goswami, 2005). Moreover, it is also conceivable that reading practice trains our short-term memory for verbal material (a notion that has been little explored experimentally so far).

2.2.4. Pseudoword repetition

A task that partly involves verbal short-term memory is pseudoword repetition. Many studies have reported that individuals with dyslexia perform more poorly on pseudoword repetition than control participants (e.g. Brady, Poggie, & Rapala, 1989; Brady, Shankweiler, & Mann, 1983; Hulme & Snowling, 1992; Kamhi & Catts, 1986; Snowling, 1981; Snowling, Goulandris, Bowlby, & Howell, 1986; Van Bon & Van Der Pijl, 1997; Van Daal & van der Leij, 1999), compatible with the notion that a phonological core deficit provides a causal explanation for dyslexia. But note that Reis and Castro-Caldas (1997) found that illiterates also performed much worse than literates on pseudoword repetition (replicated in Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998). Petersson and colleagues have argued that this is related to an inability to handle certain aspects of sub-lexical-phonological structure (Petersson, Reis, Askelöf, Castro-Caldas, & Ingvar, 2000) and suggest that phonological representations, or the processing of these representations, are differently developed in literates and illiterates (Petersson et al., 2000, 2001; cf. Smith et al., 2014). Consistent with this interpretation, Boada and Pennington (2006) provided evidence that reading-impaired children have less fine-grained phonological representation, linked to poorer performance in pseudoword repetition tasks (see Rispens & Baker, 2012, for further discussion).

Again, it is noteworthy that there are some reports that the accuracy of pseudoword repetition in pre-literate children predicts subsequent literacy levels (e.g. Gathercole & Baddeley, 1993). But as for the studies of phonological awareness as a predictor of later reading abilities, although these show that phonological processing abilities are important for reading acquisition, they do not show that pre-literate differences in pseudoword repetition are caused by an underlying phonological deficit. We conjecture that an important mediator of performance is the same for illiterates and people with dyslexia; namely, a lack of adequate experience, resulting in less fine-grained, multiplexed phonological representations.

2.2.5. Rapid automatised naming

A great number of studies show slowed RAN in participants with dyslexia (see Araújo, Reis, Petersson, & Faísca, 2015, for a recent meta-analysis). RAN refers to the time required for an individual to quickly and accurately name an array of well-known visual stimuli (e.g. letters, digits, objects, or colours). So far no RAN study has been carried out with illiterate participants. But yet again, RAN performance correlates positively with reading skills in readers with no history of reading impairments (Araújo et al., 2015). Araújo et al. (2015) also showed that there is an independent association between RAN and reading competence in individuals with dyslexia when the effect of phonological skills is controlled.

The RAN deficits in participants with dyslexia are interesting because it has been argued that picture naming involves many perceptual and cognitive “stages” including visual object recognition, conceptual preparation, lexical selection, morpho-phonological code retrieval, phonological encoding, syllabification, phonetic encoding, and articulation (Indefrey & Levelt, 2004; Levelt et al., 1991). Araujo, Huettig, and Meyer (2016) recently tested skilled adult readers and readers with dyslexia on a serial object-naming RAN task, independently manipulating word frequency and phonological neighbourhood density. Eye-movement measures revealed that both lexical frequency and neighbourhood density effects occur at early stages of lexical-phonological encoding *and* final stages of word production in both groups. Importantly, the effect of reading competence was always in the direction of less efficient processing for reading impaired than control readers, thus suggesting that the deficit spans all stages of naming. This finding is consistent with the notion that many aspects of RAN deficits in individuals with dyslexia are a consequence of reduced reading experience rather than a deficit at one specific stage of the naming process (though this account remains to be tested in illiterate individuals).

2.2.6. Anticipatory eye movements

Huettig and Brouwer (2015) used an eye-tracking method and observed that adults with dyslexia anticipate visually presented target objects that are about to be mentioned in a concurrent spoken sentence later than control participants. In addition, participants’ word reading scores correlated positively with their anticipatory eye movements, providing a possible link between reading experience and anticipatory spoken language processing.

Similar findings have also been observed with illiterates. Mishra, Singh, Pandey, and Huettig (2012) presented low and high literates in India with simple every-day spoken sentences which included a target word (e.g. "door"). As participants listened to the sentences they were asked to look at a visual display of four objects (a target, i.e. the door, and three visual distractor objects). The spoken sentences were created to encourage predictive eye gaze to the visual target objects. The high literacy group started to shift their eye gaze to the target object well before the onset of the spoken target word. The low literates on the other hand did not anticipate the targets and looked at the targets only once they heard the target mentioned in the spoken sentence more than a second later. This suggests that reading experience modulates predictive spoken language processing. Note that there was no hint of a delay in *non-anticipatory* language-mediated eye movements in the dyslexic group in Huettig and Brouwer (2015) and only small delays in the low literate group in Mishra et al. (2012). This strongly suggests that the general word-object mapping in adults with dyslexia and low literates is similarly fast and efficient as that of literate adults with no reading disorders. It means that the prediction differences are unlikely to be mere deficits in visual scene processing (as reading is a highly trained visual skill and correlates with the skill of interpreting 2D visual representations such as line drawings, cf. Bramão et al., 2007; Reis, Faísca, Ingvar, & Petersson, 2006; Reis, Petersson, Castro-Caldas, & Ingvar, 2001). Mani and Huettig (2014) provided converging evidence for the role of literacy in listeners' anticipation of upcoming spoken language. They tested 8-year-old German children at the beginning of literacy acquisition and found a robust positive correlation between children's word reading and their prediction skills in a similar eye-tracking task. Furthermore, James and Watson (2013) found that reading experience as measured by performance in the Comparative Reading Habits questionnaire (Acheson, Wells, & MacDonald, 2008) and the American Adult Reading Test (Blair & Spreen, 1989) is linked to predictive spoken language processing even among American college students. To sum up, illiterates and people with dyslexia show similar language prediction deficits, with evidence consistent with the notion that this at least partly reflects their common reduced reading exposure rather than a causal impairment due to a reading disorder.

2.2.7. Mirror invariance

The similarities in performance between illiterates/low literates and individuals with dyslexia are not only apparent in tasks involving spoken language but are also evident in tasks involving visual processing (e.g. Lachmann, Khera, Srinivasan, & van Leeuwen, 2012; Lachmann & van Leeuwen, 2008). Note that the visual routines supporting object recognition that humans have acquired during evolution can actually impede reading acquisition. Mirror invariance (Pegado, Nakamura, & Hannagan, 2014) or symmetry generalisation (Lachmann, 2002), for instance, is the ability to quickly identify visual stimuli irrespective of their (e.g. left-right) orientation. This ability is well investigated in monkeys (Logothetis, Pauls, & Poggio, 1995; Noble, 1966; Rollenhagen & Olson, 2000), and humans (Biederman & Cooper, 1991; Bornstein, Gross, & Wolf, 1978; Stankiewicz, Hummel, & Cooper, 1998). In order to learn to read, however, mirror invariance must be suppressed, in particular in the alphabetic phase (cf. Frith, 1986) of reading acquisition. In this phase the letters of a word, i.e. the graphemes, are decoded into the corresponding sound one by one, and the sounds are merged together into syllables and words. Fine details of each individual grapheme, its orientation (e.g. *b* and *d*) and the order of graphemes in the configuration are crucial. Alphabetic reading remains, however, a strategy of skilled reading (Coltheart, 1978). Pegado et al. (2014) demonstrated that literates, but not illiterates, displayed substantial "mirror costs" when judging whether mirror pairs (e.g. iblo oldi) were the "same" or not. Literacy also resulted in mirror costs for false fonts and pictures. Importantly, Pegado et al. (2014) found that the effect is related to reading experience: participants who had learned to read late in life also showed mirror costs (see also Pegado, Nakamura, Cohen, & Dehaene, 2011).

Here again, similar results can be observed in individuals with dyslexia. Lachmann and Van Leeuwen (2007) showed that mirror discrimination abilities develop more slowly in children with dyslexia and that they perform better than individuals with no reading impairments on mirror invariance (and related) tasks. Converging evidence comes also from beginning readers. Cornell (1985), for instance, found that beginning readers find it difficult to discriminate mirror pairs (e.g. *b* and *d*). Cornell (1985) estimates that it takes about two years of reading experience for "mirror confusion" to disappear. In short, mirror confusion in individuals with dyslexia is not necessarily a cause of their reading impairments but it is conceivable that it is linked to a lack of adequate reading experience.

2.3. Similarities in brain structures and fMRI responses

Structural (Vandermosten et al., 2012, for review) and functional (Vandermosten, Hoeft, & Norton, 2016, for review) imaging studies have revealed abnormalities in people diagnosed with developmental dyslexia (for a comprehensive discussion of brain networks involved in normal reading see Dehaene & Cohen, 2011; Nakamura et al., 2012; Price, 2012; Pugh et al., 1996; Rueckl et al., 2015). There are once again some noteworthy similarities between illiterates/low literates and individuals with dyslexia, which we will now discuss.

2.3.1. Structural imaging

Several studies have reported differences in the structure of the corpus callosum (i.e. white matter tracts connecting the two hemispheres of the brain) between illiterates and literates. Castro-Caldas et al. (1999) showed that the posterior mid-body region of the corpus callosum is significantly thinner in Portuguese illiterates than literates. This finding was replicated by Petersson, Silva, Castro-Caldas, Ingvar, and Reis (2007) who used voxel-based morphometry on structural MRI data and observed greater white matter density in the posterior third of the mid-body region of the corpus callosum in literates (4 years of school attendance between 6 and 10 years of age) than in illiterates. It is interesting to note that a rostral to caudal myelination process of the corpus callosum during childhood and early adulthood has been characterised (Thompson et al., 2000). In particular, the white matter fibres that cross over in the posterior mid-body region of corpus callosum interconnect the parieto-temporal regions and undergo extensive myelination during the typical period of reading acquisition (i.e. 6–10 years of age). This suggests that acquiring reading and writing skills at the appropriate age shapes not only the morphology of the corpus callosum and the corresponding interhemispheric connectivity but also the pattern of interaction between the interconnected inferior parietal regions. Carreiras et al. (2009) compared illiterates with individuals who acquired reading late in life and also observed a greater amount of white matter in the splenium of the corpus callosum. These results strongly suggest that reading experience strengthens white matter pathways in the corpus callosum.

Very similar structural differences in the corpus callosum have been reported in developmental dyslexia. Dougherty et al. (2007), Robichon and Habib (1998), and Rumsey et al. (1996) all reported reduced white matter in the corpus callosum. Carreiras et al. (2009) concluded in their paper that white matter differences in the corpus callosum are likely to be a consequence of differences in reading experience rather than the cause of reading difficulties. We agree.

2.3.2. Functional neuroimaging

A number of cross-sectional MRI studies with adults and children have suggested that functional deficits and structural disruptions of the thalamus are a cause of developmental dyslexia (Diaz, Hintz, Kiebel, & von Kriegstein, 2012; Jednoróg et al., 2015; Livingstone, Rosen, Drislane, & Galaburda, 1991; Preston et al., 2010). Skeide et al. (2017) recently combined a controlled longitudinal reading intervention with resting-state fMRI in a sample of 30 illiterate Indian adults. Evidence for plasticity was found in the intrinsic functional connectivity of the right superior colliculus and the bilateral pulvinar nuclei of the thalamus. Moreover, the coupling between these regions and the right occipital cortex increased and the individual levels of coupling were correlated with individual gains in decoding skill. These results suggest a reading-related, functional reconfiguration upstream to the visual cortex. Thus, faulty subcortical activity reported in developmental dyslexia might be consequential and not causal.

Finally, it has long been observed that written language processing is consistently left-lateralised in most readers. Petersson et al. (2007) used PET with illiterates and low literates. Their analysis revealed a positive functional left-right difference in the literate participants. The illiterate participants in contrast showed a negative left-right difference in the inferior parietal region. Petersson et al. (2007) concluded that literates are relatively left-lateralised and that literacy influences the functional balance between the left and right inferior parietal regions. This is consistent with functional connectivity findings related to the inferior parietal region and differences between controls and participants with dyslexia (Horwitz, Rumsey, & Donohue, 1998). In addition, many studies have found that increased bilateral processing is associated with reading disorders such as developmental dyslexia (e.g. Shaywitz et al., 2007). Eisner et al. (2016) investigated the effects of literacy cross-sectionally across groups in India before training ($N = 91$) as well as longitudinally (a group of 29 illiterates was trained in reading and writing for 6 months). Reading ability was correlated with left-lateralised processing of written materials (but not other visual categories) in various regions along the dorsal and ventral streams. Importantly, training-related changes in the lateralisation of responses to written stimuli (e.g. posterior fusiform gyrus) in their study suggest a causal relationship between the degree of hemispheric asymmetry and reading ability. These results also suggest that bilateral processing of written materials is related to the relative lack of reading experience and not necessarily diagnostic of a reading disorder such as dyslexia.

3. Potential counter-arguments

There are a number of counter-arguments one may raise against the view that the performance differences between individuals with dyslexia and literate controls are, to a non-negligible extent, direct consequences of reduced reading experience. In this section we consider three counter-arguments.

3.1. Some people with dyslexia read as much or even more than some people with no reading impairments

We have argued so far that children who struggle with reading acquisition quickly get a lot less reading experience than children who excel at reading. This can be compared to a snowball effect, that is, a situation where something relatively small and insignificant grows exponentially at a rapid pace. Reading experience accumulates not only in the size of reading-related knowledge but also in the speed of reading acquisition. We have argued that this fact has been underappreciated by the research community. Clearly however, this does not hold for all individuals with dyslexia. Parents and educational institutions often spot reading difficulties early and provide opportunities for additional reading training. We do acknowledge that there are many reading-impaired people with approximately equal or sometimes even more reading experience than individuals with no reading impairments. However, another factor we believe has been underappreciated is that often, (perhaps small) impairments in people with dyslexia lead to substantial suboptimal reading experience.

3.2. So-called "compensated dyslexics"

A similar argument concerns the fact that many individuals with dyslexia are able to enter as well as successfully complete higher education programmes (e.g. university courses). University students with dyslexia, often referred to as "compensated dyslexics", presumably have enough reading experience to be able to succeed at the highest educational level. Although reading-impaired individuals often receive special support in educational settings (e.g. an increased time to answer exam questions) there is no doubt that many of these people who have gone through higher education, for instance, have read much more than many non-reading-impaired individuals who have not entered higher education programmes. Nevertheless, we believe that the characterisation of their reading experience as suboptimal (and examining the consequences of suboptimal experience) is important.

3.3. Reading level control groups

A final counter-argument concerns the fact that many studies involving participants with dyslexia attempt to account for differences in reading experience by testing reading-matched samples. For example, if affected individuals in Grade 5 are matched to children with the same reading level, for example in Grade 3, but still show differences in phonological tasks or tests probing other functions, one may argue that it cannot be concluded that reading experience is an important factor. Note that reading level control groups are argued to be inappropriate (as they fail to account for many confounding variables such as age, see Van den Broeck & Geudens, 2012, for detailed discussion of this argument). However one may still want to question how we can suggest that it is reading experience that plays a crucial role if participants have equivalent reading skills but show differences on tasks assumed to tap certain reading-relevant core skills. Again, we believe that the answer to these questions is that many of these reading-experienced, compensated, and reading level-matched individuals with dyslexia have had substantial suboptimal reading experience and that suboptimal reading procedures/strategies often become automatised in affected individuals.

4. A substantial number of dyslexia research findings are a proxy for *suboptimal* reading experience

4.1. What do we mean by suboptimal reading experience?

It is important at this stage to point out that reading acquisition is a form of procedural learning (Lachmann & van Leeuwen, 2014; Nicolson, Fawcett, Brookes, & Needle, 2010). There are many human activities that become automatised by learning. When we cycle or drive a car, most of the time we are not aware of the sequence of movements we are initiating: a chain of motor commands has become automatised. Reading and writing are particularly pertinent examples of an overlearned behaviour arrived at through extensive practice (cf. Logan, 1988). Many of us have had the experience of the mind wandering and thinking about something else when reading a novel, yet we may continue to read for several pages before noticing that we are no longer taking in any meaningful information from the book. Writing is typically preceded by a conscious decision to write but people are usually not aware of their detailed finger movements. Reading and writing require the recruitment of pre-existing visual and auditory processing skills, which have to be fine-tuned for the new purpose. For instance, the newly acquired procedures have to be optimised for word reading and reading longer texts, and coordinated to allow for efficient grapheme-phoneme mapping (to read alphabetic scripts) and phoneme-grapheme mapping (to write alphabetic scripts). Finally, these new coordination skills become automatised (Lachmann & van Leeuwen, 2014).

Note however that automatisation is far from instantaneous and typically requires years of practice (e.g. Lachmann & van Leeuwen, 2008). As discussed above, a consistent print-to-sound mapping is very helpful in this regard and is the reason why Italian children, for instance, learn to recode letter strings with 90% accuracy within a few months (Goswami et al., 1997; Seymour et al., 2003) in contrast to children learning to read English, who acquire the same level of accuracy only after 3–4 years of reading instruction (Goswami et al., 1997). There are many other factors that impede the acquisition of reading routines and make overlearning challenging. One possibility is that relatively minor deficiencies in low-level auditory (cf. Ahissar, Protopapas, Reid, & Merzenich, 2000; Christmann, Lachmann, & Steinbrink, 2015; Hämäläinen, Salminen, & Leppänen, 2013; Richardson, Thomson, Scott, & Goswami, 2004; Talcott & Witton, 2002) and low-level visual (cf. Becker, Elliott, & Lachmann, 2005; Slaghuis & Ryan, 1999; Stein, 2002; Stein & Talcott, 1999) abilities result in suboptimal reading routines. Note that we do not claim here that these deficiencies are the one and only cause of dyslexia. We merely point out that it is conceivable that such low-level auditory and visual deficiencies have by themselves very little behaviourally observable effects but nevertheless can result in the abnormal coordination of reading routines and inefficient procedural learning, thereby exerting large effects on reading acquisition. Another example is that failures or inefficiencies in the procedural learning required to process symmetry (Pegado et al., 2011; Perea, Moret-Tatay, & Panadero, 2011) may lead to inefficient coordination of reading routines and result in suboptimal reading experience. We do not argue here that inefficiencies in procedural learning are the major cause of dyslexia. We believe however that relative minor impairments can greatly exacerbate the reading disorder if they result in suboptimal reading experience.

4.2. Consequences of suboptimal reading strategies and their automatisation

As with reduced reading experience, we believe that suboptimal reading experience also has far-reaching and real consequences for cognitive performance in people with reading impairments (cf. Kosmidis, 2017). To illustrate the point we give a few examples here, though the list should not be considered exhaustive. Inefficient reading strategies may slow down the phonological restructuring associated with learning alphabetic orthographic scripts and thus have secondary (albeit small) effects on performance in low-level speech perception tasks such as categorical perception (see Section 2.2.1). Deficient reading strategies slow down the emergence of fully proficient phonemic awareness when learning alphabetic writing systems (see Section 2.2.2). Suboptimal reading routines and processing strategies slow down the development of more fine-grained phonological representations resulting in poorer performance in verbal memory tasks (Section 2.2.3) and pseudoword repetition (Section 2.2.4). Like reduced reading experience, inefficient reading strategies impede the development of proficient general language skills. This becomes apparent in poorer performance at all stages of RAN (Section 2.2.5) and less anticipation of upcoming language input (Section 2.2.6). Suboptimal reading routines such as a failure to efficiently and automatically suppress symmetry may lead to distracting active and conscious symmetry suppression. This has the result that mirror discrimination abilities develop more slowly in children with dyslexia (Section 2.2.7). Finally, it is easily conceivable that engrained deficient reading procedures could result in differences in fMRI bold responses as well as structural brain differences (Section 2.3).

5. Conclusion

In the present opinion paper we have considered experimental evidence concerning categorical perception, phonological awareness, verbal short-term memory, pseudoword repetition, RAN, prediction in spoken language processing, and mirror invariance, as well as results from structural and functional brain imaging. The impairments/differences observed in individuals with dyslexia are, to a striking degree, also shown by illiterate individuals who have received no reading instruction or very little. This is, we propose, no coincidence. Similarities in performance of course do not necessarily imply similar underlying causes. However, we conjecture that the dyslexia research community should take seriously the possibility that a common factor could be a lack of reading experience. We suggest that some (though of course not all) individuals with dyslexia read much less than people with no reading impairments. And indeed it is hardly surprising that individuals engage much less in an activity that they find difficult and frustrating.

We have pointed out throughout this article that there are many reading-impaired people with approximately equal or even more reading experience than individuals with no reading impairments. We have made the case that not all reading experience is the same. Indeed, people with dyslexia have by definition altered reading experience. We conjecture that the reading experience of many such individuals can be described as suboptimal reading experience, involving the acquisition and practice of reading routines and processing strategies that result in an abnormal functional coordination of reading. What is underappreciated by the research community, we believe, is the extent to which people struggling to acquire reading skills quickly fall behind, right from the beginning of reading acquisition, and typically never catch up. Reading difficulties have a snowball effect: small difficulties become larger and larger until the consequences of suboptimal reading experience become huge and in a certain sense causing the affected individual's brain to remain low literate.

All the findings reviewed above suggest at the very least that the proposed causes of developmental dyslexia are open to reinterpretation as consequences of quantitative and qualitative differences in reading experience. It is important to point out here that we do not deny that reading impairments such as developmental dyslexia have an underlying cause (or even several independent causes) but we believe it is telling that an impartial reading of the research literature to date suggests that a cause has not yet been identified. Some may criticise us for not providing an opinion on the underlying cause of dyslexia in this paper. If a substantial number of the performance differences between reading impaired and non-reading impaired individuals are a consequence of reduced and/or suboptimal reading experience, then what is the cause of developmental dyslexia? One may point out that even if we are right there must still be a cause for dyslexia. By not suggesting a cause are we not ducking the crucial question? This has been intentional. Our aim has been to draw attention to the fact that many of the impairments observed in people with developmental dyslexia are also shown by illiterate individuals who have received no reading instruction, or very little. Our intention has been to illustrate that it is conceivable that a very large proportion of dyslexia research findings may simply reflect reduced and suboptimal reading experience. It is up to the dyslexia research community to convincingly demonstrate that particular research findings are not only (or even partly) a secondary consequence of reduced and suboptimal reading experience. We do not want to dilute this message by simultaneously providing an alternative suggestion for a cause of dyslexia.

How can this be achieved? First and most importantly, to make progress we need more experimental studies that quantify how much children and adults with dyslexia actually read. Second, studies must assess more rigorously the quality and type of reading experience that participants get. Accurate assessments of home literacy environments will be crucial (cf. Boerma, Mol, & Jolles, 2017; Katzir, Lesaux, & Kim, 2009; Mol & Bus, 2011; Stanowich & West, 1989). Third, cross-sectional studies will continue to be useful but we need to recognise and take more seriously their limitations. Cross-sectional comparisons, we suggest, should be treated as exploratory and considered at best indicative with regard to causal explanations. Our review suggests that the validity of cross-sectional studies of dyslexia is increased if an illiterate (illiterate adults) or pre-literate (children) control group rather than a "normal" control group of highly literate individuals is included in the study. Fourth, the gold standard will have to be tightly controlled large-scale longitudinal studies. It is indispensable that hypotheses from cross-sectional studies are validated by longitudinal studies. Some such investigations have already been carried out (Bradley, Corwyn, Burchinal, McAdoo, & Garcia Coll, 2001; Bus, Van IJzendoorn, & Pellegrini, 1995; Linkersdörfer et al., 2015; Lyytinen, Erskine, Hämäläinen, Torppa, & Ronimus, 2015; Maurer et al., 2011; Wimmer, Mayringer, & Landerl, 2000) or are currently being conducted. It is important that future longitudinal studies are large-scale enough to include enough individuals who will develop dyslexia (i.e. enough prereaders with and without familial and/or genetic risk of dyslexia, cf. Hakvoort, van der Leij, Maurits, Maassen, & van Zuijen, 2015; Saygin et al., 2013; Vandermosten et al., 2016; Willems, Jansma, Blomert, & Vaessen, 2016), and that reading experience is monitored meticulously throughout any study. Conducting such a study is no mean feat and will require a large, multiple lab effort. But clearly, if we want to determine the cause(s) of developmental dyslexia with a sufficient degree of confidence there is no other way.

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