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I Can Read It in Your Eyes:

What Eye Movements Tell Us about Visual-Attention Processes in Developmental Dyslexia

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ABSTRACT

Most studies today agree about the link between visual-attention and oculomotor control during reading: attention seems to affect saccadic programming, that is, the position where the eyes land in a word. Moreover, recent studies show that visuo-attentional processes are strictly linked to normal and impaired reading. In particular, a large body of research has found evidence of defective visuo-attentional processes in dyslexics. What do eye movements tell us about visual attention deficits in developmental dyslexia? The purpose of this paper is to explore the link between oculomotor control and dyslexia, taking into account its heterogeneous manifestation and comorbidity. Clinical perspectives in the use of the eye-movements approach to better explore and understand reading impairments are discussed.

Key words: Eye Movement; Reading; Visuo-attentional Processes; Children; Developmental Dyslexia

Introduction

Learning to read is a key topic of debate today, both in terms of its implications in school failure and illiteracy, and regarding what the best teaching methods are. More generally, it is known that oral and written language skills play a key role in school success. Learning depends on the student's ability to understand and use oral language effectively for academic purposes. After elementary school, reading proficiency is essential for learning academic subjects and developing new cognitive skills. Students who have poor oral-language and/or poor reading skills are at a serious risk for academic failure and dropping out of school (Savage, Carless, & Ferrero, 2007; Snowling, 2000, 2006).

During the last century, studies on reading abilities and their development have yielded a diverse array of methodological approaches. Traditionally, in order to assess literacy skills for clinical purposes (diagnosis and intervention), the *psychometric approach* to reading is employed. This approach focuses on words, sentences, and text passage reading by means of standardized tests. In regards to decoding, two parameters are usually considered: speed (in terms of syllables per second or words per second, for example) and accuracy (in terms of number of errors) (for Italian and French examples, see Bellocchi & Bastien-Toniazzo, 2011). Reading comprehension is usually assessed by having the child answer questions, assign corresponding pictures, or judge the meaningfulness of sentences or words. This approach comes from a very huge body of experimental research based on the investigation of a more fine-grained level of cognitive processing involved in reading. For this finer level, the second approach is used. In the experimental tasks employed, participants are asked to name or recognize briefly presented single words manipulated with respect to different lexical or orthographic properties (e.g. lexicality, frequency, length). Usually, variables such as naming latency and accuracy are used to measure word or pseudoword identification. Thanks to this *single word approach* (as it was called by Huestegge, Radach, Corbic, & Huestegge,

2009), a great deal of information about language processing has been collected, allowing researchers to develop models of single-word identification or recognition (e.g. Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Seidenberg & McClelland, 1989; Zorzi, Houghton, & Butterworth, 1998). However, despite its unquestionable importance, this approach has some limitations, since it can only examine offline processing that occurs during decoding. In order to investigate and infer ongoing cognitive processing during reading, *eye-movement recording* is considered to be a valuable approach. Using this approach, a large body of data has been collected showing that eye movements are related to moment-to-moment cognitive processing during reading (for a review, see Rayner, 1998). In particular, the literature on eye movements in reading has increased our knowledge about visual attention processes during reading. Reading is known to be primarily a linguistic task and a large body of data shows that there are many linguistic factors that affect word processing (e.g., word length and frequency). However, reading also requires a visual analysis that enables the precise decoding of the written words.

There is a great deal of evidence indicating that readers are not processing only the fixated word (Rayner, 1998). So the question that should be addressed is: How much useful information can a reader obtain during eye movements? Using the *eye-contingent display change technique*, it has been shown that the *perceptual span* of English readers (and of alphabetic languages in general, which are read from left to right) usually extends from 3-4 spaces to the left of the fixation point to about 14-15 spaces to the right; this rightward asymmetry seems to be linked to the direction of reading (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). When the text is hard to read, the perceptual span tends to be smaller. However, the span actually needed to identify a word is narrower than the total perceptual span, and generally does not exceed 7-8 letter spaces to the right of the fixation point (Rayner, Well, Pollatsek, Bertera, 1982). Within this

“perceptual span”, two types of information are acquired. Firstly, readers are able to identify words in the area closest to the fixation point (this area is called the *fovea*). Secondly, beyond that region (*parafovea*), readers are able to obtain grosser information such as the initial letters of words, letter features, and word length. Saccades determine where the subject will look next in the text, and the fixation duration determines when the next movement is made.

Given that a number of studies today agree about the link between attention and oculomotor control, an important question that could be addressed in order to better understand the ability of the oculomotor system to program where the eyes land and move is: What cognitive processes are involved in eye-movement control? Both eye fixations and saccadic movements seem to be related to processes involved in attention and parafoveal/peripheral vision. The most straightforward control mechanism of saccade generation is visuo-spatial attention. The general idea here is that whatever captures our attention is foveated. This implies that attention is allocated to the target before the saccade is executed and in turn, that allocated attention is necessary for generating the saccade. Findings such as the *parafoveal-on-foveal effect* (e.g., Kennedy & Pynte, 2005) and *preview benefit* (e.g., Rayner, 2009) suggest that attention modulates the size of the region that is attended: spatial attention is not only restricted to the currently fixated word but can also be extended to the word located in the parafovea (Rayner, 1998).

Furthermore, attention seems to affect saccadic computation, that is, the positioning of the eyes land in a word. Although there is large variability, many studies have shown that readers of languages read from left to right tend to make their first fixation between the beginning and the middle of the word (e.g., O’Regan, 1981; O’Regan & Jacobs, 1992; McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Vitu, 1991; Li, Liu, & Rayner, 2011). This position was first called the *preferred viewing location* (PVL) by Rayner (1979). The PVL distribution curve is asymmetrical but only for character-based strings (like words and hashes), not

for continuous lines, as Ducrot and Pynte (2002) showed. This last result suggests that the landing position is determined by an eye-guiding mechanism that is based on a perceptual low-level preprocessing step that detects the presence or absence of spaces between characters. When the stimulus is discrete, the participant takes the direction of attentional scanning (left-to-right) into account, which results in asymmetrical landing-position pattern (Ducrot & Pynte, 2002). As Rayner and colleagues (2001) posit, the position to initially fixate in a word is probably the center of the word, which also appears to be largely influenced by low-level visual factors such as word length and how far the launch site is from the target word. Later, O'Regan and Lévy-Schoen (1987) distinguished between PVL and what it is now referred to as the *optimal viewing position (OVP)*. This position is considered to be “optimal” for word identification because it reduces the probability of refixation (*refixation OVP effect*) and thus shortens recognition time, but it seems to increase the total time spent fixating a word (*gaze duration OVP effect*) (Vitu, McConkie, Kerr, O'Regan, 2001). As for PVL, the OVP curve¹ is asymmetrical depending on reading habits and the characteristics of the language (suffixed or not). However OVP and PVL seem not to be related to the same mechanisms, that is, the OVP effect occurs only when the subject is processing a linguistic stimulus, so it can be used to assess the visual processing of words being read (but see Brysbaert, Vitu, Schroyens, 1996, and Nazir, 2000, 2003, for a different view). Finally, PVL is mainly tied to the properties of the oculomotor system, since this point is where first fixation will naturally land in discrete stimuli and it can therefore be used to evaluate visuo-attentional processing during reading.

Attention and Eye Movements in Children with Typical Reading Development

¹ Varying fixation location within a word generates an inverse J-shaped function for recognition accuracy as the fixation location moves from the first letter to the last letter of the word, with greater accuracy for fixation on the left part of the word (Farid & Grainger, 1996; Nazir, O'Regan, & Jacobs, 1991; O'Regan & Jacobs, 1992; O'Regan, Lévy-Schoen, Pynte, & Brugailière, 1984; Vitu, O'Regan, & Mittau, 1990).

It is well known that to learn to read, children must develop good linguistic skills such as phonological awareness, phonological decoding, and orthographic processing. These skills are assumed to longitudinally predict word-reading development, in different ways that depend on differences between languages and orthographies, (e.g. Goswami & Bryant, 1990; Snowling, 2000; 2006; Vellutino, Fletcher, Snowling, Scanlon, 2004; for a review, see also Kirby, Desrochers, Roth, & Lai, 2008). However, to successfully decode written words children also need to develop good visual skills. In particular, it has been suggested that underlying the sublexical reading strategy there is a mechanism of graphemic selection that is based on the automatization of visuo-attentional processes (e.g., Ruffino et al., 2010). That is, to read new words by applying grapheme-to-phoneme conversion rules, which is typical of the alphabetic stage, the child must be able to segment the fixated information. This means shifting from distributed attention to more focused attention. Rapid serial encoding enables normal grapheme/phoneme integration, that is, the ability to build a sublexical representation automatically. Rapid serial encoding treats letters as parts of a single object (the string) and allows for the formation of visual word forms. Moreover, to decode a word that is fixated in normal reading, the reader must be able to inhibit all surrounding letters and words. For such focusing operations, attentional processes must play an important role (Ducrot & Grainger, 2007). It is thus possible to hypothesize that if attentional or parafoveal/peripheral processes are deficient in some way, then reading will either not be optimal or not possible. More recently, Franceschini and colleagues (2012) even showed that visual-spatial attention in preschoolers was an important predictor of reading development. In particular, children who had poor reading skills during the first or second year of reading education had made significantly more errors on a visual-search task and a spatial-cueing task than normal readers had when they were in kindergarten. These findings raise an important question about the role of these skills in learning to read.

In line with these considerations, the *multiple trace memory model* for polysyllabic word reading hypothesizes analytical and global strategies in which a good capacity for selective attention is fundamental (e.g., Ans, Carbonel, & Valdois, 1998; Valdois, Carbonel, Juphard, Baciú, Ans, Peyrin, & Segebarth, 2006; Valdois, Bosse, & Tainturier, 2004). Moreover, the *SERIOR model* (Whitney, 2001, 2008) takes the bottom-up influence of attention on reading into account, describing how letter position is coded and extracted from the retinotopic representation until lexical access is achieved.

More specifically, what do eye movements tell us about saccadic programming skills in learning to read? Despite the many studies on skilled readers' eye movements, very little is known about children's eye-movement control during reading, and, about how it develops with age and typical or atypical reading development. Important findings show that the amount of information that can be extracted during a single eye fixation during reading is tightly linked to the development of reading ability. In support of this claim, Rayner (1986) found that when reading skill improves, the amount of information that can be extracted during a single fixation increases as well. Moreover, not only is the information extracted from the perceptual span already asymmetrical after one year of reading instruction, but the word-length span and the letter-feature span become equal to those of adults during the elementary years. More recently, it has been shown that children reading in a transparent orthography (Finnish) can develop their letter-identity span during middle school as well (Häikiö, Bertram, Hyönä, & Niemi, 2009). In addition, Blythe and colleagues (2009) demonstrated that the children's lesser performance in disappearing-text reading compared to adults is linked to sentence difficulty not to an age-related ability to capture visual information from the page. This ability is already well-acquired by the age of 7, which provides a good beginning for normal linguistic processing, and consequently, reading development. That is, 40-57 ms of

presentation is enough for children to extract the visual information needed to read six-letter word, like adults.

Focusing on saccadic computation, Ducrot and colleagues (2003) showed that during early reading acquisition there was an OVP effect in a word-identification task. Normal beginning readers exhibited the typical adult-like inverted *J*-shape curve by the end of the first year of reading instruction. More recently, these results were confirmed in two experiments where a classical Stroop paradigm was used (Perret & Ducrot, 2010). Children and adults obtained an OVP effect that impacted the Stroop effect: both interference and facilitation effects were reduced when the first fixation was located at the end of the word rather than at the OVP. Together, these results on children's eye-movement behavior suggest that visuo-attentional processes linked to reading become well-established during the early stages of formal instruction.

To conclude, visuo-attentional processes like saccadic computation (OVP and PVL) have not been deeply investigated in terms of development until now (but see Ducrot et al., submitted, for preliminary data). In particular, the establishment of the PVL, which seems to be due to an eye-guiding mechanism based on low-level perceptual processing could be also affected by reading-experience factors, which are strictly linked to instruction or reading exposure. Moreover, the development of reading-related oculomotor skills may also be affected by the presence of severe reading problems, such as *developmental dyslexia*. In the rest of this paper, we will focus on this issue, which constitutes a key topic of debate today.

Attention and Eye Movements in Children with Developmental Dyslexia

Do children with specific reading impairment have different eye-movement patterns than typical developing readers? And what do eye movements tell us about visual-attention deficits, which are often thought to be associated with developmental dyslexia?

In a traditional view based on an *IQ-discrepancy model*, developmental dyslexia is defined as a specific disability in learning to read and spell in spite of normal intelligence, adequate instruction, socio-cultural opportunity, and no sensory defects in vision or hearing (W.H.O., 1992). Many cognitive deficits are associated with dyslexia. In addition to poor reading skills, the core symptoms include weak phonological processing, spelling difficulties, and sloppy writing (Vellutino & Fletcher, 2005). Other symptoms, such as unstable visual perception, clumsiness, and distractibility have also been reported (Stein & Walsh, 1997). Dyslexia is also frequently associated with other learning disabilities, mainly language disabilities (Snowling, 2000; 2006) and attention deficits (e.g., Pennington, 2006). There is still considerable debate about the main causes of dyslexia (Ramus & Ahissar, 2012; see Vellutino et al., 2004, for a review). One of the most widely accepted explanations posits a core deficit at the phonological level of processing. In particular, the so-called phonological theory asserts that dyslexics have a specific impairment in the representation, storage, and/or retrieval of speech sounds that prevents the proper acquisition of the grapheme-phoneme correspondence necessary for learning to read in an alphabetic system. Researchers have different hypotheses as to the nature of phonological deficits, but no one questions the causal role of phonology in dyslexia (Ramus et al., 2003).

Despite phonological deficits, there is evidence indicating the presence of visual (e.g., Atkinson, 1991; Boden & Giaschi, 2007, for a review; Ramus, 2004; Ramus et al., 2003; Spinelli, De Luca, Judica, Zoccolotti, 2002; Stein, 2001; Stein & Walsh, 1997) and oculomotor deficits in dyslexics (e.g., Bucci, Brémond-Gignac, & Kapoula, 2008; Kapoula, Bucci, Ganem, Poncet, Daunys, & Brémond-Gignac, 2008). At the biological level, these visual deficits are attributed to a dysfunction of the magnocellular pathway (or M-stream), which is assumed to be involved in low-spatial-frequency processing and eye-movement control. Indeed, dyslexics often report visual impairments like “jumping letter”, “dancing line”, and blurred text (Shovman & Ahissar, 2006;

Stein & Walsh, 1997). Since Orton's (1925) study, many typical reading errors such as line skipping, letter reversal (i.e., reading "b" as "d"), and mirror writing have been seen as a manifestation of a basic deficit in visual processing.

Some studies have tried to enrich our knowledge about visual-motor behavior in dyslexic children. These studies have focused on very low-level oculomotor skills, without taking into account their interaction with higher processes such as linguistic ones. One of these studies showed that dyslexic readers had an abnormally longer latency for saccades and vergence (Bucci, Brémond-Gignac, & Kapoula, 2008). Moreover, the authors also showed that dyslexic children had poor binocular coordination of saccades and fixations when exploring paintings, suggesting an oculomotor deficit (Kapoula, Bucci, Ganem, Poncet, Daunys, & Brémond-Gignac, 2008). More recently the same results were also found when children were asked to read a text (Jainta & Kapoula, 2011). The authors suggested that these deficits are linked to immaturity of the oculomotor learning mechanisms via which oculomotor coordination and stable fixation are achieved. However, another study by the same research group was aimed at further investigating the speed and the accuracy characteristics of dyslexics' natural eye movements (saccades, vergence, and combined movements) in exploring space. These skills, which are assumed to be linked to the premotor and central circuits involved in the triggering of eye movements, were found to be as good as those of normal readers (Bucci, Vernet, Gerard, & Kapoula, 2009). As a whole, these studies suggest that eye movements of dyslexic readers may or may not differ from those of normal readers. Again, these controversial results could reflect the heterogeneity of the manifestations of dyslexia on one hand, or they could be interpreted as being due to the different types of materials or conditions (reading vs natural space exploration) used in the experiments. More generally, the presence of low-level visual deficits, and their link to developmental dyslexia, are controversial because only a low percentage of dyslexics seem to be characterized by these visual impairments

(from 0 to 25%, Ramus et al., 2003). Moreover, there is considerable debate in the literature about whether these deficits play a causal role in dyslexia or whether they reflect an underlying deficit in the processing of written words. Thus, some authors suggest that visual deficits are a consequence rather than a cause of reading difficulty (Shovman & Ahissar, 2006). Finally, no studies have shown that low-level processing develops more particularly during written-language acquisition, nor that this type of processing becomes more effective as expertise in reading increases. Furthermore, there is no evidence that specific training programs would succeed in improving the reading skills of dyslexics (e.g., Kavale & Mattson, 1983).

Unlike those presented above, many studies have highlighted the characteristics of dyslexics' eye movements that are specifically linked to reading. In general, compared to age-matched control readers, dyslexics' eye movements in word, pseudoword, or sentence reading are characterized by more and longer fixations, shorter saccades, and more regressions (Biscaldi, Gezeck, & Stuhr, 1998; Hawelka, Gagl, & Wimmer, 2010; Hutzler & Wimmer, 2004; McConkie, Zola, Grimes, Kerr, Bryant & Wolff, 1991; Rayner, 1986). Moreover, the eye movements of dyslexic readers show a smaller number of words that receive a single fixation or were skipped, an greater number of words with multiple fixations, a marked effect of word length on gaze duration, and prolonged gaze durations for singly-fixated words, thereby extending the results of other studies on regular orthographies (e.g., for Italian: De Luca, Di Pace, Judica, Spinelli, Zoccolotti, 1999; De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Zoccolotti, De Luca, Di Pace, Judica, Orlandi, & Spinelli, 1999; for German: Hawelka, Gagl, & Wimmer, 2010; Hutzler & Wimmer, 2004). Trying to make a link between the dual-route model (e.g., Coltheart et al., 2001) and the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006), authors have interpreted this pattern as a failure of orthographic whole-word recognition and as an inefficient lexical route followed by over-reliance on sublexical decoding (Hawelka et al., 2010). In other words, eye-movement recording during

reading might be very useful for identifying the strategy used by readers to decode words and for underlining the characteristics of abnormal reading patterns in children with developmental dyslexia. However, the nature of the link (specific or not) between atypical eye-movement patterns and dyslexia is still under debate. Firstly, a similar pattern has also been found in younger readers with the same reading level (Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986;). As we know, using a reading-level control group is fundamental when exploring the existence of a causal link between a deficit and the specific reading disorder. In line with this view, the absence of a difference between dyslexics and younger readers with the same reading level would mean that this pattern is not specific to dyslexia. Secondly, the same pattern has been found for adults reading a difficult passage (Henderson & Ferreira, 1990; Rayner, Slattery, & Bélanger, 2010). Thirdly, these atypical characteristics disappeared when the task was not reading (e.g., identification of letter sequences in a non-reading task; Hutzler et al., 2006).

Since it is known that eye movements during reading are fundamentally linked to visuo-attentional processes, a growing body of literature is now focusing on these skills in developmental dyslexia. Several studies have found defective visuo-attentional processes in dyslexics. Based on research showing that dyslexic readers are influenced more by crowding than are aged-matched controls (e.g., Atkinson, 1991; Spinelli et al., 2002), some studies have demonstrated that increasing inter-letter spacing or inter-word spacing improves the legibility of texts, especially for dyslexic children (Perea, Panadero, Moret-Tatay, & Gomez, 2012; Zorzi et al., 2012). This effect seems to be linked to dyslexics' abnormally good parafoveal processing during peripheral letter-identification tasks (Geiger, Lettvin, & Zagarra-Moran, 1992). However, there are dyslexics who seem to be more sensitive to visual crowding than normal readers and other dyslexics who are not (Bellocchi, Ducrot, & Bastien-Toniazzo, resubmitted). In particular, the first type of dyslexic is characterized by a moderate reading deficit; the second is greatly impaired compared to normal

readers. These results emphasize the importance of considering the heterogeneous performance of dyslexics.

In addition, Whitney and Cornelissen (2005) hypothesized that a visuo-attentional deficit impairs the encoding of spatial position during reading acquisition. Sluggish attention can have a detrimental effect on orthographic processing, and in particular, on the segmentation of letter strings into graphemes. The “sluggish attentional shifting” hypothesis is also supported (Hari & Renvall, 2001) by Facoetti and colleagues (2003), who showed that dyslexic children had auditory and visual selective-attention deficits in the automatic orienting and focusing of spatial attention (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000). It has been argued that these deficits impair the development of phonological representations, which are assumed to be the causal core deficit of dyslexia. They also suggest an asymmetrical allocation of attention to the right visual field in dyslexia, which has been interpreted as a left mini-neglect phenomenon (Facoetti et al., 2001). More recently, Facoetti and colleagues (2010) showed that preschoolers at familial risk for developmental dyslexia are impaired both in visual-spatial attention and syllabic segmentation tasks. In particular, the lack of a cueing effect at a short SOA² (i.e., 100 ms) means that these children exhibit a delayed time course in attention orienting. This study suggests that the combination of visual-spatial attention and phonological skills (i.e., syllabic segmentation) is more reliable than a single measure for identifying at-risk children.

A deficit of visual-attentional orienting in developmental dyslexia was also found by Valdois and colleagues (Ans et al., 1998; Bosse & Valdois, 2003; Valdois et al., 2004). Their explanation is based on the multiple-trace memory model for polysyllabic French word reading, which argues for a global or analytic mode of reading. Visual attention is needed to focus the “attentional window” on a subcomponent of the word in the analytic mode. Thus, a deficit in the

² stimulus onset asynchrony.

visual-attention process may impair word identification and the encoding of memory traces. Valdois and colleagues (2004) identified the visuo-attentional deficit as the causal core in a subgroup of dyslexics, independently of a magnocellular dysfunction. Furthermore, after selecting a group of dyslexics with a reduced visual attention span and exploring their eye movements, Prado and colleagues (2007) showed that this specific group, contrary to normal readers, could only process a few letters at each fixation and could not increase the number of letters processed in a reading task. This could suggest that a smaller visual-attention span prevents dyslexics from processing many letters simultaneously as normal readers do. The authors found no differences between this specific group of dyslexics and normal readers on non-reading tasks such as visual search. This last result suggests again that poor visuo-attentional abilities impair dyslexics' eye-movement patterns during (text) reading only.

Finally, as stated in the previous sections of this paper, saccadic computation is a remarkable source of information about the allocation of visual attention during reading or word identification. What happens when these skills are impaired? Is saccadic computation impaired in dyslexia? To the best of our knowledge, very few studies have been carried out to investigate saccadic computation (i.e. OVP and PVL effects) in dyslexic readers. Ducrot and colleagues (2003) found that dyslexic children showed differences in their patterns of viewing-position effects: even though they showed an OVP effect as normal readers do, dyslexics had a symmetrical curve. The absence of left-right asymmetry in the OVP curve suggests abnormal processing of information outside of foveal vision for dyslexics, as Geiger and colleagues (1992) found, and could thus reflect a deficit in visuo-attentional processing. It has been argued that dyslexics may have a narrow perceptual span (Aghababian & Nazir, 2000). Moreover, dyslexics' initial fixation position in word recognition is not "optimal" and positioning errors are more frequent, leading to more refixations than normal readers (Ducrot et al., in preparation; Hawelka et al., 2010).

In conclusion, all these studies on visuo-attentional processing have shown that difficulties in orienting, focusing, and shifting attention, as well as deficits in the visual-attention span and in saccadic computation, are linked to developmental dyslexia. As of now, all these skills have been investigated separately but it would be useful to find out whether or not these defective visuo-attentional processes occur together in dyslexia. Moreover, it would be worthwhile to examine whether these deficits are common to dyslexia and other associated developmental disorders. Topics on comorbidity in developmental dyslexia will be developed and discussed in the following section.

Discussion: Eye movements and Clinical Perspectives in Developmental Dyslexia

Developmental neuropsychology can be seen as the study of how brain-behavior relations develop in typical and atypical cases (Pennington, 2009). In this view the relationship between theoretical and clinical science is two-directional: it is known that we cannot understand clinical syndromes or atypical development without a theory of normal functioning; at the same time, clinical research results enrich and in some cases force revisions our interpretations of typical cognitive functioning. In our opinion, this is a crucial point for all developmental studies, and this approach is also fundamental in the case of developmental dyslexia.

As stated in the introduction, following Huestegge and colleagues' interesting overview (2009), different approaches and methods are used to study reading development: psychometric approach, single word approach, and oculomotor approach. In investigating and inferring ongoing cognitive processing during reading, eye-movement recording is considered the most informative approach. This approach has significantly improved our knowledge of reading impairment as well. In particular, what it is clear is that eye-movement patterns are strictly linked to the visuo-attentional processes specific to reading behavior.

From a clinical perspective, all of the studies presented above encourage us to address various questions regarding the definition of some clinical “eye-movement markers” specific to developmental dyslexia. Taking into account the studies presented in this paper, three types of eye-movement measures, can be considered: (1) characteristics of low-level visuo-motor control such as binocular coordination, saccades, vergence, and combined movements (e.g., Kapoula, Bucci, Ganem, Poncet, Daunys, & Brémond-Gignac, 2008; Jainta & Kapoula, 2011), (2) characteristics of “global” eye-movement measures such as number of fixations, gaze duration, refixation, and word skipping (e.g., De Luca et al., 1999; Hutzler et al., 2004; Hawelka et al., 2010), and (3) characteristics of “specific” eye-movement measures such as the OVP effect or the distribution of saccadic landing sites in children (e.g., Brysbaert et al., 1996; Ducrot et al., 2003, in preparation; Lehtimäki & Reilly, 2005). Among these measures, the last two are specifically linked to attention allocation during reading or word identification. In this line, eye-movement can be used to better describe the manifestation and heterogeneity of dyslexia.

Measurement of eye movements has been employed so far to study the neuropathology of childhood and adolescent psychiatric disorders. In particular, visually-guided saccades, antisaccades, memory-guided saccades, and smooth pursuit have been measured in a very large array of disorders such as attention deficit hyperactivity disorder (ADHD), oppositional defiant disorder, conduct disorder, autism spectrum disorders, childhood-onset schizophrenia, Tourette’s syndrome, obsessive-compulsive disorder, anxiety and depression (for comprehensive reviews, see Karatekin, 2007 and Rommelse, Van der Stigchel, and Sergeant, 2008). In general, these studies have focused on delineating oculomotor impairments in disorders, and making inferences about their neural bases. The regions involved in the control of eye movements, such as the frontal eye fields, the lateral intraparietal area, and the superior colliculus, are also strictly involved in covert

visual attention (e.g., Doré-Mazars, Pouget, & Beauvillian, 2004): this is fundamental evidence, once again, that eye movements are an excellent means of investigating attention.

Furthermore, eye-tracking studies reveal the extent to which impairments are specific to one disorder or are common across disorders. For example, there is evidence for abnormalities in scan patterns in both schizophrenia and pervasive developmental disorder but not in ADHD. Dyslexia is a complex and heterogeneous developmental disorder that is frequently associated with other neurodevelopmental disorders such as specific language impairment, ADHD, or developmental coordination disorder. It is known that comorbidity largely aggravates the symptoms and problems of children with a learning disability. While 26% of the ADHD population examined by Capano and colleagues (2008) exhibited comorbid reading problems, Vellutino and colleagues (2004) reported a comorbidity rate of attentional problems between 30% and 70% in dyslexic children, depending on the setting and how ADHD was defined. As we can see, attentional deficits are frequently associated with developmental dyslexia, so this must be taken into consideration in studies on the dyslexic population. For example, some differences in eye-movement patterns during single-word reading were found when a group of “pure” dyslexics was compared with another group characterized by comorbidity of dyslexia and attentional deficits (Thaler, Urton, Heine, Hawelka, Engl, & Jacobs, 2009). First of all, “pure” dyslexic children obtained high reading accuracy but severe reading fluency, which is the typical profile for transparent orthographies (i.e., German); in contrast dyslexic children with attentional deficits showed lower reading accuracy and milder-reading fluency impairment. Moreover, the former group of children made the highest number of fixations but exhibited shorter mean single fixations than the latter group did. Comorbid children reading strategy seemed to deviate less from normal readers with and without attentional problems. The attentional problems associated with dyslexia seem to have influenced the reading strategy, resulting in a higher error rate. In order to underline overlaps between dyslexia and other

learning disabilities, eye-movement recording could again be an excellent method. More studies directly comparing different learning disabilities would provide invaluable information on their specificities or commonalities and on the occurrence of oculomotor or visuo-attentional deficits in dyslexia.

Finally, in investigating the development of cognitive processes and disorders, one should take into account the neuroconstructivist framework (Karmiloff-Smith, 1992, 1998, 2007). According to this theory, the study of developmental disorders should be based on longitudinal studies from early childhood in which several assessment sessions are implemented, in order to identify such problems as early as possible (Goswami, 2003). This method allows researchers to investigate the causes of developmental disorders by considering the different developmental trends that can lead to different phenotypic outcomes. Indeed, this approach also highlights the importance of considering environmental factors likely to have different effects in terms of their nature and the moment at which they occur during development. These considerations are fundamental for prevention of learning disorders like developmental dyslexia. Early assessment affording an accurate indication of potential areas of difficulty constitutes a keypoint in the efforts of schools and clinical services to treat the specific problems faced by children with learning disabilities (Everatt, Smythe, Adams, & Ocampo, 2000). Specifically, objective assessment procedures and tools supporting these procedures are essential for identifying children at risk, and for planning educational programs. Early assessment and treatment for children at-risk for learning impairments can help identify learning disabilities and lessen their impact by keeping the achievement gap as narrow as possible. At the current time, most tools available to professionals are designed for the evaluation and remediation of child language problems, particularly difficulties related to the acquisition of meta-phonological skills (Frith, 1985; Goswami & Bryant, 1990). This approach relies on a unified view of dyslexia whereby all disorders specific to reading acquisition

are secondary to a phonological core deficit identified as a causal factor. As we have seen above, despite the evidence that all dyslexics suffer of a phonological deficit, an increasing number of studies today are showing that associated visuo-attentional deficits and atypical eye-movement patterns are present during reading, at least in a subgroup of developmental dyslexics (e.g., Bosse, Tainturier, & Valdois, 2007; Bosse & Valdois, 2009; Ducrot et al., 2003). Even if no consensus has yet been reached about whether these impairments are involved in the etiology of developmental dyslexia, they have to be taken into consideration in order to better understand the symptomatology of dyslexia and to plan remediation programs. It seems that it is even possible to train oculomotor control during reading. Lehtimäki and Reilly (2005) created an oculomotor reading aid for beginning readers (called the *OVP game*) which teaches readers to land their saccades at the OVP of each word. This device gives real-time feedback to the subject about his or her fixation position. The authors showed that the training has a slight effect on the landing-site distribution and a desirable effect on gaze duration, the mean number of fixations per word, and the distribution of the number of fixations per word. Concerning prevention, there is strong evidence suggesting that the problems children experience in learning to read during the elementary years and beyond are related to the preliteracy skills that they bring with them from preschool and kindergarten (e.g., Lonigan, 2006; Wagner, Torgesen, & Rashotte, 1994). In particular, the emphasis is placed more specifically on the need for additional studies to validate currently-available detection and diagnosis tools and techniques, in order to identify children at-risk for learning impairments at an early age. Of course, any decision regarding therapy for a given disorder must be preceded by a diagnostic stage, which itself requires accurate assessment of the symptoms and their severity.

In conclusion, based on these considerations, four main points could be considered for future research: (1) Identify visuo-attentional prerequisites to reading development, as they are highlighted

by oculomotor skills, by exploring normal readers' and pre-readers' abilities; this could be useful for early identification of children at-risk for reading disabilities. (2) Investigate oculomotor impairment in dyslexia in comparison with other developmental disorders, in order to define occurrences and overlaps. (3) Identify co-occurrences of visuo-attentional deficits and reading disorders, in order to identify the percentage of dyslexics with associated disabilities. (4) Develop specific tools for diagnosis and early identification, in order to identify precise cognitive dysfunctions and premorbid impairments for providing ad-hoc remediation by using the eye-movement recording method.

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