Eye movements in children during reading: a review

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Abstract: Over the last decades, the analysis of eye movements has proven very useful to investigate the cognitive processes underlying reading. However, from a developmental perspective, this technique has yet hardly been used to better understand the children's acquisition of reading. This chapter aims at presenting a review of the studies comparing the eye-movement patterns observed in children with those observed in adult readers. Firstly, it presents the differences and similarities in eye-movement patterns between those two groups, and then it proposes different attempts at explaining these differences in terms of oculomotor, visual and linguistic constraints.

Key words: Eye movements ; Children; Reading

Résumé : L'analyse des mouvements des yeux a été très largement utilisée ces dernières années en psychologie de la lecture pour mieux rendre compte des traitements cognitifs sous-jacents. Cependant, cette technique a été jusqu'à présent peu utilisée dans une perspective développementale, pour mieux comprendre les processus d'apprentissage et de la lecture chez les enfants. Ce chapitre présente une brève revue des études qui ont comparé les mouvements des yeux chez les enfants à ceux des adultes. Nous y décrivons dans un premier temps ce qui distingue les patterns oculaires de ces deux populations, et présentons ensuite les résultats d'études tentant d'expliquer ces différences en terme de contraintes oculomotrices, visuelles et linguistiques.

Mots-clés : Mouvements des yeux ; Enfants ; Lecture

Introduction

Reading is the remarkable ability to derive meaning from black marks on a white page. In to-day's world, profuse in printed stimuli, the ability to read is essential and determines one's ability to successfully achieve many of one's daily tasks. Depending on the speed at which one reads and understands these few lines, one may believe that it is a process quite easily acquired. In fact, the development of reading takes time and practice, and requires that a wide array of abilities, strategies and knowledge be coordinated (Cain, 2010). Some of these factors specifically pertain to linguistic competence, including letter knowledge, word knowledge (i.e. lexicon or mental dictionary of words), morphology (i.e. the form of words), grammar and syntax (i.e. the combination of words into sentences) and semantics (i.e. meaning). Broader cognitive processes also play a critical role in the processing of information during reading, such as attention, memory, or visual processing (for a review, see Dehaene, 2009).

In this sense, reading is essential in order to retrieve information from a textual material, and this skill relies on eye movements. When reading, the reader's eyes move across the page, allowing them to decode the written words. The assessment of eye-movements (EM) - a technique that has become widespread over the last thirty years - has become both a major advance and a valuable approach in the study and understanding of the reading process. The eye movement recording technique relies on lenses, infrared sensors and/or video images to provide the position and timing of eye fixations, with a high spatial and temporal accuracy. Based on this approach, a large body of data has been collected, providing excellent on-line indication of moment-to-moment cognitive processes during reading (for a review, see Rayner, 1998). It has been used for isolated words, sentences or texts, to better understand the mechanism accounting for *the place* where the eyes are fixated as well as those accounting for *the time* when the eyes are moved (for reviews, cf. Liversedge & Findlay, 2000; Radach & Kennedy, 2013; Rayner, 1998; 2009).

However, while EM recording has attracted considerable attention as a useful data source in skilled adult readers, very few researches conducted in children use this technique. Until fairly recently, EM recording was largely ignored in studies on the acquisition of reading, and more specifically on its impact on the retrieval and processing of visual information from a developmental perspective. Reading is first and foremost a visual task and the extraction of printed information facilitates word recognition. Consequently, to successfully decode written words, children also need to develop good visual skills.

The aim of this chapter is to provide a brief overview of the current knowledge on children's eye-movement during reading and to draw a comparison with the adults' (for a more detailed review, cf. Blythe & Joseph, 2011). We should also mention that our review only focuses on children with typical reading abilities. The topic of children with reading impairments would require a dedicated report (cf. Bellocchi, 2013; Bellocchi, Muneaux, Bastien-Toniazzo & Ducrot, 2013; Prado, Dubois, & Valdois, 2007,

for data on eye movements in children with developmental dyslexia). This chapter is divided into six sections, namely: basic characteristics of eye movements, preferred viewing location, information retrieval, perceptual span, length and frequency of words, effects and comprehension processes.

Basic characteristics of Eye movements

Reading is a complex process during which readers control their eye movements to adapt to incoming printed information. To that end, our eyes progress along the lines of text, performing saccades and fixations (Figure 1).
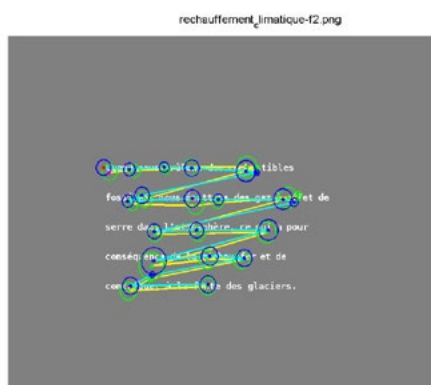

Figure 1. Example of a scanpath: a particular sequence of eye-movements. Both eyes are represented. The center of the circle is the place of fixation and its radius is proportional to the fixation duration.

Saccades are rapid eye movements, usually measured in degrees per second (from around 10 deg/sec for small microsaccades to over 300 deg/sec for large saccadic movements), which allow to direct the eyes from one location to another in the text. During reading, the average saccade size is about 8-9 character spaces (Cano-Tobías, Granados-Ramosb, & Alcaraz-Romeroc, 2014). While eyes make saccadic movements, motion is not perceived and no visual information is retrieved. This perceptual stability results from a reduction of visual sensitivity and is called "saccadic suppression". It allows for the perception of a stable environment (Bremmer, Kubischik, Hoffmann, & Krekelberg, 2009). It has been suggested that the number of saccades produced is correlated to understanding issues, meaning that words have to be read again (Rayner, Chace, Slattery, & Ashby, 2006). In most cases, saccades follow the word order, which means that the eyes move onto the next word, yet 15 to 25% of all saccades are regressions, which means that the eyes move further back in the text (Inhoff & Weger, 2005; Rayner & Pollatsek, 1989). Again, text difficulty and/or difficulties encountered by readers strongly influence(s) the number of regressions performed by the readers.

As the name implies, fixations are ocular activities consisting in setting one's eyes on a particular location, so that the desired word falls on the high-acuity area of the retina called the fovea (Kowler, 2011). In this way, during each successive fixation, visual information on the orthography of a word is retrieved, so that the word can be lexically identified to achieve sentence comprehension. In skilled

adult readers, the average duration of a fixation ranges from 200 to 300 msec. Fixation durations are highly valuable indicators of local processing difficulties. A reader refixates approximately 15% of the words in a text, which implies that they are subjected to additional fixations before the reader moves to another word. Refixations on a word mainly result from difficulties in cognitive processing occurring during the first fixation (Cutter, Drieghe, & Liversedge, 2015; Vergilino-Perez, Collins & Doré-Mazars, 2004), which in turn are often caused by a "wrong" starting position in a word, implying that the word needs two or more fixations to be processed (cf. below section Preferred Viewing Location). The refixation probability increases with word length and word frequency (cf. below section Length and Frequency words effects).

Compared to skilled adult readers, children typically make more sustained fixations, shorter saccades, with about 25% of their eye movements consisting of regressions, which accounts for their slower reading (Blythe & Joseph, 2011).

More particularly, a seminal study by Rayner (1986) reported the developmental changes in eye-movement patterns in children, showing that (Reichel et al., 2013):

- reading speed simultaneously increases with age, ranging from 95 words per minute (wpm) among 7–8-year-olds, to 210 wpm among 11–12-year-olds (vs. 290 wpm among adults)

- mean saccade length increases with age, ranging from 2.8 characters among 7–8-year-olds to 6.4 characters among11–12-year-olds (vs. 6.8 characters among adults)

- mean number of fixations per sentence decreases with age, ranging from approximately 15 among 7–8_year-olds to approximately 8 among 11–12-year-olds (vs. 6 among adults)

- mean fixation duration decreases with age, ranging from 280ms among 7–8-year-olds to 240ms among 11–12-year-olds (vs. 235ms among adults)

- mean number of regressions per sentence decreases with age, ranging from 4 among 7–8-year-olds to 2.5 among 11–12-year-olds (vs. 0.6 among adults).

Moreover, while skilled readers recognize the majority of words during one single fixation (Rayner & Pollatsek, 1989), beginning readers make multiple fixations on the same word (McConkie et al., 1991; Rayner, 1986). Besides, both the average number of fixations on a word and percentage of words subjected to multiple eye fixations decrease as reading skills improve (Aghababian & Nazir, 2000).

This developmental pattern has been independently replicated across different studies focusing on eye movements in children of various ages, educational backgrounds, languages, and using different protocols (Reichle et al., 2013, Blythe & Joseph, 2011). Accordingly, we will review in the next sections the few studies that have attempted to understand the reason for these differences existing between the children's eye-movement and the eye-movement of adult skilled readers during reading.

Preferred Viewing Location

The initial in-word "landing" position is the area initially fixated by the eyes after a first pass saccade, and is classically calculated as the initial letter position fixated divided by the total number of letters in the word (Dambacher, Slattery, Yang, Kliegl, & Rayner, 2013). Rayner (1979) labeled this first landing position as the *Preferred Viewing Location* (PVL). O'Regan and Lévy-Schoen (1987) distinguished between PVL, which represents the spot where the eyes actually land, and what is now referred to as the *Optimal Viewing Position* (OVP; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989), which represents the location in a word where performance should be optimal and in which the word recognition time is minimized (Li, Liu, & Rayner, 2011). More specifically, the time required to identify a word is shortest when the eyes initially fixate near the middle of the word. This is called the *Optimal Viewing Position* effect. This phenomenon is thought to result from a quick drop in visual acuity on either side of the foveal part of the retina, the center of the word thus becoming the position where most letters of the same word can be seen at a single glance (Vitu, McConkie, Kerr, & O'Regan, 2001). The OVP can be seen as the optimal position in terms of word perception, while the PVL represents the actual fixation location in sentence reading (Liu & Li, 2013).

In adult skilled readers of left-to-right reading languages, the PVL stands a little to the left of the center of the word, between the beginning and the middle of the word, and tends to be closer to the center in shorter words (e.g., McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan & Jacobs, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; Rayner, 1979; Vitu, 1991). Many studies have shown that with an initial fixation on this area, word identification improves, requiring less time, while the probability of refixation is reduced. Conversely, if readers initially land on the beginning or on the end of a word, they are more likely to refixate the word (cf., McConkie et al., 1989, for continuous reading; O'Regan et al., 1984, for isolated words).

Studies conducted on the eye landing position in children have shown little difference in the initial landing positions between children and adults (Figure 2), with both groups making their first fixation near the center of the word on average (Zang, Liang, Bai, Yan, & Liversedge, 2013, children between 8 and 9 years old vs. adults; Joseph, Liversedge, Blythe, White, & Rayner, 2009, children between 7 and 11 years old (mean age of 10 years and 4 months) vs. adults; Vitu et al., 2001, 12-year-old children vs. adults).
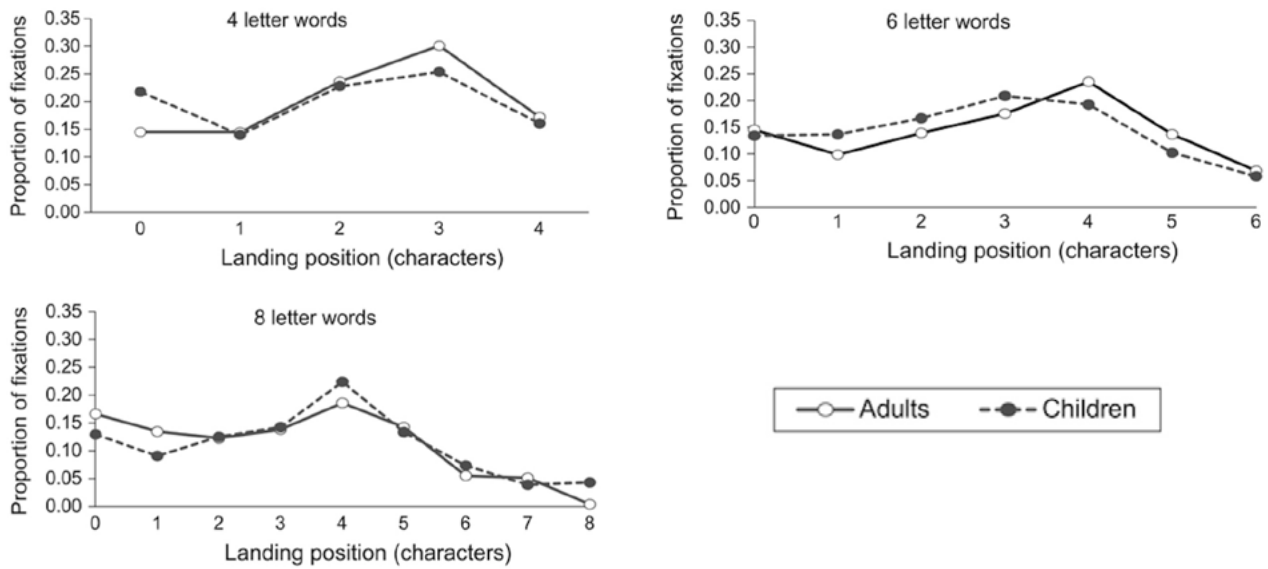
Figure 2.Extract from Blythe, Liversedge, Joseph, White, & Rayner (2009).Mean initial landing positions of adults and children on eight-(top panel), six- (middle panel) and four- (bottom panel) letter words.

Similarly, both children and adults are more likely to refixate a word if the initial fixation occurs away from the center of the word, presumably because their initial fixation does not allow them to retrieve the visual information necessary to complete lexical identification (Blythe & Joseph, 2011). When refixating words, the eyes of adults yet systematically target parts of the word that are remote from the location of the initial fixation, whereas children's refixations aim at a smaller area, resulting in shorter saccades. Similar results were recently observed in children and adults reading Chinese (Zang et al., 2013), with differential effects of landing position for single and multiple fixation situations in both groups: for single fixations, there were clear preferred viewing location effects (i.e. closer to the beginning/center of the word), which occurred further into the word among adults compared with children, in multiple fixation situations. Adults targeted refixations contingent on initial landing positions to a greater degree than children did.

In a nutshell, at the end of the 1st year of reading instruction, we observe atypical variation in recognition performance depending on where readers set their eyes in the word. During reading, this spot influences eye-movement patterns. This is an early and strong phenomenon in reading.

Information Retrieval

The time course of information retrieval on each fixation may account for the differences in eye-movement between children and adults, since the extent of possible cognitive control in reading is dependent on the speed of information retrieval. To investigate this issue, the *disappearing text* paradigm has been used (Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003). In this paradigm, whenever the reader fixates a word, a timer is set to countdown to a predetermined time (typically 60 msec). Once the specified time has elapsed, the word disappears. As the

reader moves his eyes to fixate the next word of a sentence, the previously fixated word reappears, while the newly fixated word disappears after the specified period, and so on (Figure 3). In this way, the reader's opportunity to visually process the fixated word is time-limited.

Figure 3. Extract from Rayner et al. (2003). Example of a disappearing text.* indicates the fixation location. In this example, when the reader fixates the word "church", it stays visible for 60ms. Then it disappears until the reader makes a fixation on a new word, here the word "underwent".

In the case of skilled adult readers, the collection of visual information occurs extremely quickly. The reading process is normal with no detrimental effect on comprehension for periods comprised between 50 and 60ms. This does not mean that words are completely processed in 50-60ms, but rather that this lapse of time is sufficient for the processing system to encode the word (Rayner, 2009).

In general, children find the *disappearing text* paradigm more difficult than normal reading conditions, although the effects on their EM are relatively small. More specifically, the manipulation of the disappearing text had hardly any impact on the eye-movement behavior of readers aged 7 years and older (Blythe, Häikiö, Bertam, Liversedge, & Hyönä, 2011, 8 to 9 years old children vs. 10 to 11 years old children vs. adults; Blythe et al., 2009, 7-11 years old children vs. adults in experiment 1, 7-9 years old children vs. 10-11 years old children vs. adults in experiment 2), regardless of the tested presentation durations (40ms, 60ms, 80ms, 120ms). In global measures, such as sentence-reading times, children were able to read the disappearing text without showing signs of disruption to their cognitive processing, thus exhibiting data patterns that were similar to skilled adult readers' (Blythe, 2014). Those results seem to indicate that children retrieve basic visual information from the text nearly as quickly as adults, suggesting that differences in EM patterns between children and adults are induced by spatial limitations rather than temporal ones.

Perceptual Span

There is a great deal of evidence indicating that readers do not process only the fixated word (Rayner, 1998), but also that visual processing is spatially limited. The area of text from which the information is processed during a fixation is called the perceptual span (McConkie & Rayner, 1975). To assess the size of this perceptual span, or in other words how much useful information a reader can retrieve during eye movements, the *gaze-contingent moving window* paradigm has been used (for a review, cf. Rayner, 2014). This technique consists in experimentally defining a window framing the

actual fixation point and somehow "maiming" the text outside this window, generally by replacing the letters by "x" or random letters. The window moves in synchrony with the reader's eyes as they progress along the sentence, exposing a new textual area. The pace at which these changes occur is fast enough for the reader to phenomenologically experience the synchronous movement of the window with their eye movements (Figure 4). The underlying idea of this paradigm is the following: when the window is large enough for readers to acquire all the information that they would typically retrieve from a fixation, the window size will not differ from a normal reading situation; conversely, when the window becomes smaller than the perceptual span, reading will be disrupted (Rayner, Abbott, & Plummer, 2015). The size of the window for which the reading speed is equal to the reading speed under standard reading conditions determines the perceptual span.

Window size	Sentence
No window	He visits a new country each year on vacation.
4L/14R window	—————————-ew country each yea—————————
4L/10R window	—————————-ew country each —————————-
4L/6R window	—————————-ew country —————————
4L/2R window	—————————-ew coun—————————

Figure 4. Extract from Whitford, O'Driscoll, Pack, Joober, Malla, &Titone (2013).Example of a gaze-contingent moving window paradigm. * indicates the fixation location. L corresponds to the number of characters to the left of the fixation. R corresponds to the number of characters to the right.

The size of the perceptual span is also relevant in the *gaze-contingent boundary* paradigm (Rayner, 1975), especially to examine the nature of the information retrieved from a parafoveal word before it is fixated (McConkie & Rayner, 1975; Rayner, 1975). This technique consists in placing an invisible boundary in front of the target location and replacing the preview letter string with the correct target word during the first saccade that crosses the boundary. The visibility of a parafoveal word N+1 during fixations on pre-target words N is thus under experimental control and displayed only after the readers' eyes cross an invisible boundary located between words N and N+1.Two conditions are usually tested: a correct-preview condition, in which the preview and the target are identical, and a no-preview condition, in which the preview does not contain any of the features of the target word (Blythe, 2014). Preview benefit is indicated by a difference between fixation durations on target word N+1 when the preview is available during the previous fixation vs. when the preview is denied (Yan, Pan, Laubroch, Kliegl, & Shu, 2013).
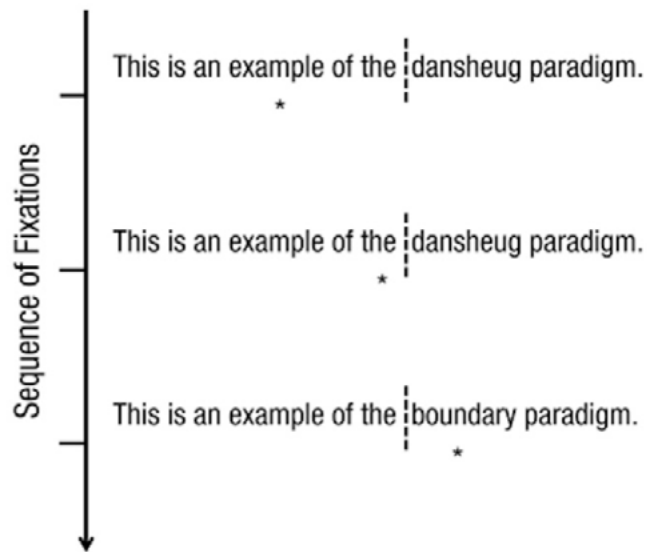
Figure 5. Extract from Blythe (2014).Example of a gaze-contingent boundary paradigm. * indicates the fixation location. The vertical line represents the invisible boundary.

For normal skilled adult readers, the perceptual span is asymmetric about the point of fixation, extending from 3-4 letters to the left to approximately 14-15 letters to the right of the fixation point (in English and other left-to-right reading alphabetic languages; McConkie & Rayner, 1976). This asymmetry gives the opportunity to pre-process information from the right of the fixation point and reflects the shift in attention to upcoming words, for the programming of an eye-movement necessarily results in covert attention shifting to the saccade target (Deubel & Schneider, 1996). The asymmetry and extent of the perceptual span are not constant.They depend on various factors, including textual (Apel, Henderson, & Ferreira, 2012; Henderson & Ferreira, 1990; Rayner, 1986) and individual (Ashby, Yang, Evans, & Rayner, 2012; Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986; Rayner, Slattery, & Bélanger, 2010; Veldre & Andrews, 2014) properties. Readers dynamically adjust the size of their perceptual spans, and it is well known that difficulty reduces the perceptual span, because foveal processing then requires more resources, thereby reducing the amount of information retrieved from the right of the fixation point. The perceptual span is also related to the written characteristics of the language that is read. For example, the perceptual span of Israeli or Urdu readers is asymmetric to the left because the reading direction of these languages is leftwards (Paterson et al., 2014; Pollatsek, Bolozky, Well, & Rayner, 1981).

Studies using the *boundary paradigm* with children (Häikiö, Bertram & Hyönä, 2010 in Finnish; Marx, Hawelka, Schuster, & Hutzler, 2015, in German; and Tiffin-Richards & Schroeder, 2015, in German) showed preview benefit effects for children. Recently, Pagán, Blythe and Liversedge (2016) investigated parafoveal preprocessing of letter identity and position information in a word's initial trigram during silent sentence reading, both in children and adults. Results show that adults and children (mean age 9 years old) alike were able to preprocess information regarding the identities of letters within the initial trigram of the parafoveal word. As for adults, reading was equally disrupted, re-

gardless of the participant's age, when the availability of information to the right of the fixation point was restricted, indicating that their perceptual span is asymmetric to the right of the fixation point, as is the case for skilled readers. Apparently, 1 year of reading experience allows beginning readers to direct much of their attention to the right of the fixation point. Moreover, the window size which allowed for maximum reading speed was smaller in the case of more difficult sentences (Henderson & Ferreira, 1990).

Besides these similarities, some differences were also found between adult and children readers. Rayner (1986) compared children in late second, fourth, and sixth grades with adult skilled readers as they read sentences in the moving window paradigm. He found that younger readers did have a slightly smaller perceptual span than skilled readers, the span of younger readers extending about 11 character spaces to the right of the fixation points versus approximately 15 spaces for skilled readers. Häikiö, Bertram, Hyönä, and Niemi (2009) replicated this result, examining the span for letter identity in children aged 8, 10, and 12, as well as in adults reading Finnish. They have shown that by age 12, children's letter identity span extends as far as the adult's. They have also found that the number of letters that could be identified during a fixation (the letter identity span) was smaller for slower (for all ages included in their sample) than for faster readers. Thus, 7 to 9-year-old children were found to have a perceptual span of 3 to 4 letter spaces to the left of the fixation point and 11 letters to the right; while the span was 3 to 4 letters spaces to the left and 14 letters to the right of the fixation point in 11-year-old children (see also Sperlich, Schad & Laubrock, 2015).

In summary, despite the fact that children have a shorter perceptual span than adults, they do preprocess information from the word to the right of the fixation point. Presumably because of a lower cognitive processing efficiency, beginning readers need to focus more on the fixated word than skilled readers and use the parafoveal and peripheral information less efficiently. The perceptual span increases with age as the result of the reader's increasing skill, with the processing difficulty consequently decreasing when reading (Pagán et al., 2016). It appears that the span is limited by cognitive rather than perceptual factors.

Word Length and Frequency Effects

As seen before, the eye-movement pattern in skilled adult readers depends on the characteristics of the text, and two very strong effects have been observed in the adult eye-movement literature: the word length and word frequency effects. Word frequency and word length strongly impact word skipping and fixation durations (Rayner, Slattery, Drieghe, & Liversedge, 2011). Although 75-85% of words are typically fixated at least once (Brysbaert, Drieghe, & Vitu, 2005), words that are short in length, occur frequently in the printed text, are acquired at an early age, and/or are predictable in particular sentence contexts are sometimes skipped altogether, while words that are long, infrequent, acquired late, and/or are unpredictable are often fixated more than once (Rayner, 1998, 2009; Reichle et al., 2013). Moreover, reading words that consist of 2 or 3 graphemes usually takes only one fixation, while

words comprising 4 to 12 graphemes may require more fixations (Rayner, 1998). As a consequence, the number of fixations is greater in nouns, adjectives and verbs than in conjunctions, pronouns and prepositions, due to the type and length of these grammatical categories (Cano-Tobías et al., 2014). Likewise, frequent words are often read within a single and shorter fixation, certainly because the recurrent presentation of words and common sentences allows for a faster identification, while the processing operations required to grasp the meaning of a word become more rapid and accurate (Reichle et al., 2013).

To our knowledge, very few studies have tried out word length and/or frequency to investigate whether these strong effects observed in adult readers are also present in children (Blythe et al., 2006, with 7-11 years old children vs. adults; Blythe et al., 2009, with 7-11 years old in their first experiment and 7-9 years old vs. 10-11 years old in their second experiment; Hyönä & Olson, 1995, with 10.5 years old; Huestegge, Radach, Corbic, & Huestegge, 2009, 8 years old vs. 10 years old; Joseph et al., 2009, with 7 years old vs. 11 years old vs. adults; Joseph, Nation, & Liversedge, 2013, 8-9 years old vs. adults; Luke, Henderson, & Ferreira, 2015, adolescents aged between 11 and 13 years old; and Tiffin-Richard & Schroeder, 2015, 7.8 years old / 2nd grade vs. adults; Vorstius, Radach, & Lonigan, 2014, 632 children in grades 1–5). Concerning word length, an overview of the results shows that children display the same eye-movement pattern as adults, although these effects are more significant in children than adult readers. Therefore, this data suggests that younger readers need additional processing time on long words compared to older readers, and that this need decreases with age (Joseph et al., 2009). The studies on the influence of frequency on children's eye movements are somewhat inconsistent. Blythe et al. (2006) found no influence of word frequency on children's fixations, whereas the first experiment of Blythe et al. (2009) showed significant effects of word frequency on first fixation durations and gaze durations, while their second experiment revealed significant effects on both these measures and on single fixation durations. Hyönä and Olson (1995) observed that low-frequency words were subjected to more fixations and regressions than high-frequency words. In the study conducted by Huestegge et al. (2009), no effect of frequency was observed on the initial fixation durations, but gaze durations were significantly affected as well as the total reading time, including revisiting fixations (i.e. longer in infrequent words). Joseph et al. (2013) clearly observed effects of frequency on gaze durations and total reading times in 8-year-old children, as well as Vorstius et al. (2014) who found that fixation durations were affected by word frequency, resulting in longer fixation durations on low-frequency words.

Various methodological reasons can explain the relative inconsistency of these results, namely the way the frequency of the words is established (i.e. from an adult and/or children corpus), the control of the Age-of-Acquisition (i.e., the age at which a word was first acquired in childhood) or lack thereof and/or some of the other variables (e.g., familiarity, concreteness, number of morphemes) known to affect fixation durations. Breaking away from the previous studies, Tiffin-Richard and Schroeder (2015) have used age-relevant word frequencies for children and found significant effects of word length and frequency both in children and adults, with generally greater effects in children. Moreover,

the interaction between word length and word frequency significantly impacted the gaze duration and eye-movement measures throughout the total viewing time in children, but not in adults.

While further investigations are necessary, these results tend to suggest that eye-movement behavior for low-frequency and long words are not the same in children and adult skilled readers, leading to stronger effects in children. This demonstrates that the linguistic characteristics of a text drive the children's eye movements as they read, and that children have already developed lexicons according to the number of times they have encountered a word, even if lexical access is slower in children than in adults (Joseph et al., 2013).

Comprehension processes

Finally, data on eye movement is highly relevant to assess the processes of on-line comprehension. In adult skilled readers, the processing of ambiguous sentences, inconsistencies or impossible events result in longer fixation and refixation times on target words (i.e. ambiguous, inconsistency or impossible word), and in a higher probability of making a regressive eye movement (cf. for example Rayner, Chace, Slattery, & Ashby, 2006; Warren, McConnell, & Rayner, 2008). Adult skilled readers are able to derive the meaning of a sentence or a text from both the information inherent to the meanings of words and their knowledge of the real world.

Joseph, Liversedge, Blythe, White, Gathercole, and Rayner (2009) investigated the eye-movement behavior of children aged 7 to 12 in the context of the reading of sentences containing semantic improbabilities and anomalies, before comparing it with the adults'. During first pass, both groups would show consistent and substantial differences in the reading time of anomalous and control sentences. Joseph and Liversedge (2013) conducted two experiments on the adults' and children's processing of syntactic ambiguities during reading (children 6.5 - 11.7 years old (mean age 9 years old) vs. adults in experiment 1; 6.5-9 years old (mean age 7.9 years old) vs. 9.5-11.7 years old (mean age 10.4 years old) vs. adults in experiment 2). Results showed that children took a little longer than adults to detect and respond to syntactic misanalysis in both experiments. Finally, Engelhardt (2014) investigated sentence processing in children and adolescents (between the ages of 9 and 16 years old -mean age 13.58 years old) in garden path sentences containing a temporary syntactic ambiguity. He found out that older participants were more likely to make regressions to the disambiguating verb and had a greater tendency to correctly answer comprehension questions.

As a whole, while there is little difference in anomaly detection between children and adults, children - and especially younger children - tend to show longer-lasting effects of a greater magnitude. It seems that children and adults possess a similar underlying processing mechanism for syntax analysis, which yet operates on a slower time course. This data suggests that there are similarities between children and adults in terms of basic thematic assignment processes implemented during reading, or in other words that they equally process the role that a noun phrase plays with regards to the

action or state described by the verb of a sentence. However, they differ in their ability to integrate pragmatic and real-world knowledge into the discourse representation.

Conclusion

As there is currently little research on the eye movements of beginning readers, it is difficult to draw any firm conclusion. Altogether, data collected shows that: by the age of 7 years old, children accurately target their saccades close to the center of the word, just like adults; the speed at which visual information is encoded during reading is similar to the adults'; the characteristic left-right asymmetry of the perceptual span (for left-to-right reading alphabetic languages) is developed by the age of 7; the spatial extent of the perceptual span increases with development, up to 11 years old and is related to the reading skill (Liversedge, Gilchrist, & Everling, 2011). In this way, while the spatial aspects of information encoding continue to develop up to 11 years old, the initial point of fixation of children and the speed at which a word is visually encoded are developed just a few years after the beginning of a formal reading instruction, maybe even before (Blythe & Joseph, 2011). Moreover, some characteristics of the material being read have a greater impact on the eye movements of children than on the adults'. In particular, greater word length and frequency effects were found in children than in adults. Children and adults present similarities in their ability to derive the meaning of a sentence from pragmatic information and lexical representation, although they showed differences in terms of the efficiency of this process. These findings are consistent with the idea that lexical processing is slower in children than in adults. Recently, Luke et al. (2015) showed that children with more detailed lexical representations presented more efficient eye movements, and analyses of eye movements during reading revealed a significant influence of lexical richness on a variety of reading behaviors, such as gaze durations and word refixations. These changes are also consistent across the different languages (e.g., English, German, Finnish…) and education systems that have been examined, often despite non-trivial differences in both (e.g., English words on average contain fewer letters and have less transparent grapheme-to-phoneme correspondences than Finnish words; Reichle et al., 2013; Seymour, Aro, & Erskine, 2003).

A number of methodological and theoretical challenges need to be taken into account in future researches. One of the reasons for the small number of studies on eye movements in children relies on the difficulty to record accurate eye movements in children, which requires the participant to sit still, often for prolonged periods of time. This is even more difficult with children than with adult participants. However, with the improvement of eye-tracking technologies, EM measurement will be more accurate and easier to obtain, from larger samples of children across a broader age spectrum.

Another difficulty that should be taken into account is the construction of the linguistic material, an issue that we have already pointed out regarding the words frequency. Indeed, in some studies, researchers have used different materials for readers of different ages, in order to adapt the reading difficulty to each group. In contrast, in other studies, they have presented the same linguistic mate-

rial to children and adults alike, in order to avoid differences in material as a confounding variable between groups. This implies that the stimuli were very easy to read for the adult participants. Regardless of the method, the benefits and limitations must be taken into account in the analysis and interpretation of the results.

A third methodological issue is the setting up of the different age groups. Most of the time, groups are split by age. But we know that children of the same age vary in terms of reading ability and several studies have shown that variability in the children's eye movement data is much greater than in the adults' (Joseph et al., 2008). Currently, the different age groups constituted can gather children with different reading skills within a same age group. In future researches, it would be more accurate to establish the groups based on the reading abilities.

To this day, with the exception of the study conducted by Huestegge et al. (2009), only cross-sectional eye movement studies on reading development are available. However, that longitudinal design could facilitate the understanding of the way both chronological age and reading skill might contribute to the development of eye-movement behavior during reading.

Finally, while we may believe that eye movement research on children's reading will keep on flourishing like the past few years, eye-movement records do not clearly show what the reader is thinking or trying to do at any time. A future challenge in the use of eye movements is to interpret the meaning of fixations, to determine whether a fixation represents a superficial or deeper processing. The Eye-Fixation-Related potential technique, consisting in the joint recording and analysis of eye-movement and EEG data, seems to be a good answer to this limitation (cf. for example Frey, Ionescu, Lemaire, López-Orozco, Baccino & Guérin-Dugué, 2013). This recent approach consisting in segmenting brain activity based on eye-movement behavior presents various major advantages. As previously emphasized, one of these advantages is that the eye-movement system is closely related to cognitive functions such as perception, attention and memory. The segmentation based on eye movement therefore offers a great opportunity to study brain activity in relation to these processes, EM constituting a natural marker to segment the ongoing brain activity (Nikolaev, Pannasch, Ito, & Belopolsky, 2014). This technique allows to directly associate brain activity with the properties of the current fixation, and to better understand how each piece of information on a fixation is integrated into the information from previous and subsequent fixations. Moreover, co-registration enables naturalistic conditions of reading, involving continued exploration (*free viewing*). Co-registration is thus a very useful approach to study the EEG and EM involved in complex reading behavior. Eye-Fixation-Related technique also has the main advantage to allow for the investigation of aspects of the reading process that are difficult or impossible to study through serial visual presentation (SVP), as traditionally used in EEG research in reading. ERP studies using these RSVP methods have provided some insight into word processing, but these paradigms are non-ecological and too remote from natural reading conditions. For example, they are not able to address reading speed differences between individuals (Ditman, Holcomb, & Kuperberg, 2007) and it has been shown that different presentation rates (e.g., linked to the number of characters) may induce a bias towards the engagement of different cogni-

tive processes (Camblin, Ledoux, Boudewyn, Gordon, & Swaad, 2007). Also, they cannot be used to investigate the role of para-foveal perception during reading. The timing and extent to which upcoming words are preprocessed is still controversial and can be studied in greater detail with EFRPs (Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011). For the time being, this technique is faced with specific methodological challenges, particularly due to effects of overlap between EEG responses elicited by successive fixations, that can interfere with effects resulting from experimental conditions. However, as more and more solutions are now proposed (Devillez, Guyader, & Guérin-Dugué, 2015; Nikolaev, Meghanathan, & van Leeuwen, 2016), we hope that this technique will shed new light on the issue of the development of reading skill, to better understand how both linguistic processing and eye-movement control change with development.

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