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Developmental eye-tracking research in reading: Introduction to the special issue

Sascha Schroeder[1], Jukka Hyönä[2], and Simon P. Liversedge[3]

[1]Max Planck Institute for Human Development, MPRG Reading Education and Development (REaD), Berlin, Germany
[2]Department of Psychology, University of Turku, Turku, Finland
[3]Centre for Visual Cognition, University of Southampton, Southampton, UK

Extending our understanding of the interplay between visual and cognitive processes during reading is essential to understand how reading develops and changes across the lifespan. Monitoring readers' eye movements provides a fine-grained online protocol of the reading process as it evolves over time, but until recently eye movements have rarely been collected for young developing and ageing people. Developmental eye-tracking constitutes an emerging and innovative field that addresses various theoretical questions related to changes in the process of reading across the lifespan and the mechanisms that drive intra-individual trajectories and create inter-individual differences among readers. The aim of this editorial is to briefly summarise the current state of the field and to outline which questions are currently being investigated and presented in this Special Issue.

Keywords: Development; Eye-tracking; Reading.

Normal reading development is vital for leading a successful life in a modern society. There is a substantial body of research on reading development and reading disabilities using offline measures such as word reading or text comprehension (see Joshi & Aaron, 2006, for a review). However, studies investigating the development of reading skills using online measures are still rather rare. Nevertheless, detailed knowledge of the cognitive mechanisms involved in reading is necessary to understand how the reading process changes during reading development and across the lifespan.

Reading is a complex psychological process in which the visual and the linguistic systems interact with each other (see Liversedge, Gilchrist, & Everling, 2011, for an overview). Extending our understanding of the interplay between visual and cognitive processes is, therefore, essential to understand how children learn to read. Eye movements, which have proven invaluable for understanding the cognitive processes of adult readers (see Rayner, 2009, for a review), have until recently rarely been collected for young developing readers or ageing people. This is very surprising because developmental aspects of eye movement behaviour were historically one of the first areas to have been investigated using this method (Buswell, 1922; Taylor, 1965). Monitoring readers' eye movements provides an extremely accurate and fine-grained online protocol of the reading process as it evolves over time (e.g., how much time the reader needs to encode a word before she is ready to move to encode the subsequent word; see Liversedge & Findlay,

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2000; Rayner, 1998). Thus, it is an excellent tool to help us to understand how comprehension during reading takes place via interactions between visual and language processing systems and how these interactions change over the lifespan.

One reason for the scarcity of eye movement studies assessing reading performance in populations other than college-age participants is technical in nature: Even in adults eye-tracking can be a challenging method. Researchers working with special populations such as children or older adults face additional problems (such as lack of concentration or calibration problems due to glasses). Over the last two decades, eye movement recording systems have been developed that make it feasible to collect high-quality recordings from school-age children or older adults. As a consequence, in recent years an increasing number of researchers have started to make significant contributions to the current understanding of eye movement control in children's reading development and reading decline in older adults. Nevertheless, such studies are still quite rare and scattered across different languages and scientific disciplines (psychology, linguistics, education, and developmental science).

Given the current state of affairs, there is increasing interest in broadening the scope of research to investigate inter- and intra-individual differences in eye movements and to bridge the gap between developmental and educational applications. This interest is documented in book chapters (e.g., Blythe & Joseph, 2011), opinion articles (e.g., Blythe, 2014), as well as in a recent special issue focusing on eye movement studies with children (Miller & O'Donnell, 2013). Similarly, there is now a substantial number of eye-tracking studies investigating reading processes in older adults using various manipulations and paradigms (e.g., Risse & Kliegl, 2011; McGowan, White, Jordan, & Paterson, 2014; Rayner, Yang, Castelhano, & Liversedge, 2011), and a solid and reliable knowledge base on their foveal and parafoveal reading behaviour is now available (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006, for reviews). Developmental eye-tracking thus constitutes an emerging and innovative field of research that addresses various theoretical questions concerning age-related changes in the process of reading. However, although the basic aspects of eye movement behaviour during reading development are well established, we still lack a theoretical understanding of the factors that drive developmental changes. Present research efforts reported in this Special Issue aim at investigating these mechanisms and their consequences for the observed changes in reading skill across the lifespan.

The Special Issue is based on the contributions presented at the symposium "Developmental Eye-Tracking Research in Reading" which was held October 23–26, 2013 in Hannover, Germany. It was generously funded by the VW Foundation and represented an opportunity to bring together many of the world's leading eye movement researchers from a number of international groups working on developmental questions. During the meeting, these researchers presented their latest experimental findings and discussed theoretical and methodological challenges associated with developmental eye-tracking studies. Contributions covered various theoretical issues as well as methodological and technological questions. The aim of this editorial is to briefly summarise the present state of the field and outline outstanding questions currently being investigated and also presented in the Special Issue.

DEVELOPMENTAL ASPECTS OF EYE MOVEMENTS IN READING: WHAT WE KNOW

In recent years, a growing body of studies has accumulated which describes the basic development of readers' oculomotor behaviour and lexical and post-lexical processing across the lifespan. The literature on children's eye movements during reading has recently been reviewed elsewhere (Blythe & Joseph, 2011; Reichle et al., 2013). However, it might be helpful to summarise some of the established findings in order to provide a context for the questions that are addressed in the studies published in the Special Issue. In addition, we think that it is interesting to relate some of the results that have been found in children to those observed for older adults, in order to more clearly establish similarities and differences in their eye movement behaviours.

Generally, it is well known that children read more slowly than adults; they tend to make shorter saccades, fixate and refixate words more frequently and for a longer time, and show higher regression probabilities, but lower word skipping rates (Buswell, 1922; Rayner, 1986; Taylor, 1965). This pattern of eye movement behaviour has been observed very consistently, with different types of

materials, and is rather typical for developing readers. Similarly, older (65+ years) readers typically make more and longer fixations (and, as a consequence, show longer reading times than young adults), but in contrast to developing readers, in alphabetic languages they make longer saccades and skip words more often than young adults (Kliegl et al., 2004; Rayner et al., 2006). Thus, there are some similarities, but also some marked differences between the eye movements of children, younger adults and older adults.

With regard to basic oculomotor processes and the decision of where to move their eyes, children's and adults' eye movement behaviour seems quite similar: Even young children with minimal reading experience target their saccades towards the word centre and show a similar pattern of initial landing positions in words as a function of word length as adults (Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie et al., 1991). At present, it is unclear whether children are able to target refixations on words as effectively as adults (see Vitu, McConkie, Kerr, & O'Regan, 2001; though see also Joseph et al., 2009). Children are also not slower than adults in their rate of visual processing. Using the disappearing text paradigm (Blythe, Liversedge, Joseph, White, & Rayner, 2009; see also Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2010; Rayner, Liversedge, White, & Vergilino-Perez, 2003) has shown that beginning readers did not differ from adult readers in how long a word needed to be physically present in order for successful encoding to occur. Similarly to adults, children as young as 7 years old required only approx. a 60-ms exposure time in order to extract visual information necessary for linguistic processing. Similar results have been observed in older adults (Rayner et al., 2011); that is to say, they did not need more time for visual processing than young adults. Children also show striking similarities to adults in binocular coordination, although there are also some differences (Blythe et al., 2006; see Kirkby, Webster, Blythe, & Liversedge, 2008, for a review). Taken together, children and adults behave very similarly with respect to where to move the eyes in text and how the encoding of visual information takes place. Thus, the basic mechanisms of eye movement control seem to be well established in young children, though note that the visual-attentional system does still undergo substantial maturational change during childhood and adolescence.

Parafoveal processing of text information (i.e., processing of a word that occurs prior to it being fixated) is a hallmark of skilled adult reading (Rayner, 1975). Yet, it has been shown that also children are capable of parafoveal word processing. Moreover, even beginning readers have asymmetrical perceptual spans that are more extended to the right (in orthographies read from left to right). Using the moving-window paradigm, Rayner (1986) showed that second graders' perceptual span extends 11 characters to the right of a fixation (see also Underwood & Zola, 1986). Very similar results have been obtained more recently with regard to children's letter-identity span, that is, the region of text around the fixation in which the identity of letters can be identified (Häikiö, Bertram, Hyönä, & Niemi, 2009). Thus, after only one year of reading instruction, beginning readers direct their attention more to the right of fixation and apparently extract sufficient information from it in order to successfully guide their next saccade to a position optimal for word encoding. Similarly, it has been shown that parafoveal preview effects in Finnish second graders are larger within words than across words, as in adult readers (Häikiö, Bertram, & Hyönä, 2010).

Yet, the spatial extent of the effective field of vision increases with age and only becomes fully adult-like in Grade 6 (Häikiö et al., 2009; Rayner, 1986). This increase is generally attributed to changes in attention allocation over the words in a sentence. In particular, because foveal word identification is more resource-intensive for children, it is argued that they cannot allocate the same amount of attention to upcoming words as adults. Even in adults, the amount of parafoveal processing varies with text difficulty (Rayner, 1986)—for example, with the frequency of the foveal word (the foveal load hypothesis, see Henderson & Ferreira, 1990; White, Rayner & Liversedge, 2005)—and increases as a function of participants' reading skill (Chace, Rayner, & Well, 2005). Thus, age-related changes in parafoveal processing might be mainly attributable to differences in linguistic processing difficulty. However, virtually nothing is known about the nature of these developmental differences, that is, which kinds of information can be extracted from the parafovea beyond word length or letter-identity information.

Decreased parafoveal processing has also been reported for older adults, that is, they show slightly smaller and less asymmetric perceptual spans (Risse & Kliegl, 2011; Rayner, Castelhano, & Yang, 2009) and obtain less preview benefit from the parafoveal word than young adults (Payne &

Stine-Morrow, 2012). Alongside decline in cognitive resources that affects their linguistic processing efficiency, these changes might also be related to older adults' sensory deficits. During normal ageing the visual system changes substantially and older adults usually suffer from subtle visual deficiencies that might affect their text processing (McGowan et al., 2014). As visual acuity is especially important for parafoveal processing, these deficits might be particularly relevant here.

Studies investigating children's foveal processing are more numerous. Experiments have shown that the length of a word strongly affects children's eye movements. Children fixate longer words more often and for longer durations (Blythe et al., 2010; Hyönä & Olson, 1995; Joseph et al., 2009). Usually, word length effects are larger in children than in adults (Joseph et al., 2009), decrease in magnitude from Grade 2 to 4 (Huestegge, Radach, Corbic, & Huestegge, 2009), and are stronger for less skilled than for skilled readers (Hyönä & Olson, 1995). The evidence indicates that younger and less skilled readers are more likely to adopt a serial decoding strategy, as revealed by robust word length effects (Rau, Moeller, & Landerl, 2014).

Also word frequency has a strong influence on children's foveal processing, with longer fixation times and more fixations for infrequent than for frequent words. Again, these effects tend to be stronger in children than in adults, especially if word frequency norms appropriate for children are used (Joseph, Nation, & Liversedge, 2013). This indicates that the decision of when to move the eyes from one word to the next is mainly under cognitive control in children. However, as most of the studies have manipulated frequency experimentally by typically contrasting high-frequency words to low-frequency words, we do not know the trajectory of children's frequency effects across the frequency continuum and do not know where, and how, exactly they diverge from adults' frequency effects. However, it can be expected that differences are likely most pronounced in the low-frequency range (Kuperman & van Dyke, 2013).

To date, few studies have examined effects other than lexical variables on children's eye movements, although higher order post-lexical integration effort seems to be an obvious candidate to explain children's less fluent reading. With regard to children's syntactic processing, Joseph and Liversedge (2013) showed that adults and children exhibit similar parsing preferences for prepositional and adverbial phrases, but that

children are delayed relative to adults in their response to initial syntactic misanalyses. Corroborating findings have been reported by Engelhardt (2014) for children's and adolescents' processing of garden-path sentences (i.e., sentences that are likely to lead to a syntactic misanalysis). With regard to semantic processing, Joseph et al. (2008) found that children and adults do not differ in their ability to detect semantic anomalies, but children are delayed in their evaluation of the plausibility of a sentence. Thus, children's and adults' basic thematic assignment process seems to be similar, but children are less apt to use pragmatic information in order to construct a discourse representation.

A different line of research investigating comprehension monitoring in children (e.g., Connor et al., 2015; van der Schoot, Reijnjes, & van Lieshout, 2012; Vorstius, Radach, Mayer, & Lonigan, 2013) complements the findings on semantic processing. These studies show that fifth and sixth grade students are generally able to detect inconsistent information within a sentence (van der Schoot, Vasbinder, Horsely, Reijntjes, & van Lieshout, 2009; Vorstius et al., 2013) or between sentences (Connor et al., 2015; van der Schoot et al., 2012). However, they seem to have difficulties repairing such inconsistencies, and there are large inter-individual differences in children's monitoring behaviour. In addition, poor comprehenders appear to have particular problems in constructing and updating their situation model to maintain coherence in text (van der Schoot et al., 2012) and to distinguishing between important and unimportant text information (van der Schoot, Vasbinder, Horsely, & van Lieshout, 2008). By contrast, older adults have been shown to engage more extensively in situation model building processes in order to regulate their overall reading effort and maintain a sufficient level of comprehension (Stine-Morrow et al., 2010).

As regards older adults, as mentioned earlier, older readers tend to make fewer fixations that are longer in duration than those of younger adults (Kliegl et al., 2004; Rayner et al., 2006). They also tend to make longer saccades and skip words more frequently than younger readers but make more regressions back to skipped words (Laubrock, Kliegl, & Engbert, 2006; Rayner et al., 2009). This pattern is attributed to older adults' risky reading strategy adopted to compensate for their overall slower reading rate (Rayner et al., 2006). Because cognitive processing is more effortful in older adults, they may rely more upon their world

knowledge and prior discourse context to predict upcoming text information. Nevertheless, they exhibit normal word frequency and word predictability effects, which tend to be larger than in younger adults (Laubrock et al., 2006).

In sum, the reviewed studies indicate that there are both differences and similarities between the eye movement characteristics of children, younger adults, and older adults. In order to explain some of these differences, simulations using computational models of eye movement behaviour have been carried out (see e.g., Engbert & Kliegl, 2011; Reichle, 2011). For example, Reichle et al. (2013) used the E–Z Reader model to test several hypotheses regarding how changes in oculomotor, visual, and linguistic processes might drive eye movement development. According to these simulations, the main difference between children and adults is explained by overall lexical processing speed, possibly accompanied by corresponding changes in post-lexical processing. Thus, according to this work, most of the observed developmental differences between children and adults seem to be driven by changes in linguistic processing proficiency. By contrast, adjustments in saccadic programming and execution, that is, low-level oculomotor aspects of eye movement behaviour, were not sufficient to simulate the full pattern of children's eye movements in reading.

The E–Z Reader model has also been used to model the differences between younger and older adults' eye movement behaviour (Rayner et al., 2006). These simulations indicate that lexical processing is also slowed down in older adults. In addition, variables controlling for older adults' parafoveal processing extent and the probability of guessing predictable words also had to be adjusted in order to fully explain all developmental changes. Thus, according to the simulations based on the E–Z Reader model, there are both shared and distinct mechanisms that drive age-related changes in eye movement behaviour during reading (Reichle et al., 2013). Thus, whereas some factors, such as the increasing quality of lexical representations through accumulating print exposure, develop rather continuously across the lifespan, other factors, such as visual processing difficulties, might show a different developmental trajectory and become increasingly influential in different ways in older adults. At present, however, the relative influence of these factors and their interactions with age are largely unclear.

Similar simulations (Laubrock et al., 2006) have been conducted using the SWIFT model (Engbert & Kliegl, 2011; Reichle, 2011), which—in contrast to the serial E–Z Reader model—assumes that attention is allocated as a gradient and several words can be processed in parallel. Within this framework, older adults' reading behaviour can successfully be modelled by assuming that their attentional gradient is smaller (explaining why average fixation duration is longer in older adults) and more skewed to the right (which explains why they skip words more often). Until now, comparable simulations aiming at modelling children's eye movement behaviour with SWIFT have not been reported. However, it is reasonable to assume that a key aspect to explain developmental effects will be related to the size and form of the attentional span.

In sum, there is a considerable degree of consistency between the published studies with regard to how eye movements change during reading development. A general conclusion is that children and adults do not differ very much in terms of their efficiency of oculomotor control, but that most of the developmental changes are related to the rate of lexical (and potentially other linguistic) processing. A unifying explanation seems to be that beginning readers (and older adults suffering from cognitive decline and/or visual deficits) have to allocate more attentional and processing resources to the fixated word and, as a consequence, are less able to engage in concurrent processing of extrafoveal information to the same degree as young adult readers. Thus, in order to fully understand development in eye movement control during reading it is necessary to understand the nature of change in the cognitive systems associated with word recognition and other aspects of language processing (as well as, potentially, with changes in the relationship between the two). According to the available data, the basic factors that significantly influence reading seem to be how fast the meaning of printed words can be accessed, and how efficiently higher order language processing skills can be used to integrate word meanings into a coherent linguistic structure (Reichle et al., 2013).

DEVELOPMENT OF EYE MOVEMENTS IN READING: CONTRIBUTIONS OF THE SPECIAL ISSUE

A prime example of the development of children's eye movements is the relative magnitude of parafoveal processing. Reduced demands in

processing the currently fixated word will increase parafoveal preprocessing of the upcoming word, which in turn decreases the demands in processing this word during the next fixation, which will again facilitate parafoveal preprocessing of the sub-sequent word, etc. This constellation, thus, consti-tutes a positive, self-enhancing feedback system. Unsurprisingly, therefore, there have been recent moves to study the mechanisms of children's parafoveal processing in more detail, and this topic also features prominently among the studies presented in the Special Issue.

Sperlich, Schad, and Laubrock (2015) used the moving-window paradigm to investigate children's parafoveal processing in German. Adding to the previous evidence on the preprocessing of letter feature information (Rayner, 1986), they report an increase in the perceptual span during the ele-mentary school years. They investigated children during Grades 1–3 and were, therefore, able to look at the early trajectory of the development of the perceptual span in a more fine-grained way than has been done in previous studies. In line with the foveal load hypothesis outlined earlier, their results showed few differences between Grades 1 and 2, but the most pronounced changes occurred between Grades 2 and 3.

To date, no research has been conducted regarding qualitative changes in the nature of children's parafoveal processing, that is, in the differential sensitivity to specific information asso-ciated with upcoming words. This is the case, despite there being a large body of research on this topic for adults (see Schotter, Angele, & Rayner, 2012, for a review). However, the first studies on this issue are starting to accrue. Using the boundary paradigm, Tiffin-Richards and Schroeder (2015) compared children's and adults' parafoveal preprocessing of phonological and orthographic information in German (see Blythe, Pagan, & Dodd, 2015, for a similar study investig-ating phonological effects in foveal processing in English). They found that children but not adults showed phonological parafoveal preview benefits. In contrast, adults demonstrated transposed-letter effects, indexing orthographic parafoveal processing, whereas children showed these effects only under specific conditions. Together, their pattern of results suggests a developmental shift from the use of phonological to orthographic information in the parafovea (see Ziegler, Ber-trand, Lété, & Grainger, 2014, for corroborating evidence using masked-priming in French). In the future, studies investigating other aspects of the

development of parafoveal processing (e.g., syl-lable or morphological information) are needed.

The study of Tiffin-Richards and Schroeder (2015) along with other recent studies (e.g., Blythe et al., 2010; Häikiö et al., 2010; Jordan, McGowan, & Paterson, 2014; Rayner et al., 2011) demon-strates that the display-change paradigms (the moving-window and the boundary paradigm) can be successfully used with children and older adults. It can be expected that the use of these methods will greatly enhance our knowledge about the amount and nature of children's parafoveal pro-cessing. An important assumption underlying these methods is that invalid previews do not impose any processing cost but serve as a neutral baseline condition. Marx, Hawelka, Schuster, and Hutzler (2015) investigated this question by com-paring standard invalid previews (such as repla-cing all letters of a parafoveal word with xs or with different letters that preserve the overall shape of the word) with previews in which the visual salience of the parafoveal word was manipulated incrementally (by displacing 0, 10, or 20% of the pixels from the preview). They replicated the results found for adults (Hutzler et al., 2013) by showing that German-speaking fourth and sixth grade students exhibit substantial interference in the x-condition and also from same shape/different letter-masks (see also Kliegl, Hohenstein, Yan, & McDonald, 2013). These interference effects not only demonstrate that children in Grades 4 and 6 show substantial parafoveal preview, but they also suggest that preview benefits reported in studies that have used x-masks may be overestimated. As a consequence, Marx et al. advocate the use of the incremental visual degradation method in future studies. However, up to now, this method has only been used to manipulate the visibility of several words simultaneously, and it is unclear whether studies investigating more localised phenomena will profit from it.

Related to the question of the nature of parafoveal extraction of text information is the issue of the grain size (Ziegler & Goswami, 2005) optimal for developing readers' foveal processing. Two studies reported in the Special Issue have investigated this question in rather different ways. Häikiö, Bertram, and Hyönä (2015) investigated whether segmenting words in syllables with hyphens (or colour information) is helpful for beginning readers of Finnish, an agglutinating and multisyllabic language. In support of their prior findings (Häikiö, Bertram, & Hyönä, 2011), they observed that the use of hyphens, commonly

used in ABC books for beginning readers of Finnish, slows down reading of both first and second grade children compared to text that did not use hyphens at syllable boundaries. In addition, illegally used hyphens (inserted within syllables) were even more detrimental. The authors conclude that beginning readers of Finnish are able to process words as a whole and that the use of hyphens forces them to process words sequentially, syllable by syllable (or, in the case of the use of hyphens within syllables, letter-by-letter) which slows down their reading.

Similarly, Laishley, Liversedge, and Kirkby (2015) investigated which grain sizes are used by children and adults when they copy words from the board—an ecologically valid task relevant to many educational settings. For adults, they found strong word frequency effects suggesting whole word encoding. For children, by contrast, word length and frequency interacted and frequency effects were only found for short words. This indicates that children encoded long words as multiple sublexical units. Laishley et al. thus provided evidence for a developmental shift from sublexical to lexical encoding during word copying, which is in line with current models of reading acquisition (Grainger & Ziegler, 2011). Moreover, their study demonstrates that eye-tracking can be successfully used in more naturalistic situations outside laboratory settings and that this approach can be applied to investigate aspects of linguistic processing beyond silent reading.

Another domain demonstrating the importance of eye movements on reading development is the acquisition of new words. In the Special Issue, this was done by Liang et al. (2015) in a study examining reading in Chinese. A starting point for the study was the fact that in Chinese word boundaries are not demarcated by spaces as in alphabetic languages. Extending their previous work (Blythe et al., 2012), the authors investigated the effects of word spacing and positional character frequency on lexical acquisition in Chinese children. They found that both segmentation cues helped children to read new words (see also Zang, Liang, Bai, Yan, & Liversedge, 2013). In addition, the cues did not interact with each other, each influencing children's processing independently. This indicates that spacing information helps Chinese children to build more stable lexical representations, but that they are also able to identify word boundaries by using linguistic cues such as positional frequency information alone.

In recent years, the use of spacing information in reading alphabetic languages has also attracted a substantial amount of interest in the ageing literature. Generally, it has been found that removing or obscuring interword spaces substantially disrupts eye movements for all readers and is especially detrimental for reading low-frequency words (Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner, Fischer, & Pollatsek, 1998). In addition, older adults' reading of unspaced text is usually more disrupted than that of younger adults (McGowan et al., 2014; Rayner, Yang, Schuett, & Slattery, 2013). Older adults, therefore, seem to obtain greater benefits from the use of interword spaces—presumably due to limitations in visual processing that come with age. McGowan, White, and Paterson (2015) present an interesting extension of this research question. They manipulated the size of the interword spacing (0.5, 1, and 1.5 times the normal size). Although the amount of spacing led to longer sentence reading times and reduced skipping rates, it did not differentially affect younger and older adults.

Another relevant area of research concerns the question of how children's post-lexical processes develop. As reviewed earlier, very little eye movement research has been done on discourse processing among children. The Special Issue makes a significant contribution by filling in this gap. Joseph, Bremner, Liversedge, and Nation (2015) investigated the time course of the resolution of noun phrase anaphors in children to see whether such processing is modulated by individual differences in working memory and reading skill. The authors varied both the typicality and the distance between an antecedent and its anaphor. Although children showed both typicality and distance effects, they failed to resolve anaphors in the most difficult (distant, atypical) condition, suggesting that anaphoric processing is still rather demanding for children at the end of elementary school. In addition, their results showed that eye-tracking is a useful tool to investigate effects for which it is difficult to make inferences from offline data alone.

Kaakinen, Lehtola, and Paattilammi (2015) investigated online text comprehension processes by examining whether "why" questions, presented as the text title, enhance children's and adults' text processing. When there were no effects on text memory or comprehension success measured after reading, the "why" question titles did affect children's reading behaviour. Interestingly, effects differed between younger and older children:

When second graders showed effects of the titles during first-pass reading, older children showed the effect in later look-backs. More generally, the results indicate that even very young readers modify their reading behaviour according to reading assignment and task demands—factors that have been neglected in developmental studies so far.

Finally, previous research clearly indicates that there is some overlap between the mechanisms that account for differences in eye movements as a function of reading skill versus age. Because intra- and inter-individual sources of variance are naturally confounded (as younger children typically are also less skilled readers), it is crucial to disentangle the relative contributions of these two factors. Unfortunately, longitudinal studies are still rather rare in developmental eye-tracking research (but see Huestegge et al., 2009; Sperlich et al., 2015). Instead, the dominant research strategy has been to only assess children from one or two age groups and test whether they show the same effects as adults. Although this approach has certainly advanced our understanding of children's eye movement development, it has its limitations. In order to be able to assess genuine development trajectories, it is necessary to assess behaviour repeatedly over time among the same children. In addition, it is important to study inter-individual differences between children that are of the same age and investigate potential correlates of efficient reading behaviour. The study by Mancheva et al. (2015) is an important step in this direction, as it investigates inter-individual differences and at the same time relates them to a theoretical model of eye movement behaviour. In this study, the E–Z Reader model was used to simulate the eye movements of individual children and the individual model parameters were correlated with several psychometric measures. The simulations replicated the finding that the most pronounced differences between children and adults are related to the model parameter that indexes the overall efficiency of lexical processing (see Reichle et al., 2013). In addition, individual differences in this parameter correlated strongly with children's lexical skills as measured by offline tests, in particular with orthographic processing ability. This approach is extremely interesting because it demonstrates that results from experimental and individual differences studies converge and that individual differences may also be mapped onto specific features of the eye movement system.

In summary, the articles that comprise the Special Issue each aim at investigating a different aspect of reading development as it is reflected in readers' eye movement records. They provide examples of investigative research into the types of conditions and the nature of the mechanisms that drive intra-individual changes and create inter-individual differences among readers. They also show very clearly that developmental eye-tracking research has grown beyond its infancy and is now, itself, a dynamic and growing field of research.

REFERENCES

Blythe, H. I. (2014). Developmental changes in eye movements and visual information encoding associated with learning to read. *Current Directions in Psychological Science*, *23*, 201–207.

Blythe, H. I., & Joseph, H. S. S. I. (2011). Children's eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 643–662). Oxford: Oxford University Press.

Blythe, H. I., Häikiö, T., Bertram, R., Liversedge, S. P., & Hyönä, J. (2010). Reading disappearing text: Why do children refixate words? *Vision Research*, *51*, 84–92.

Blythe, H. I., Liang, F., Zang, C., Wang, J., Yan, G., Bai, X., & Liversedge, S. P. (2012). Inserting spaces into Chinese text helps readers to learn new words: An eye-movement study. *Journal of Memory and Language*, *67*, 241–254.

Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research*, *49*, 1583–1591.

Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. *Vision Research*, *46*, 3898–3908.

Blythe, H. I., Pagan, A., & Dodd, M. (2015). Beyond decoding: Phonological processing during silent reading in beginning readers. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. Advance online publication. doi:10.1037/xlm0000080

Buswell, G. T. (1922). *Fundamental reading habits: A study of their development*. Chicago, IL: Chicago University Press.

Chace, K. H., Rayner, K., & Well, A. D. (2005). Eye movements and phonological parafoveal preview: Effects of reading skill. *Canadian Journal of Experimental Psychology*, *59*, 209–217.

Connor, C. M., Radach, R., Vorstius, C., Day, S. L., McLean, L., & Morrison, F. J. (2015). Individual differences in fifth graders' literacy and academic language predict comprehension monitoring development: An eye-movement study. *Scientific Studies of Reading*, *19*, 114–134.

Engbert, R., & Kliegl, R. (2011). Parallel graded attention models of reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 787–800). Oxford: Oxford University Press.

Engelhardt, P. E. (2014). Children's and adolescents' processing of temporary syntactic ambiguity: An eye-movement study. *Child Development Research*, *2014*, 1–13.

Grainger, J., & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, *2*, 1–13.

Häikiö, T., Bertram, R., & Hyönä, J. (2010). Development of parafoveal processing within and across words in reading: Evidence from the boundary paradigm. *Quarterly Journal of Experimental Psychology*, *63*, 1982–1998.

Häikiö, T., Bertram, R., & Hyönä, J. (2011). The development of whole-word representations in compound word processing: Evidence from eye fixation patterns of elementary school children. *Applied Psycholinguistics*, *32*, 533–551.

Häikiö, T., Bertram, R., & Hyönä, J. (2015). The role of syllables in word recognition among beginning Finnish readers: Evidence from eye movements during reading. *Journal of Cognitive Psychology*, *27*, 562–577. doi:10.1080/20445911.2014.982126

Häikiö, T., Bertram, R., Hyönä, J., & Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology*, *102*, 167–181.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *16,* 417–429.

Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research*, *49*, 2948–2959.

Hutzler, F., Fuchs, I., Gagl, B., Schuster, S., Richlan, F., Braun, M., & Hawelka, S. (2013). Parafoveal X-masks interfere with foveal word recognition: Evidence from fixation-related brain potentials. *Frontiers in Systems Neuroscience*, *7*, 1–10.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 1430–1440.

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2014). Reading with filtered fixations: Adults age-differences in the effectiveness of low-level properties of the text in central vision. *Psychology and Aging*, *29*, 229–235.

Joseph, H. S. S. L., Bremner, G., Liversedge, S. P., & Nation, K. (2015). Working memory, reading ability and the effects of distance and typicality on anaphor resolution in children. *Journal of Cognitive Psychology*, *27*, 622–639. doi:10.1080/20445911.2015.1005095

Joseph, H. S. S. L., Liversedge, S. P., Blythe, H. I., White, S. J., Gathercole, S. E., & Rayner, K. (2008). Children's and adults' processing of anomaly and implausibility during reading: Evidence from eye movements. *Quarterly Journal of Experimental Psychology*, *61*, 708–723.

Joseph, H. S. S. L., Liversedge, S. P., Blythe, H. I., White, S. J., & Rayner, K. (2009). Word length and landing position effects during reading in children and adults. *Vision Research*, *49*, 2078–2086.

Joseph, H. S. S. L., Nation, K., & Liversedge, S. P. (2013). Using eye movements to investigate word frequency effects in children's sentence reading. *School Psychology Review*, *42*, 207–222.

Joseph, H. S. S. L., & Liversedge, S. P. (2013). Children's and adults' on-line processing of syntactically ambiguous sentences during reading. *PLoS ONE*, *8*, 1–13.

Joshi, R. M., & Aaron, P. G. (Eds.). (2006). *Handbook of orthography and literacy*. Mahwah, NJ: Erlbaum.

Kaakinen, J. K., Lehtola, A., & Paattilammi, S. (2015). The influence of a reading task on children's eye movements during reading. *Journal of Cognitive Psychology*, *27*, 640–656. doi:10.1080/20445911.2015.1005623

Kirkby, J. A., Webster, L. A. D., Blythe, H. I., & Liversedge, S. P. (2008). Binocular coordination during reading and non-reading tasks. *Psychological Bulletin*, *134*, 742–763.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology*, *16*, 262–284.

Kliegl, R., Hohenstein, S., Yan, M., & McDonald, S. A. (2013). How preview space/time translates into preview cost/benefit for fixation durations during reading. *Quarterly Journal of Experimental Psychology*, *66*, 581–600.

Kuperman, V., & van Dyke, J. A. (2013). Reassessing word frequency as a determinant of word recognition for skilled and unskilled readers. *Journal of Experimental Psychology: Human Perception and Performance*, *39,* 802–823.

Laishley, A., Liversedge, S. P., & Kirkby, J. (2015). Lexical processing in children and adults during word copying. *Journal of Cognitive Psychology*, *27*, 578–593. doi:10.1080/20445911.2014.991396

Laubrock, J., Kliegl, R., & Engbert, R. (2006). SWIFT explorations of age differences in eye movements during reading. *Neuroscience and Behavioral Reviews*, *30,* 872–884.

Liang, F., Blythe, H. I., Zang, C., Bai, X., Yan, G., & Liversedge, S. P. (2015). Positional character frequency and word spacing facilitate the acquisition of novel words during Chinese children's reading. *Journal of Cognitive Psychology*, *27*, 594–608. doi:10.1080/20445911.2014.1000918

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences*, *4*, 6–14.

Liversedge, S. P., Gilchrist, I. D., & Everling, S. (Eds.). (2011). *The Oxford handbook of eye movements*. Oxford: Oxford University Press.

Mancheva, L., Reichle, E. D., Lemaire, B., Valdois, S., Ecalle, J., & Guérin-Dugué, A. (2015). An analysis of

reading skill development using E–Z Reader. *Journal of Cognitive Psychology*, 27, 657–676. doi:10.1080/20445911.2015.1024255

Marx, C., Hawelka, S., Schuster, S., & Hutzler, F. (2015). An incremental boundary study on parafoveal preprocessing in children reading aloud: Parafoveal masks overestimate the preview benefit. *Journal of Cognitive Psychology*, 27, 549–561. doi:10.1080/20445911.2015.1008494

McConkie, G. W., Zola, D., Grimes, J., Kerr, P.W., Bryant, N. R., & Wolff, P. M. (1991). Children's eye movements during reading. In J. E. Stein (Ed.), *Vision and visual dyslexia* (pp. 251–262). London: Macmillan Press.

McGowan, V. A., White, S. J., & Paterson, K. B. (2015). The effects of interword spacing on the eye movements of young and older readers. *Journal of Cognitive Psychology*, 27, 609–621. doi:10.1080/20445911.2014.988157

McGowan, V. A., White, S. J., Jordan, T. K., & Paterson, K. B. (2014). Aging and the use of interword spaces during reading: Evidence from eye movements. *Psychonomic Bulletin Review*, 21, 740–747.

Miller, B., & O'Donnell, C. (2013). Opening a window into reading development: Eye movements' role within a broader literacy research framework. *School Psychology Review*, 42, 123–139.

Paterson, K. B., & Jordan, T. K. (2010). Effects of increased letter spacing on word identification and eye guidance during reading. *Memory & Cognition*, 38, 502–512.

Payne, B. R., & Stine-Morrow, E. A. L. (2012). Aging, parafoveal preview, and semantic integration in sentence processing: Testing the cognitive workload of wrap-up. *Psychology and Aging*, 27, 638–649.

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research*, 49, 1994–2000.

Rau, A. K., Moeller, K., & Landerl, K. (2014). The transition from sublexical to lexical processing in a consistent orthography: An eye-tracking study. *Scientific Studies of Reading*, 18, 224–233.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7, 65–81.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, 41, 211–236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, 62, 1457–1506.

Rayner, K., Castelhano, M. S., & Yang, J. (2009). Eye movements and the perceptual span in older and younger adults. *Psychology and Aging*, 24, 755–760.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, 38, 1129–1144

Rayner, K., Liversedge, S.P., White, S.J., & Vergilino-Perez, D. (2003). Reading disappearing text: Cognitive control of eye movements. *Psychological Science*, 14, 385–388.

Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on eye movements of young and old readers. *Psychology and Aging*, 21, 448–465.

Rayner, K., Yang, J., Castelhano, M. S., & Liversedge, S. P. (2011). Eye movements of older and younger readers when reading disappearing text. *Psychology and Aging*, 26, 214–233.

Rayner, K., Yang, J., Schuett, S., & Slattery, T. J. (2013). Eye movements of older and younger readers when reading unspaced text. *Experimental Psychology*, 60, 354–361.

Reichle, E. D. (2011). Serial-attention models of reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 767–786). Oxford: Oxford University Press.

Reichle, E. D., Liversedge, S. P., Drieghe, D., Blythe, H. I., Joseph, H. S. S. L, White, S. J., & Rayner, K. (2013). Using E–Z Reader to examine the concurrent development of eye-movement control and reading skill. *Developmental Review*, 33, 110–149.

Risse, S., & Kliegl, R. (2011). Adult age differences in the perceptual span during reading. *Psychology and Aging*, 26, 451–460.

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysiology*, 74, 5–35.

Sperlich, A., Schad, D. J., & Laubrock, J. (2015). When preview information starts to matter: Development of the perceptual span in German beginning readers. *Journal of Cognitive Psychology*, 27, 511–530. doi:10.1080/20445911.2014.993990

Stine-Morrow, E. A. L, Shake, M. C., Miles, J. R., Lee, K., Gao, X., & McConkie, G. (2010). Pay now or pay later: Aging and the role of boundary salience in self-regulation of conceptual integration in sentence processing. *Psychology and Aging*, 25, 168–176.

Taylor, S. E. (1965). Eye movements while reading: Facts and fallacies. *American Educational Research Journal*, 2, 187–202.

Tiffin-Richards, S. P., & Schroeder, S. (2015). Children's and adults' parafoveal processing in German: Phonological and orthographic effects. *Journal of Cognitive Psychology*, 27, 531–548. doi:10.1080/20445911.2014.999076

Underwood, N. R., & Zola, D. (1986). The span of letter recognition of good and poor readers. *Reading Research Quarterly*, 21, 6–19.

van der Schoot, M., Reijnjes, A., & van Lieshout, E. C. D. M. (2012). How do children deal with inconsistencies in text? An eye fixation and self-paced reading study in good and poor comprehenders. *Reading & Writing*, 25, 1665–1690.

van der Schoot, M., Vasbinder, A. L., Horsely, T. M., Reijntjes, A., & van Lieshout, E. C. D. M. (2009). Lexical ambiguity resolution in good and poor comprehenders: An eye-movement and self-paced reading study in primary school children. *Journal of Educational Psychology*, 101, 21–36.

van der Schoot, M., Vasbinder, A. L., Horsley, T. M., & van Lieshout, E. C. D. M. (2008). The role of two reading strategies in text comprehension: An eye

fixation study in primary school children. *Journal of Research in Reading*, *31,* 203–223.

Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research*, *41,* 3513–3533.

Vorstius, C., Radach, R., Mayer, M. B., & Lonigan, C. J. (2013). Monitoring local comprehension monitoring in sentence reading. *School Psychology Review*, *42,* 191–206.

White, S. J., Rayner, K., & Liversedge, S. P. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic Bulletin & Review*, *12*, 891–896.

Zang, C., Liang, F., Bai, X., Yan, G., & Liversedge, S. P. (2013). Interword spacing and landing position effects during Chinese reading in children and adults. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 720–739.

Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, *50*, 1026–1036.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*, 3–29.