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The Cognitive Deficits Responsible for Developmental Dyslexia: Review of Evidence for a Selective Visual Attentional Disorder

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There is strong converging evidence suggesting that developmental dyslexia stems from a phonological processing deficit. However, this hypothesis has been challenged by the widely admitted heterogeneity of the dyslexic population, and by several reports of dyslexic individuals with no apparent phonological deficit. In this paper, we discuss the hypothesis that a phonological deficit may not be the only core deficit in developmental dyslexia and critically examine several alternative proposals. To establish that a given cognitive deficit is causally related to dyslexia, at least two conditions need to be fulfilled. First, the hypothesized deficit needs to be associated with developmental dyslexia independently of additional phonological deficits. Second, the hypothesized deficit must predict reading ability, on both empirical and theoretical grounds. While most current hypotheses fail to fulfil these criteria, we argue that the visual attentional deficit hypothesis does. Recent studies providing evidence for the independence of phonological and visual attentional deficits in developmental dyslexia are reviewed together with empirical data showing that phonological and visual attentional processing skills contribute independently to reading performance. A theoretical model of reading is outlined in support of a causal link between a visual attentional disorder and a

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failure in reading acquisition.

INTRODUCTION

In the past four decades, many studies have attempted to identify the nature of the cognitive disorders associated with and potentially responsible for developmental dyslexia. The proposal of a phonological deficit as the cognitive basis of developmental dyslexia is now widely accepted. However, the view that a phonological deficit is the only core disorder in developmental dyslexia seems difficult to reconcile with a variety of evidence which highlights the heterogeneity of the dyslexic population. In particular, dyslexic children with opposite reading profiles have been reported. Children with surface dyslexia fail to read exception words despite normal pseudo-word reading; phonological dyslexic children show the reverse pattern—good exception word reading but poor pseudo-word reading. In addition, there have been several reports of dyslexic children who demonstrated no associated phonological deficit. Researchers who support the view that a phonological deficit is the sole core deficit in developmental dyslexia have argued that heterogeneity in the surface manifestations of dyslexia may be explained by varying degrees of severity of the phonological processing deficit, or that some reading disorders may be seen as general reading delays rather than developmental dyslexia *per se*. However, this heterogeneity of the dyslexic population also raises the interesting possibility that different performance patterns might actually reflect distinct underlying cognitive impairments. Thus, poor pseudo-word reading and phoneme awareness skills may be the consequence of an underlying phonological processing deficit, whereas poor exception word reading despite good phonological skills may follow from a non-phonological core cognitive disorder.

Defending such a hypothesis requires providing evidence for the independence between the phonological processing deficit and the second hypothesized cognitive disorder. It further requires demonstrating that the second hypothesized disorder accounts for unique variance in the reading performance of dyslexic participants beyond that explained by phonological skills. Informing a causal relationship between a cognitive disorder and specific reading disability further requires a theoretical framework clearly establishing how a dysfunction of this cognitive mechanism would hamper reading acquisition. Discussing current theories on these issues, the present paper gives empirical and theoretical arguments suggesting that a visual attentional deficit appears as a plausible second core deficit in developmental dyslexia.

This review first includes a brief summary of the well-known phonological core-deficit literature, emphasising both the strengths and weaknesses of the phonological hypothesis. Then, we discuss the validity of low-level sensory deficits, cerebellar deficits and rapid automatised naming disorders as causal factors in specific reading disability. Evidence for associated visual attentional disorders in developmental dyslexia is then reviewed before focusing on recent findings that suggest that visual attentional disorders contribute to reading acquisition disorders independently of phonological skills. Finally, we ~~finally~~ outline a theoretical model of reading which accounts for the separable influence of visual attentional processes and phonology on various aspects of skilled reading and reading acquisition.

THE PHONOLOGICAL DEFICIT HYPOTHESIS

The most widely accepted hypothesis with respect to the cognitive origin of developmental dyslexia is the phonological deficit hypothesis (Frith, 1997; Snowling, 1981, 2000; Stanovitch, 1986; Stanovitch & Siegel, 1994; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wilding, 1989, 1990). Numerous studies have shown that, compared to normal readers, developmental dyslexic children are impaired in phonological processing tasks such as non-word repetition (Elbro, Borstrom, & Petersen, 1998; Snowling, 1981; Snowling, Staskhouse, & Rack, 1986), phonemic fluency (Frith, Landerl, & Frith, 1995), picture naming (Snowling, van Wagtendonk & Stafford, 1988), phonological learning (Aguiar & Brady, 1991; Wimmer, Mayringer, & Landerl, 1998), phonemic awareness (e.g. Bradley & Bryant, 1978; Griffiths & Snowling, 2002; Morris *et al*., 1998) or verbal short-term memory (Griffiths & Snowling, 2002; Nelson & Warrington, 1980; Rack, 1985). The persistence of phonological difficulties in well-compensated dyslexic adults (Bruck, 1992; Campbell & Butterworth, 1985; Fawcett & Nicolson, 1995; Funnell & Davison, 1989; Howard & Best, 1996; Shaywitz *et al*., 1999) provides additional support to the phonological hypothesis.

Furthermore, studies on normal reading acquisition suggest a causal relationship between phonological processing skills and reading abilities: phonological awareness is strongly related to reading progress (Goswami & Bryant, 1990, for a review), children's knowledge of the phonological structure of their language is a good predictor of early reading ability (Bradley & Bryant, 1983; Elbro, 1997; Elbro *et al*., 1998; Stanovich, Cunningham, & Cramer, 1984) and phonemic awareness training improves learning to read (Bradley & Bryant, 1983; Ehri *et al*., 2001, for a meta-analysis; Castles & Coltheart, 2004, for a critical review).

These findings provide strong support to the phonological deficit hypothesis, but there are problematic data as well. First, several cases of developmental dyslexia and/or dysgraphia with good phonological skills have been reported; these cases show good pseudo-word reading, phonological awareness and verbal short term memory, and the majority of the errors they produce are phonologically plausible (Broom & Doctor, 1995; Castles & Coltheart, 1996; Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Goulandris & Snowling, 1991; Hanley & Gard, 1995; Hanley, Hastie, & Kay, 1992; Job, Sartori, Masterson, & Coltheart, 1984; Romani & Stringer, 1994; Romani, Ward, & Olson, 1999; Temple, 1984). These case studies indicate that not all developmental dyslexics have a phonological deficit, a rather unexpected finding within the phonological hypothesis framework. However, these studies often assessed performance of teenagers or young adults. Accordingly, one could argue that the phonological disorder was present earlier in development but was so well compensated as to become undetectable by the time of testing. In addition, the sensitivity of the phonological tests used in these studies can sometimes be questioned. However, two studies, which compared the performance of dyslexic readers of similar age and reading level on the same phonological tests, provide more convincing evidence for the existence of developmental dyslexia without phonological processing disorders (Hanley & Gard, 1995; Valdois *et al*., 2003). Each of these studies reported two dyslexic cases with opposite reading patterns and contrasted phonological skills. In each study, one dyslexic participant showed poor phonological awareness and made only a few phonologically accurate errors in reading or spelling (phonological dyslexia pattern) while the other showed good phonological awareness and produced a majority of phonologically accurate errors (surface dyslexia pattern). Thus, cases of developmental dyslexia with normal phonological processing have been documented despite using sensitive enough phonological measures. In other cases however, phonological and surface dyslexia differ only in the degree of severity of the phonological disorder and in the cognitive resources available to compensate for this phonological deficit (Snowling, 2000). Thus, it could be argued that dyslexic children with good phonological skills are exceptional cases and rare syndromes of no theoretical significance.

Classification studies have also identified subgroups of dyslexic children who demonstrate distinct, and even opposite patterns of reading disability, relative to patterns of normal reading performance (Castles & Coltheart, 1993; Castles, Datta, Gayan, & Olson, 1999; Genard *et al*., 1998; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Stanovich, Siegel, & Gottardo, 1997). These studies consistently found that around a third of the dyslexic sample was constituted of individuals for whom only one reading sub skill (pseudo-word or exception word reading) was outside the range of the performance of chronological age matched control children. These studies also emphasised that most dyslexic children showed stronger impairment on one sub skill than the other, thus exhibiting 'soft-signs' of either phonological or surface dyslexia. These findings clearly document the existence of individual differences in the reading behaviour of the dyslexic population, but they provide no insight on the cognitive factors underlying these different behavioural profiles.

Extending the phonological hypothesis, the severity hypothesis (Griffiths & Snowling, 2002; Snowling, Goulandris, & Stackhouse, 1994) postulates that differences in the reading profiles of dyslexic children depend on the severity of the phonological deficit, combined with variations in general processing resources, reading experience (print exposure) and compensatory strategies. The severity hypothesis is compatible with data showing that some dyslexic children specifically impaired on irregular words are also mildly impaired in phonological processing (Bailey, Manis, Pedersen & Seidenberg, 2004; Castles *et al*., 1999; Sprenger-Charolles *et al*., 2000; Stanovich *et al*., 1997). However, in addition to the case studies mentioned above, other data are less consistent with this account. For example, Manis *et al*. (1996) and Curtin, Manis, and Seidenberg (2001) found that the phonological dyslexia subgroup had difficulty analysing the phonemic structure of spoken words or pseudo-words whereas the surface dyslexia subgroup did not differ from normal readers matched on chronological age on this task. In addition, Castles *et al*. (1999) showed that their two groups of surface and phonological dyslexics had comparable low scores on the print exposure measure they used (see also Manis, Seidenberg, & Doi, 1999). The authors suggested that low print exposure would result in a phonological dyslexic pattern in poor readers with a severe phonological deficit but in the surface dyslexia pattern in children with a milder phonological deficit. However, print exposure is known to primarily affect exception word reading (Griffiths & Snowling, 2002); on the other hand, phonological deficits primarily affect pseudo-word reading, although they also prevent the normal acquisition of lexical orthographic knowledge (Share, 1995, 1999). Accordingly, one would expect that poor print exposure associated with a severe phonological deficit should result in poor reading of both exception words and pseudo-words. Finally, reading theories do not predict that mild phonological impairments should result in specific difficulties in exception word reading. Indeed, in both dual-route (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and PDP connectionist (Harm and Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989) models, phonological deficits have far more impact on pseudo-word reading than on exception word reading. Harm and Seidenberg (1999) clearly showed in a simulation that a mild phonological deficit affected pseudo-word reading but not exception word reading; severe phonological deficits resulted in a mixed profile, with impairments in both pseudo-word and exception word reading. Overall, it appears that neither mild phonological deficits alone nor poor print exposure alone can account for the profile of poorer exception word reading relative to pseudo-word reading. Therefore, the question remains open as to whether the inability of surface dyslexic children to encode the orthographic form of words could be explained by a non-phonological cognitive disorder.

However, except for case JAS (Goulandris & Snowling, 1991) whose surface dyslexia was associated with poor visual memory, most case and group studies have failed to find any specific cognitive impairment that may be responsible for a selective disorder in exception word reading. Moreover, the performance of surface dyslexic readers has consistently been found to be similar to that of younger reading-age matched controls. Consequently, it has been assumed that the surface dyslexia profile stems from a general developmental delay in overall reading ability (Manis *et al*., 1996; Sprenger-Charolles *et al*., 2000; Stanovich *et al*., 1997). Obviously, this interpretation does not apply to those cases who demonstrate a strict dissociation characterized by poor exception word reading but normal pseudo-word reading. Moreover, although the similarity between the reading performance of dyslexic readers and younger controls was clearly established in terms of accuracy, very few studies have investigated whether dyslexic children and younger controls produce comparable error patterns. Thus, contrary to the delay hypothesis, the performance of dyslexic children may be qualitatively different from that of younger controls. This hypothesis was supported by Martinet and Valdois (1999) who showed that surface dyslexic children produced proportionally more phonologically plausible errors than reading-age matched children, even though their overall scores on exception word spelling did not differ; as a matter of fact, the proportion of phonologically accurate errors produced by these children was comparable to that of chronological age-matched controls (see however Curtin *et al*., 2001). Moreover, similarity of performance with younger control children tells us ‘nothing about the causes of developmental dyslexia’ (Bryant & Impey, 1986, p. 124) and does not rule out the possibility that developmental surface dyslexia derives from a specific underlying deficit. In their simulation of this disorder, Harm and Seidenberg (1999) showed that the delay characteristic of surface dyslexia could arise from several causes including a disorder at the level of visual processing (see also, Seidenberg, 1992) or a resource limitation affecting the capacity of the network to encode dependencies that span an appropriate number of letters. Although such interpretations are not entirely supported by empirical data (Valdois *et al*., 2003), they at least demonstrate that a specific cognitive impairment affecting the normal visual processing of the entire orthographic sequence could in principle result in surface dyslexia. This visual processing deficit hypothesis will be considered in more depth in the following section.

In sum, the hypothesis that a specific cognitive deficit affecting phonological processing results in reading acquisition disorders is well supported on both empirical and theoretical grounds. However, the present critical review suggests that the phonological deficit hypothesis cannot account for the surface dyslexia profile characterized by poor exception word reading relative to pseudo-word reading. Neither can it explain reported cases of developmental dyslexia without associated phonological deficits. In addition, the proposal that the surface dyslexia pattern may be the mere consequence of insufficient reading experience or of a general reading delay is not entirely supported empirically. It follows that the surface dyslexia pattern may actually reflect a non-phonological core disorder. In the next section, we will review other deficits which have been found to be associated with developmental dyslexia and will examine whether they could be causally related to reading acquisition disorders.

CURRENT ALTERNATIVE HYPOTHESES

Low-Level Auditory Deficits

Several alternative hypotheses have been proposed as an attempt to identify the cognitive or biological bases of specific reading disability. At the cognitive level, a general non-linguistic auditory temporal deficit was proposed by Tallal and her colleagues. This hypothesis was supported by studies showing that dyslexics performed below normal readers on auditory temporal order perception tasks (Tallal, 1980; Tallal *et al*., 1996; Tallal, Miller, & Fitch, 1993). However, the hypothesis of a general non-linguistic auditory deficit is highly debated (Vellutino *et al*., 2004, for a review). One potential problem is that the auditory impairment of dyslexic children seems limited to the perception of speech sounds (Breier, Fletcher, Foorman, & Gray, 2002; Farmer & Klein, 1995; Merzenich *et al*., 1996; Mody, Studdert-Kennedy, & Brady, 1997; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001); this raises the possibility that impairments in speech perception tasks may be the consequence rather than the cause of a phonological deficit (Ramus, 2004). In addition, even though poor auditory processing skills are frequently associated with poor phonological awareness in dyslexia, this is not always the case; that is, some dyslexic individuals have phonological deficits without auditory processing deficits (Ramus *et al*., 2003). This casts doubts as to whether the auditory processing hypothesis can be seen as a core deficit responsible for developmental dyslexia independently of the phonological disorder. Be this as it may, the auditory processing deficit hypothesis does not seem to be any more suited to account for developmental surface dyslexia than the phonological deficit hypothesis. Although poor auditory processing skills affect pseudo-word reading (Witton *et al*., 1998), they do not seem to contribute to the performance in exception word reading (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999).

Low-Level Visual Deficits

Low-level visual processing deficits have also been reported in developmental dyslexia and they have been viewed as potential sources of reading acquisition disorders. In particular, many studies of developmental dyslexia have reported associated deficits in the transient visual system, manifesting themselves by impaired contrast sensitivity (Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove, Garzia, & Nicholson, 1990; Lovegrove, Martin, & Slaghuis, 1986; Stein, 2003; Stein & Fowler, 1993) and motion perception (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, & Heeger, 1998; Eden *et al*., 1996; Talcott, Hansen, Assoku, & Stein, 2000). These visual deficits in dyslexia have been linked to functional anomalies in the magnocellular visual subsystem (Livingstone *et al*., 1991; Lovegrove *et al*., 1986; Eden *et al*., 1996; see Skottun, 2000 for a critical review). Several models stress the importance of the visual magnocellular system in text reading (Breitmeyer, 1980; Chase, 1996; Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003; see also Skottun & Parke, 1999, for a critical review). Furthermore, performance on magnocellular low-level visual tasks is correlated to pseudo-word reading (Talcott, Hansen, & Stein, 1998; Witton *et al*., 1998) and is typically associated to phonological disorders (Slaghuis, Lovegrove, & Davidson, 1993; Van Ingelghem, Van Wieringen, Wouters, Vandenbussche, & Onghena, 2001; Witton *et al*., 1998). To account for the co-occurrence of phonological and low-level visual deficits, Stein and collaborators later proposed a more general amodal version of the magnocellular theory (Stein & Walsh, 1997; Stein & Talcott, 1999; Stein, 2001, 2003). This theory postulates that magnocellular temporal processing deficits result in basic visual and auditory processing impairments. The impairment in low level auditory transient processing would entail problems with phonological analysis which remains the proximal source of the reading problem. In sum, although some data suggest that a visual magnocellular disorder might contribute to poor reading performance (Chase *et al*., 2003; Vidyasagar, 1999), there is no evidence showing that low-level visual processing problems contribute to the reading outcome of dyslexic children, independently of their phonological skills. In addition, magnocellular deficits have been reported in the context of phonological dyslexia but not in surface dyslexia (Borsting *et al*., 1996; Cestnick, 2001; Cestnick & Coltheart, 1999; Spinelli *et al*., 1997), which leaves open the question of the origin of reading difficulties in this dyslexia sub-type.

Cerebellar Deficits

Similarly, the cerebellar theory of dyslexia (Nicolson & Fawcett, 1990; Fawcett & Nicolson, 2004; Nicolson, Fawcett, & Dean, 2001) postulates a close link between phonological disorders and reading acquisition disorders. Given the role of the cerebellum in motor control and automatisation, a cerebellar dysfunction would affect speech articulation; this would lead to poor phonological representations and poor phonological skills which would be directly responsible for reading acquisition disorders. The cerebellar deficit hypothesis is thus presented as a biological explanation of the co-occurrence of cognitive phonological deficits and low-level motor impairments in developmental dyslexia. As there is no evidence for a specific contribution of motor or automatisation problems to developmental dyslexia, the causal nature of the link between cerebellar dysfunctions and reading disorders is now widely debated (Wimmer, Mayringer, & Landerl, 1998; Wimmer, Mayringer, & Raberger, 1999; Ramus, Pidgeon, & Frith, 2003).

Rapid automatised naming deficits

Contrary to the hypotheses discussed above, the double-deficit hypothesis explicitly postulates that a phonological deficit and a deficit in rapid automatised naming of letters or symbols represent two independent sources of reading disability (Wolf & Bowers, 1999; Wolf *et al*., 2002). A growing number of data point to naming speed deficits in developmental dyslexia (e.g., Denckla & Rudel, 1976; Ho, Chan, Tsang, & Lee, 2002; Wimmer, Mayringer, & Landerl, 2000; Wolf & Bowers, 1999) and suggest that rapid naming abilities contribute to reading acquisition even after controlling for phonological skills (Manis, Doi, & Bhadha, 2000; Manis *et al*., 1999; Ho, Chan, Lee, Tsang, & Luan, 2004; see Wolf & Bowers, 1999, for a review; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997, for a methodological critique). Moreover, rapid naming appears to be more strongly related to reading speed and measures of orthographic knowledge than phonological skills (Manis *et al*., 1999; Bowers, Sunseth, & Golden, 1999). However, rapid naming measures and phonological skills measures are significantly correlated (Bowers, Sunseth, & Newby-Clark, 1998) and, contrary to the independence hypothesis, dyslexic children tend to exhibit both a phonological and a naming speed disorder (Wolf *et al*., 2002). It remains however that some dyslexic children exhibit a selective deficit in naming speed and that naming speed makes a specific contribution to reading acquisition disorders, particularly with respect to the acquisition of lexical orthographic knowledge. Thus, the rapid naming deficit hypothesis appears as a plausible alternative candidate to explain cases of developmental dyslexia without associated phonological disorders and with selective exception word reading (and spelling) disorders. However, further investigations are required to specify the impaired mechanism(s) which could underlie both naming speed deficits and reading acquisition disability. The hypothesis that inadequate temporal integration of letter identities might be responsible for this co-occurrence of disorders is under debate (Vellutino *et al*., 2004) and will be discussed below in relation with the visual attentional hypothesis.

VISUAL ATTENTIONAL DISORDERS IN DEVELOPMENTAL DYSLEXIA

Several lines of evidence indicate that visual attentional difficulties are correlated with developmental dyslexia. First, several studies have shown that dyslexic children are impaired in tasks in which they have to search for a target among distracters. More specifically, Marendaz, Valdois, and Walch (1996) showed that dyslexic children were impaired when the task required serial attentional search but unimpaired in parallel search. Marendaz *et al*. (1996) proposed that this visual search deficit could result either from a perceptive grouping dysfunction (reducing the number of items simultaneously processed during serial search) or from a problem in the shifting of attention. Similar findings were reported by Iles, Walsh, and Richardson (2000), who were also able to show that the visual attentional deficit was restricted to a subgroup of dyslexic children with associated magnocellular visual processing difficulties. Severe serial search disorders were also reported in a case of surface dyslexia without associated phonological problems (Valdois, 1996). In addition, several studies have shown that dyslexic children have a defective spatial orienting of visual attention (Brannan & Williams, 1981; Facoett *et al*., 2003; Facoetti & Molteni, 2001; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Facoetti, Paganoni, & Lorusso, 2000). They demonstrate an asymmetric distribution of attentional resources across the visual field, as shown by mild left inattention in cue-target reaction time tasks and abnormally high sensitivity in the right visual field (Facoetti & Molteni, 2001; Facoetti & Turatto, 2000; Hari, Renvall, & Tanskanen, 2001). In line with these findings, Valdois, Gerard, Vanault, and Dugas (1995) described a case of developmental visual dyslexia who demonstrated a right attentional bias when processing briefly presented pseudo-words. Geiger, Lettvin, and Zegarra-Moran (1992) also showed that dyslexic children were abnormally good at processing eccentrically located letters in the right visual field, suggesting a difficulty in inhibiting peripheral information (in the direction of reading) and focus attention in the centre of the gaze (see also, Rayner, Murphy, Henderson, & Pollatsek, 1989). Accordingly, recent data suggest that dyslexic people distribute attentional resources more diffusely because of difficulties in narrowing their attentional focus (Facoetti *et al*., 2000); they display slower capture of attention (Facoetti *et al*., 2003) but once their attention is engaged it cannot easily disengage (Hari, Valta, & Utela, 1999). A growing number of data therefore point to a visual attentional disorder which could contribute to the reading impairment of dyslexic children. Attentional disorders affecting speed in parallel processing (Yap & van der Leij, 1993) might interfere with letter order encoding, leading to letter sequence errors and confusions between visually similar words. Indeed, there are case reports of dyslexic children without phonological deficits who are more prone to such localisation errors (McCloskey & Rapp, 2000; Romani *et al*., 1999). The relation between visual attention and reading acquisition was further explored by Casco, Tressoldi, and Dellantonio (1998) in non selected children engaged in a cancellation task. They found that the lowest the performance in the cancellation task, the slower the reading rate and the higher the number of visual errors. Thus, children's performance in a search task involving selective attention appears to be related to their reading performance. However, this relation was established without controlling for the influence of phonological skills, thus undermining the specific role of selective attention in reading acquisition. This is all the more detrimental that other data suggest that the spatial attention deficit in dyslexia is not restricted to the visual modality but also extends to auditory information processing (Facoetti *et al*., 2003; Hari & Kiesilä, 1996). Accordingly, Hari and Renvall (2001) proposed the 'sluggish attentional shifting' (SAS) theory of dyslexia according to which sluggish attentional capture and prolonged attentional dwell time would impair processing of rapid stimulus sequences in all sensory modalities. According to the SAS theory, visual attentional deficits should typically co-occur with phonological processing and phonological awareness deficits in developmental dyslexia. Although the nature of the visual attention deficit highlighted in the previous studies should affect reading performance, it remains to be shown that this deficit does contribute to the reading performance of dyslexic children, independently of their phonological skills.

ARE VISUAL ATTENTIONAL AND PHONOLOGICAL DEFICITS INDEPENDENT PREDICTORS OF READING ACQUISITION DISORDERS?

We now turn to our own research which aims to demonstrate that visual attentional and phonological disorders can dissociate, that visuo-attentional skills predict reading performance independently of phonological skills, and that a visuo-attentional deficit thus constitutes a plausible alternative core disorder in developmental dyslexia. We first present two case studies which show a remarkable dissociation in their phonological versus visuo-attentional skills. We later demonstrate that the results observed in these case studies generalise to a larger sample of French- and English-speaking children. But, beforehand, we present some details of the tests that we used to assess dyslexic children, in particular with respect to their visuo-attentional abilities.

Assessment of Phonological and Visuo-Attentional Deficits

Our general methodology has been to submit dyslexic children, chronological-age (CA) matched controls and reading-age (RA) matched controls to a comprehensive battery of tests aimed to assess reading and spelling abilities, phonological skills and visuo-attentional skills. We present the visuo-attentional tasks in more detail here, because, to our knowledge, they have not been used before to assess visuo-attentional processing in developmental dyslexia.

To assess visuo-attentional abilities, we used two tasks of whole and partial letter-string report that were created by Averbach and his colleagues (Averbach & Coriell, 1961; Averbach & Sperling, 1968) to study the processing of letter information perceived during a single fixation. Since then, the whole and partial report procedures have been used in a wide range of visual attention studies and with several variants to assess both normal (Dixon, Gordon, Leung, & Di Lollo, 1997; Giesbrecht & Dixon, 1999; Hagenaar & Van der Heijden, 1995; Mewhort, Campbell, Marchetti, & Campbell, 1981) and impaired (Arguin & Bub, 1993; Duncan *et al.*, 1999; Duncan *et al.*, 2003; Habekost & Bundesen, 2003; Rapp & Caramazza, 1991) visual attention processing. In our studies, the whole report task consisted in showing the participants arrays of five letters (e.g., R H S D M) and asking them to report the identities (not locations) of as many letters as they could. To avoid eye movements, each horizontally centred letter string remained on the screen for only 200 ms. In the partial report condition, the participants were shown similar arrays of five letters but were asked to report a single cued letter on each trial. The cue, a vertical bar, appeared at the offset of the letter string for 50 ms and indicated the location of the letter to be reported.

The whole report task is a classical experimental procedure in the study of attentional capacity. It provides an estimate of the total amount of information that can be extracted from a brief visual display and encoded in visual short-term memory (Bundesen, 1998). The partial report task measures how the total attentional capacity is distributed across letters in the string. The exogenous attentional system is used to select relevant information. When the cue is presented for a short time immediately after the letter display, as in our studies, performance essentially reflects visual feature information processing before decay in iconic memory. Even though they both involve reporting verbal material, the whole and partial report tasks cannot be considered as verbal or verbal short-term memory tasks. Consistent with this view, it has been shown that performance in the whole report task is barely affected by a concurrent verbal short-term memory task (Scarborough, 1972). In addition, the patterns of errors produced in the whole report task reflects visual rather than verbal confusions (Wolford, 1975). In partial report, a single letter has to be reported, so it is unlikely that verbal short term memory is a major factor. Indeed, Dixon and Shedden (1993) showed that partial report is only minimally affected by articulatory suppression. Thus, whole and partial report tasks are considered as primarily reflecting visual attention and visual short-term memory components. An extensive use of these tasks allowed Sperling to propose a theory of visual-information processing (Sperling, 1970) and, more recently, a computational model of attention dynamics (Shih & Sperling, 2002). These tasks were also used to validate theories specifying visual attention mechanisms and their timing (Bundesen, 1990; 1998; for a review, see Gegenfurtner & Sperling, 1993). The whole and partial report tasks therefore appear quite appropriate to investigate visual attention skills in developmental dyslexia.

Case Studies Showing a Dissociation Between Phonological and Visuo-Attentional Skills

Valdois *et al*. (2003) assessed the phonological and visual attentional skills of two teenagers who exhibited contrasted reading profiles: Laurent had a phonological dyslexia profile and Nicolas a surface dyslexia profile. They were submitted to a comprehensive battery of metaphonological tasks including sound categorisation, phoneme and syllable deletion, phoneme segmentation and spoonerisms. When compared to CA matched controls, Laurent performed outside the normal range on all phonological awareness tasks. His performance was low even as compared to children matched on reading age. Laurent also showed poor formal verbal fluency and poor verbal short-term memory. Thus, Laurent's dyslexia was clearly accompanied by a general phonological deficit. In marked contrast, Nicolas's performance was above average as compared to children of the same chronological age. Nicolas's excellent metaphonological skills, his good pseudo-word reading and spelling, his phonologically accurate reading and spelling errors, his good verbal fluency and verbal short-term memory provided strong evidence that his difficulties in exception word reading and spelling were not due to an underlying phonological disorder.

In addition, Laurent and Nicolas were submitted to the whole and partial report tasks described above. In both tasks, Laurent's performance was well within the normal range of CA controls, whatever the position of the letters in the string. Thus, Laurent showed good visual attentional skills despite poor phonological processing skills. In sharp contrast, Nicolas was able to report none of the 5-letter strings as a whole in the whole report condition, a score outside the range of both CA and RA controls. He further demonstrated a strong positional effect on this task. His ability to report the last two letters of the string was particularly impaired and his performance on these two positions was even worse than that of younger children matched on reading age. A quite similar pattern emerged in partial report with a lower performance than RA controls on the two last letters of the string. Nicolas's poor performance in both the whole report and partial report tasks provide evidence that he suffered from a visual attentional impairment despite good phonological skills. Valdois *et al*. (2003) also demonstrated that Nicolas exhibited similar positional effects when reading briefly presented real words, thus suggesting a relationship between the visual attentional disorder revealed in the report tasks and his reading performance. This study shows that phonological and visual attentional disorders can dissociate in developmental dyslexia. It further suggests that both disorders might independently contribute to impaired reading performance.

Generalizing the Findings to Larger Samples in Different Languages

To support the hypothesis that phonological and visual attentional disorders constitute two independent sources of reading impairment, Bosse, Tainturier, and Valdois (2004; see also Valdois & Bosse, 2004; Bosse, Tainturier, & Valdois, submitted) conducted two group studies on large samples of French and British developmental dyslexic children. The French study assessed 68 dyslexic children, whose performance was compared to that of two control groups matched on chronological age and reading age. All the participants were administered tasks of regular word, exception word and pseudo-word reading, tasks of phoneme awareness (phoneme deletion, phoneme segmentation and acronym) and the two visual-attentional tasks of whole and partial report. Both correlation and factor analyses showed that phonological and visual attentional scores were unrelated measures tapping independent cognitive mechanisms. Using the factorial scores derived from the principal component analysis in a hierarchical regression analysis, Bosse *et al*. (2004) found that both the phonological and visual attentional processing skills were significant and independent predictors of the dyslexic children reading scores. In addition, attentional processing skills accounted for a substantial amount of unique variance in both irregular word and pseudo-word reading, as did phonological skills.

Furthermore, the analysis of the distribution of phonological and visual attentional factorial coefficients revealed that dyslexic participants could belong to one of four distinct subgroups: a selective phonological deficit subgroup, a selective visual attentional deficit subgroup, a mixed subgroup showing both deficits, and finally a group of children who did not show abnormal performance on either phonological or visuo-attentional measures. More interestingly, most French dyslexic children (63%) were classified as having a selective phonological or visuo-attentional cognitive disorder, as expected under the hypothesis that the two deficits are independent sources of reading acquisition disorders.

A replication of the French study was conducted with British children in order to confirm previous findings while controlling for additional potentially confounded variables. The British participants were administered tests of intellectual efficiency, semantic verbal fluency and vocabulary level, in addition to the reading, metaphonological and visual attentional tasks. The results revealed that the contribution of visual attentional skills to reading performance remained even after controlling for the children's level of intellectual efficiency, verbal fluency, and vocabulary in addition to metaphonological skills. Furthermore and as previously, most English dyslexic children (60%) were found to exhibit a single phonological or visual attentional disorder.

Overall, these data show that visual attentional disorders and phonological disorders dissociate in a good number of dyslexic children. Critically, they also demonstrate that phonological and visual attentional abilities make independent contributions to dyslexic reading performance. Thus, the visual attentional disorder appears as a plausible second core deficit in developmental dyslexia since it can predict dyslexic reading in the absence of a phonological deficit. In the next section, we will see that the hypothesis of a causal relationship between visual attentional problems and reading acquisition disability also has theoretical support.

A THEORETICAL ACCOUNT OF THE ROLE OF VISUAL ATTENTIONAL PROCESSING IN SKILLED READING AND READING ACQUISITION

Although models of eye movement control in reading (Reichle, Rayner, & Pollatsek, 2003) and some models of word recognition (Behrmann, Moscovitch, & Mozer, 1991; Laberge & Samuels 1974; Laberge & Brown, 1989) emphasise the role of visual attention, most reading theories do not specify the attentional processes involved in the visual analysis of letter strings, assuming that they are peripheral mechanisms that are not an integral part of the reading process (Coltheart *et al*., 1993; Coltheart *et al*., 2001; Harm & Seidenberg, 1999; Plaut *et al*., 1996; Seidenberg & McClelland, 1989).

On the contrary, the connectionist multi-trace model of polysyllabic word reading (Ans, Carbonnel, & Valdois, 1998) provides a theoretical description of how visual attentional processes operate in reading and how they can lead to specific reading disorders when damaged. The model postulates that reading can take place through two types of reading procedures, a global and an analytic one. The two procedures differ in the kind of visual attentional and phonological processing they involve. Global processing always proceeds first, the analytic procedure only coming into play if global processing has failed. An essential feature of this model is the inclusion of a visual attentional window (VAW) through which information from the orthographic input is extracted. The two reading procedures differ in the size of the VAW involved. In global reading mode, the VAW extends over the whole sequence of the input letter-string. When shifting in analytic mode, the VAW narrows down to focus attention on the first part of the orthographic input. Analytic processing then proceeds through a narrow VAW which shifts from left to right, focalising attention on the different parts of the input successively. Letters within the VAW are maximally activated and processed in parallel whereas letters outside the window are only minimally activated or not at all. In the analytic mode, a phonological output is generated for each group of letters that fall within the VAW, and this process is sequentially reiterated until the VAW has reached the end of the letter string.

The two reading procedures also differ with respect to phonological processing. In global processing, the entire phonological output is generated in a single step. In analytic processing, phonological outputs corresponding to each focal sequence (i.e. letters within the VAW) are successively generated and have to be maintained in short-term memory in order to remain available at the end of processing. In global mode, phonological information emerges from the activation of word traces in memory whereas sublexical memory traces are recruited in the analytic mode. Although the two procedures are not *a priori* dedicated to the processing of a particular type of letter string (real word or pseudo-word), most familiar words are processed as a whole by the network, whereas global processing typically fails for pseudo-words which are analytically processed.

The network was tested for its ability to account for acquired dyslexia following specific damage. Ans, Carbonnel, and Valdois (1998) demonstrated that a moderate reduction of the VAW size prevents reading in global mode. This reduction simulated a surface dyslexia profile, with a selective disruption of irregular word reading giving rise to regularization errors. Performance was more severely impaired following a more severe reduction of the VAW. Irregular words continued to be the most affected class of items, but the number of errors increased on both regular words and pseudo-words. It was further assumed that a very severe reduction of the VAW would result in the profile of letter by letter reading thus affecting the network ability to read all types of letter-strings. In contrast, acquired phonological dyslexia was interpreted as resulting from an independent disorder affecting phonological processing.

The multi-trace model has not yet been adapted to simulate reading acquisition and developmental dyslexia. Nonetheless, it provides new insights on the way selective visual attentional or phonological deficits might impact on reading acquisition and result in patterns of developmental surface or phonological dyslexia. In the network, each new word is learned in both global and analytic mode. In global mode, a new word memory trace is created during reading each time the entire orthographic input and the entire phonological output of the input item are simultaneously available. It follows that a new word trace can be created either following global processing (typically with a supervisor) or when the assembled phonology of the letter string is maintained in short term memory at the end of analytic processing. Thus, we propose that normally developing beginning readers acquire new lexical knowledge in two situations: (1) when they are provided with the entire phonological correspondence of the orthographic sequence or (2) after having generated the phonological sequence themselves through analytic processing, provided that they can also relate the entire phonological sequence with the entire input orthographic sequence. Hence, reading in analytic mode would also contribute to the development of lexical knowledge, an hypothesis which is in line with the self-teaching hypothesis proposed by Share (1995, 1999, 2004). In the model, learning in analytic mode also consists in creating memory traces which encode the relationship between simultaneously presented orthographic and phonological sublexical segments. Similarly, it can be assumed that beginning readers acquire sublexical knowledge each time they are able to parse a whole phonological sequence into relevant phonological units together with processing in parallel the letters of the corresponding sublexical orthographic units.

Within this theoretical framework, a phonological deficit affecting the acquisition of sublexical knowledge and/or the maintenance of phonological information in short-term memory should affect analytic processing more than global processing. Thus, phonological deficits are expected to interfere primarily with pseudo-word reading (developmental phonological dyslexia profile). However, a purely phonological disorder could also interfere with the self-teaching mechanism which contributes to the acquisition of new word traces. This could in turn affect global processing, leading to a mixed dyslexia pattern characterized by poor pseudo-word and irregular word reading.

Furthermore, the model predicts that a visual attentional disorder reducing the number of letters that can be identified in parallel could also lead to developmental dyslexia, albeit of a different type. Indeed, a reduction of the VAW through which information from the orthographic input is extracted should result in an inability to create word traces, interfering with the normal development of the global reading procedure. This difficulty to establish lexical knowledge should be primarily detrimental to irregular word reading, leading to a pattern of developmental surface dyslexia. Regular word and pseudo-word reading should remain unaffected as far as the VAW is large enough to process groups of letters that correspond to relevant orthographic units. A more severe reduction in the size of the VAW would end up affecting regular word and pseudo-word reading as well. The model therefore predicts that a selective visual attentional impairment should result in a selective exception word reading disorder or in a mixed disorder affecting both exception word and pseudo-word reading, depending on the severity of the visuo-attentional deficit.

CONCLUSION

Notwithstanding the obvious importance of phonological abilities in reading acquisition and the clear relationship between phonological disorders and dyslexia, the phonological hypothesis fails to give a fully satisfactory account of the variability in dyslexic reading profile and associated deficits. In this paper, we have argued that a visual attentional deficit constitutes a plausible second core deficit in dyslexia. Using data from both single case and group studies, we have endeavoured to demonstrate that phonological and visual attentional deficits are independent sources of reading acquisition disorders. Our case studies further showed that a visual attentional disorder without a phonological disorder can produce the pattern of developmental surface dyslexia, which has been particularly difficult to account for within the phonological hypothesis. In contrast, the pattern of phonological dyslexia was found to be associated with a phonological disorder in the absence of visual attentional problems suggesting that a phonological disorder primarily affects pseudo-word reading.

The multi-trace memory model of polysyllabic word reading (Ans *et al.*, 1998) provides a useful framework to try to explain the respective roles of phonological and visual attentional disorders on reading acquisition difficulties. Surface dyslexia may be seen as arising from a reduction of the size of a visual attentional window through which information is extracted from the orthographic sequence to be read. Irregular words are particularly vulnerable to such a reduction because disambiguating their pronunciation requires distributing attention over the whole orthographic sequence. As for selective disorders in pseudo-word reading (phonological dyslexia profile), the multi-trace model proposes that they result from an independent phonological disorder affecting the establishment of sublexical memory traces and/or the maintenance of phonological information in verbal short term memory. However, the model further predicts that mixed reading profiles can result from either a selective phonological deficit, a selective visual attentional deficit, or a combination of both. Indeed, although less orthographic information is required for accurate pseudo-words processing, a severe visual attentional impairment that would limit orthographic encoding to, say, one or two letters at time would clearly affect the ability of the system to process multi-letter graphemes and contextual graphemes, thus affecting pseudo-word reading as well, at least in languages with relatively deep orthographies such as English or French. In line with the self-teaching theory of Share (1995), a phonological impairment is also expected to affect the establishment of lexical orthographic knowledge on top of pseudo-word reading abilities. Obviously, a double deficit would result in poor performance on both irregular words and pseudo-words. Accordingly, the multi-trace memory model provides a straightforward explanation of the preponderance of mixed reading profiles in developmental dyslexia.

At this stage, it is important to ask how our proposal of a visual attentional disorder as a core deficit in dyslexia relates to other alternative accounts put forward in the literature. As mentioned earlier, rapid naming speed disorders might also provide an explanation of cases of developmental dyslexia without associated phonological disorders. However, the rapid automatised naming task for letters, which involves the rapid naming of visually presented non-pronounceable letter strings, no doubt shares common processes with the global report task we have been using to investigate visual attentional abilities. The two tasks probably assess a number of shared visual (or visual attentional) and phonological processes, although the report task alone evaluates the contribution of visual attentional skills to encoding of information in visual short term memory. We believe that this specific role of visual attentional processing is of the utmost importance in the establishment of lexical orthographic knowledge in long term memory. Further research is required to evaluate the relative contribution of performance on letter report tasks versus naming speed tasks to reading performance. Our prediction is that the visual attentional abilities assessed in the report tasks should be stronger predictors of irregular word reading accuracy and speed than performance in rapid naming tasks.

In addition, we have seen earlier that several other studies have argued for the existence of a visuo-attentional disorder in dyslexia, although they did not establish the specific contribution of this disorder to reading performance over and above that of associated phonological skills. At this stage, it is not entirely clear to what extent the report tasks that we have been using tap on the same mechanisms as other tasks used in the literature to investigate visual attentional skills. It can be assumed that left mini-neglect and preferential processing of stimuli in the right visual field should affect performance in the global and partial report tasks. In the same way, difficulties to focalize attention might prevent the normal shifting of selective attention in global report or the selective processing of the cued letter in partial report. However, in supporting the hypothesis of a visual attentional disorder dissociated from phonological problems, our approach dissociates from the sluggish attention shifting theory which assumes problems in processing rapid stimulus sequences in all sensory modalities.

In conclusion, it seems increasingly unlikely that a phonological disorder is the sole cause of reading acquisition difficulties in developmental dyslexia. Indeed, several hypotheses for alternative deficits have been proposed in the last few years to try to account for the variability in dyslexic reading profiles and associated deficits. We have argued that a visual attentional disorder is the underlying cause of reading acquisition disorders in a non-negligible number of dyslexia cases. Importantly, we provided evidence that visual attentional skills contribute to reading performance independently of phonological skills.

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