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# Using E-Z Reader to examine the concurrent development of eye-movement control and reading skill

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ABSTRACT

Compared to skilled adult readers, children typically make more fixations that are longer in duration, shorter saccades, and more regressions, thus reading more slowly (Blythe & Joseph, 2011). Recent attempts to understand the reasons for these differences have discovered some similarities (e.g., children and adults target their saccades similarly; Joseph, Liversedge, Blythe, White, & Rayner, 2009) and some differences (e.g., children's fixation durations are more affected by lexical variables; Blythe, Liversedge, Joseph, White, & Rayner, 2009) that have yet to be explained. In this article, the E-Z Reader model of eye-movement control in reading (Reichle, 2011; Reichle, Pollatsek, Fisher, & Rayner, 1998) is used to simulate various eye-movement phenomena in adults vs. children in order to evaluate hypotheses about the concurrent development of reading skill and eye-movement behavior. These simulations suggest that the primary difference between children and adults is their rate of lexical processing, and that different rates of (post-lexical) language processing may also contribute to some phenomena (e.g., children's slower detection of semantic anomalies; Joseph et al., 2008). The theoretical implications of this hypothesis are discussed, including possible alternative accounts of these developmental changes, how reading skill and eye movements change across the entire lifespan (e.g., college-aged vs. older readers), and individual differences in reading ability.

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"Words, letters, and letter-groups flash into greater distinctiveness from moment to moment, and there is some thought of a mental traversing of the lines. If we watch closely, we are apt to find some sort of inner utterance of what is being read, and we have a notion of the meaning of it all... Thus reading appears to the casual introspection of the reader. We find, however, that underneath this apparent simplicity, there is an astounding complexity of processes. These have been built up slowly, and by an immense amount of practice, until they have organized and settled into the smoothly running machinery of our present-day reading."

–Huey (1908, p. 24)

## Introduction

It has long been appreciated that the ability to read is one of the most complex cognitive skills that we routinely perform but did not specifically evolve to perform (Huey, 1908; Rayner & Pollatsek, 1989; Rayner, Pollatsek, Ashby, & Clifton, 2012). Inherent in this appreciation is an understanding that reading skill is acquired through extensive practice, like other complex skills. Understanding the nature of the complex developmental processes that contribute to reading skill is essential for fully understanding how children learn to read (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001, 2002). It is, therefore, somewhat surprising that eye movements, which have proven invaluable behaviors for understanding the cognitive processes of adult readers (for reviews, see Rayner, 1998, 2009), have until fairly recently been largely ignored in the study of reading acquisition (for a review, see Blythe & Joseph, 2011). This oversight is unfortunate because enough has already been learned about the differences between the eye movements of children vs. adults to suggest that these discrepancies provide an insight into how cognition interacts with the visual and oculomotor systems during reading, as well as how these interactions change as a beginning reader develops into a skilled reader.

The remainder of this article will attempt to start to redress this oversight within the theoretical context of a specific model of eye-movement control during reading—the *E-Z Reader* model (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009; Reichle, Pollatsek, Fisher, & Rayner, 1998; for a review, see Reichle, 2011). Our objective is to use the model to test the feasibility of several existing hypotheses about how development affects the patterns of eye movements that are reported when children who are beginning readers (i.e., children who can read simple sentences but who have limited reading experience and proficiency) become skilled adult readers. In the remainder of this article, therefore, we first review what is known about the eye movements of children vs. adult readers, including a discussion of known differences and possible accounts of those differences. We then provide a brief overview of the E-Z Reader model and report a series of simulations that were designed to evaluate the feasibility of existing accounts of why eye movements change in the manner that they do as beginning readers become skilled readers. The value of these modeling exercises are threefold: First, they provide more formal hypotheses about why eye movements change as reading skill develops; second, they provide a method for evaluating the feasibility of these hypotheses; and finally, they provide new theoretical insights about the development of reading skill that can in turn be the impetus for future experiments, including ones that might lend further support for or falsify the assumptions of the E-Z Reader model.

## Eye movements in children vs. adults

The following sections review what is currently known about the eye movements of children who are reading, how their eye movements (as a group) are similar to but, in important ways, different from those of adults, and two general accounts that have been provided to explain these similarities and differences. The discussion of these topics is organized into four sections corresponding (respectively) to the basic or more global characteristics of the eye movements, and how these eye movements might be affected by oculomotor and visual constraints, lexical processing, and higher-level (post-lexical) language processing.

*Basic characteristics of eye movements*

Contrary to subjective experience, our eyes do not move smoothly across the line of printed text, but instead make brief, ballistic movements called *saccades*. These saccades move the points of fixation to new viewing locations, where the eyes remain relatively stationary for brief periods called *fixations* so that visual information from the viewing location can be extracted from the printed page. This movement of the eyes is necessary because the type of high visual acuity that is required to identify the features of printed words is limited to a very small region of the retina, the *fovea*, which subtends approximately two degrees of angle (i.e., 6–8 character spaces with typical font sizes and reading distances) in the center of the visual field.

A considerable amount is known about the characteristics of eye movements during reading at this very basic level of description (for comprehensive reviews, see Rayner, 1978, 1998, 2009; Rayner & Pollatsek, 1989; Rayner et al., 2012). For example, although the majority of saccades move the eyes forward through the text, 10–15% of eye movements are *regressions* that move the eyes back to earlier parts of the text. These regressions are thought to generally reflect difficulty with language processing (e.g., misanalysis of a sentence's syntactic structure; Frazier & Rayner, 1982), but may also occasionally reflect uncertainty about the identity of previously viewed words (Levy, Bicknell, Slattery, & Rayner, 2009; Slattery, 2009). There are also *return sweeps* that move the eyes from the end of one line of text to the beginning of the next, so that the eyes can continue advancing through the text. Although individual fixations can vary quite markedly in their duration (50–1000 ms), in adult readers they tend to be a little over 200 ms in duration on average, and their durations are modulated by a wide variety of different perceptual, cognitive, and oculomotor variables (as will be discussed below). And although 75–85% of words are typically fixated at least once (Brysbaert & Vitu, 1998), words that are short in length, occur frequently in 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).

As already indicated, there has been remarkably little empirical work examining children's eye movements during reading and how these behaviors are similar/dissimilar to those of adult readers. A recent review by Blythe and Joseph (2011), however, indicates that there is a considerable degree of consistency with respect to how the global characteristics of eye movements change as a child who is learning to read becomes a skilled adult reader. As one might guess, these changes cause the overall rate of reading to increase as skill increases; that is, as children become more skilled at reading, the overall rate at which the eyes progress through a text increases, often despite the fact that the overall difficulty of the texts being read also tend to increase (Blythe & Joseph, 2011). These changes are also consistent across the different languages (e.g., English, German, Finnish, etc.) and education systems that have been examined thus far, 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; Seymour, Aro, & Erskine, 2003). Because little is known about how these differences might contribute to the key findings that will be reported below, the languages, ages, and grades of the children in the main studies discussed below, along with the ages at which formal education begins in the countries where the studies were conducted, are listed in Table 1. It is important to note, however, that even the youngest children who participated in the studies listed in Table 1 have well developed spoken language skills (e.g., knowledge of phonology, word meaning, syntax, and pragmatics; Rayner et al., 2001) and were pre-screened to ensure that they were able to read at a level appropriate for their age/grade.

One study demonstrating these basic developmental changes was reported by Rayner (1986), who compared the eye movements of three different groups of children (7–8, 9–10, and 11–12 year-olds) to those of adults across four experiments, with each group reading either materials appropriate for second grade (in Experiments 1–3) or fourth grade vs. college (in Experiment 4). Because the general pattern of results was remarkably consistent across the experiments, only those from Experiment 1 will be mentioned here: As the ages of the children increased, so too did their overall reading rate, ranging from 95 words per minute (*wpm*) with the 7–8 year olds to 210 wpm with the 11–12 year-olds and 290 wpm with the adults. This increase in proficiency with age reflected several more basic changes. First, mean saccade length increased with age, ranging from 2.8 characters with the

**Table 1**
Languages, ages, grade levels, and ages at which formal education begins for the children who participated in the main studies discussed in this article.

| Study | Language | Ages (years) | Grades | Age formal education begins (years) |
|---|---|---|---|---|
| Blythe et al. (2009) | (UK) English | 7–9; 10–11 | 2–3; 4–5 | 5 |
| Blythe et al. (2011) | Finnish | 8–9; 10–11 | 2; 4 | 7 |
| Häikiö et al. (2009) | Finnish | 8–9; 10–11; 12–13 | 2; 4; 6 | 7 |
| Huestegge et al. (2009) | German | 8; 10 | 2; 4 | 6 |
| Hyönä and Olson (1995) | (US) English | 9–12 | 3–6 | 6 |
| Joseph et al. (2008) | (UK) English | 7–12 | 2–6 | 5 |
| Joseph et al. (in press) | (UK) English | 8–9 | 3 | 5 |
| Rayner (1986) | (US) English | 7–8; 9–10; 11–12 | 2; 4; 6 | 6 |
| Vitu et al. (2001) | (US) English | 12 | 5 | 6 |

*Note:* Conditions of interest within a study (i.e., age groups and their corresponding grades) are separated by semi-colons.

7–8 year-olds to 6.4 characters with the 11–12 years olds and 6.8 characters with adults. Second, the mean number of fixations per sentence (which were 6–9 words in length) decreased with age, ranging from approximately 15 with the 7–8 year-olds to approximately 8 with the 11–12 year-olds and 6 with the adults. Third, the mean fixation duration also decreased with age, ranging from 280 ms with the 7–8 year-olds to 240 ms with the 11–12 year olds and 235 ms with the adults. Finally, the mean number of regressions per sentence also decreased with age, ranging from 4 with the 7–8 years olds to 2.5 with the 11–12 year-olds and 0.6 with the adults. Thus, to summarize, as the children increased in age and reading ability, their patterns of eye movements came to more closely resemble those of adults, such that they made both longer saccades and fewer, shorter fixations, fewer of which occurred after regressions. And, as Blythe and Joseph (2011) document, this basic developmental pattern has been independently replicated across several different studies that have examined eye movements of children of different ages, educational backgrounds, languages, and experimental manipulations (Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2011; Blythe et al., 2006; Blythe, Liversedge, Joseph, White, & Rayner, 2009; Buswell, 1922; Huestegge, Radach, Corbic, & Huestegge, 2009; Häikiö, Bertram, Hyönä, & Niemi, 2009; Häikiö, Hyönä, & Bertram, 2010; Joseph & Liversedge, 2013; Joseph, Nation, & Liversedge, in press; Joseph, Liversedge, Blythe, White, & Rayner, 2009; Kirkby, Blythe, Drieghe, & Liversedge, 2011; McConkie et al., 1991; Taylor, 1965).

Rayner (1986) also documented two other important facts about how children read. Both of these facts have to do with the *perceptual span*, or the "region from which useful information can be obtained during a fixation in reading" (Rayner, 1986, p. 212). In adults, it is known that useful visual information is only extracted from a very small spatial extent of the printed page. As indicated earlier, part of the reason for this is that the type of high visual acuity that is necessary to identify the features of printed words is largely delimited to the fovea. However, part of the reason for this limitation also has to do with how visual attention is allocated. This latter fact has been demonstrated using a variety of different *gaze-contingent paradigms* in which the text that is available to be processed on a computer monitor is manipulated contingent upon where the reader is looking (Rayner, 1979b).

Rayner's (1986) experiment used a particular type of gaze-contingent paradigm called the *moving window* (McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979), which is schematically illustrated in Fig.1. The figure shows how a single line of text would appear across three successive fixations in the paradigm. As the figure shows, a "window" of normal text is displayed around the point of fixation, with the text outside of this window being distorted in various ways (e.g., individual letters being replaced with *X*s). Each time a subject moves his or her eyes, the text being displayed on the monitor is updated (refreshed) either during the saccade or within a few milliseconds after the onset of the next fixation so that the virtual window effectively "moves" with the point of fixation. Because useful visual information is not acquired during a saccade (Matin, 1974), subjects rarely notice the display changes that occur each time the monitor is updated. Importantly, however, both the characteristics of the window (e.g., its size and degree of symmetry) and how the material outside of the window is distorted (e.g., whether the individual letters are replaced with similar-looking letters or *X*s, whether or not the blank spaces between the words are maintained, etc.) affect the subjects' overall reading

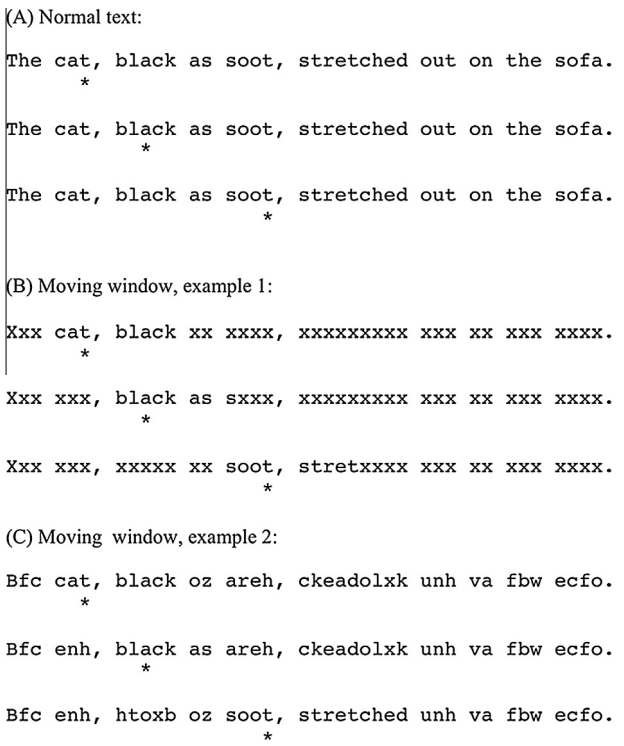


**Fig. 1.** A schematic diagram illustrating the moving-window paradigm (McConkie & Rayner, 1975). All three panels show the same sentence across three successive fixations (the locations of which are indicated by the asterisks). Panel A shows the normal viewing condition. Panel B shows an example of the moving-window paradigm in which all of the letters outside of a window extending 3 character spaces to the left and 7 character spaces to the right of fixation have been replaced with *X*s, but preserving the blank spaces between words. Panel C shows another example of the moving-window paradigm in which all of the letters outside of a window consisting of the fixated word and one word to the right of fixation have been replaced with letters of similar shape, but again preserving the blank spaces between words.

rate. This simple fact allows one to estimate the perceptual span; that is, by comparing the rate of reading when the text is displayed normally to the rate of reading when a particular type of moving window is used, it is possible to determine the types of information that readers extract at various eccentricities from the point of fixation. For example, adult readers of alphabetic languages like English (which are read from left to right) only extract information from a region extending 3–4 character spaces to the left of fixation (or the beginning of the currently fixated word) to about 15 character spaces to the right of fixation, while the region of lexical processing is even more restricted: Information about letter shapes (e.g., whether a letter has an ascender or descender) is only extracted up to 10 character spaces to the right of fixation, and information about letter identity and hence the identity of words is only extracted from 7–8 character spaces to the right of fixation (McConkie & Rayner, 1975). Finally, the claim that the perceptual span is a function of attention rather than visual acuity was perhaps most convincingly demonstrated by Pollatsek, Bolozky, Well, and Rayner (1981) in a study involving English–Hebrew bilinguals; when these subjects read English, their perceptual span extended to the right of fixation, but when they read Hebrew (which is read from right to left), their perceptual span extended to the left of fixation. This final result also indicates that the perceptual span is affected by cultural differences, including differences between languages and/or writing systems.

As indicated previously, Rayner (1986) had children from three different age groups and adults read easy and difficult sentences using the moving-window paradigm. Using this procedure, Rayner replicated the basic findings related to the perceptual span for adult readers, but also documented

how the perceptual span of children differed from adults, and how the span of children changed with both development and the difficulty of the text being read. More specifically, even the youngest children (7–8 year olds) had perceptual spans that extended asymmetrically to the right of fixation, and this perceptual span extended approximately 11 characters as compared to an adult perceptual span of 14–15 character spaces. Furthermore, the results of Experiment 4 showed that the perceptual span was modulated by the difficulty of the text that was being read; that is, for 9–10 year-old children, the size of the perceptual span actually decreased as the text being read became more difficult to understand (i.e., varying from easy, age-appropriate text to difficult, college-level text). This last result has been interpreted as showing that, as the text being fixated becomes more difficult to process, less time and/or fewer attentional resources are available for parafoveal processing, thus reducing the size of the perceptual span and providing an account of this finding that is consistent with the well-documented interaction between foveal processing load and parafoveal preview (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005).

Similar findings were also been reported by Häikiö et al. (2009) in an experiment that examined the perceptual span in four groups of native Finnish speakers: Children in second grade (mean age = 8 years), fourth grade (mean age = 10 years), and sixth grade (mean age = 12 years), and adults. This study also used the moving-window paradigm (McConkie & Rayner, 1975) to estimate the *letter-identity span*, or distance over which readers can identify individual letters, across the four age groups by contrasting reading under normal viewing conditions vs. a moving "window" in which the letters outside of the window were replaced by letters sharing common features (e.g., *h* and *k*, which both share ascenders). The results of this experiment indicated that the letter-identity span increased from approximately 5 characters to the right of fixation with the second graders to 9 character spaces with both the sixth graders and adults. These results, when compared to those reported by Rayner (1986), suggest that the letter-identity span is smaller than both the *letter-feature span* (i.e., distance over which letters can be discriminated based on features like overall shape), which extended approximately 7 character spaces to the right of fixation with the second graders to 11–12 character spaces with sixth graders and adults, and the *word-length span* (i.e., distance over which word boundaries are perceived), which was even larger, extending 11 character spaces to the right of fixation with the second graders and 14–15 character spaces to the right with sixth graders and adults. Thus, the two studies together show that the spatial extent of the perceptual span is modulated by the spatial frequency of the visual information that is being extracted during any given fixation, extending farthest to the right for the low-spatial frequency, coarse-grained information (e.g., word boundaries), but being quite limited in extent for the high-spatial frequency, fine-grained information (e.g., features used to identify individual letters). The studies also provide converging evidence that the perceptual span increases in spatial extent with age, but that it becomes fairly adult-like by about the sixth grade (i.e., 11–12 years of age).

The preceding experiments might be interpreted as showing that children are simply slower than adults at extracting visual information from the printed page. By this account, the longer, more frequent fixations and the smaller perceptual span that are observed with children reflect the fact that, during each fixation, children are less effective in their extraction of the visual features of the text printed on the page. Thus, the observed differences in the eye movements of children and adult readers have nothing to do with differences in their relative rates of lexical and other linguistic processing, per se, but instead reflect more basic differences in their rates of visual processing. This possibility was ruled out, however, by the results of another series of experiments that used a different type of gaze-contingent paradigm—the *disappearing-text paradigm* (Liversedge et al., 2004; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003).

In experiments using this paradigm, each word of the text being read disappears (or is masked) some short amount of time (e.g., 60 ms) after it is first fixated, and remains invisible until the subjects move their eyes to fixate another word, which in turn disappears. In this way, each time a subject looked at a word, s/he would have 60 ms to view that word and extract whatever visual information was necessary to identify it before it disappeared from view. Several experiments using this paradigm have demonstrated that this seemingly severe inhibition of text visibility is remarkably unobtrusive, and that adults can read text at a normal rate and with normal comprehension even when the text

only remains visible for 40–60 ms per fixation (Liversedge et al., 2004; Rayner, Juhasz, Ashby, & Clifton, 2003; Rayner, Yang, Castelhano, & Liversedge, 2011; Rayner et al., 2006).

Blythe et al. (2009) reaffirmed these conclusions across two separate experiments. The first compared children (7–11 year-olds) and adults when each fixated word disappeared 60 ms after fixation. This experiment showed that, relative to adults, the children exhibited the standard pattern of making more fixations that were longer in duration, shorter saccades, and more regressions, but were no more disrupted than the adults by the disappearing-text manipulation. The second experiment compared two groups of children (7–9 and 10–11 year-olds) and adults when each fixated word disappeared 40, 80, or 120 ms after being fixated. Again, the children exhibited an overall slower rate of reading but, like adults, were not adversely affected by the disappearing-text manipulation. Finally, Blythe et al. (2011) reported very similar results in an experiment that compared 8–9 year-old, 10–11 year-old, and adult native speakers of Finnish, again, reading text in which each word disappeared 60 ms after being fixated. For the present purposes, the results from all of these studies are important because they collectively indicate that children as young as seven actually have little difficulty extracting visual information from the printed page, and that despite being much slower readers than adults, children require comparable time periods to adults in order to extract visual information necessary for linguistic processing from fixation to fixation in reading.

The studies that were just reviewed indicate that, although many aspects of children's eye movements resemble those of skilled adult readers, there are also notable differences. A basic question, therefore, is what accounts for this pattern of similarities and differences? In other words, as reading skill develops in children, what causes the aforementioned changes in their eye-movement behavior? At a general level, there are at least two possible answers to this question.

The first answer is perhaps the most intuitive—that the development of reading skill in turn causes the observed changes in eye-movement behavior. By this account, as a child's ability to read improves, so too does his/her ability to rapidly and accurately identify printed words, as well as his/her ability to perform the many other linguistic operations that are required to construct a representation of the text that is being read. As these lexical and linguistic skills continue to improve, the primary task of constructing a representation of the meaning of the words on the printed page becomes more efficient, thus requiring even less time. Thus, with a speed up in lexical and linguistic processing, less time is needed (on average) per fixation to perform these operations, so that the eyes can be more rapidly moved from one viewing location to the next. Thus, as lexical and linguistic processing becomes more efficient, fewer and/or shorter fixations will presumably be necessary to understand the text that is being read. Throughout the remainder of this article, we will refer to this first possible explanation as the *linguistic-proficiency hypothesis*. By this account, as children become increasingly skilled readers, increasing proficiency with linguistic processing causes their eye movements to become increasingly similar to those of skilled adult readers.[1]

A second possible answer to the question we posed regarding the development of eye-movement behavior is that, through extensive practice, readers are able to "tune" their oculomotor control system through learning so that the eye movements themselves become more optimal (or near-optimal) during reading. For example, there is some evidence that young children have difficulty moving their eyes as rapidly and accurately as older children and adults (for a review, see Luna & Velanova, 2011). For example, there is considerable evidence using relatively simple oculomotor tasks (e.g., moving the eyes to visual targets) that, relative to adults, children are slower at programming saccades (Cohen & Ross, 1977, 1978; Groll & Ross, 1982; Klein & Foerster, 2001; Kowler & Martins, 1982; Miller, 1969) but exhibit equally rapid saccade velocities (Fukushima, Hatta, & Fukushima, 2000; Salman et al., 2006). By this second account, therefore, the causal arrow goes from the development of

[1] Perfetti and Hart (2002; see also Perfetti, 1985, 2007) proposed that a necessary condition for skilled reading is that the reader have high-quality lexical representations—that is, representations of word spellings, pronunciations, and meanings that are fully specified and fully interconnected so that any one representation (e.g., a word's orthographic pattern) can be used to rapidly and accurately access the other two (i.e., the word's pronunciation and meaning). Although a weak form of this hypothesis has to be true (e.g., someone who does not know Chinese words could not possibly read in that language), one unstated and—as far as we know—untested prediction of the hypothesis is that, as a reader becomes more skilled, the increasingly higher quality representations in his or her lexicon should result in fluent reading, as indexed, for example, by longer saccades and fewer, shorter fixations.

adult-like eye-movement behavior to increasingly adult-like reading skill; that is, increasingly skilled eye-movement behavior (e.g., targeting saccades towards the centers of words) contributes to more efficient reading. Although this second, *oculomotor-tuning hypothesis* is less intuitive—and perhaps less plausible—than the linguistic-proficiency hypothesis, there is ample evidence that several oculomotor and visual variables do markedly affect the rate and accuracy of lexical processing. For example, the initial fixation location within a word affects the time that is required to identify the word (O'Regan & Lévy-Schoen, 1987; Vitu, McConkie, Kerr, & O'Regan, 2001). Consequently this second hypothesis also warrants some type of formal evaluation.

Finally, although it might be difficult to imagine a priori how changes in eye-movement behavior would account for the majority of the behavioral variance that is observed in the development of readers' eye movements, it is logically possible that such changes in eye-movement behavior, in conjunction with increases in linguistic processing efficiency, are both necessary to explain the observed changes. By this account, to explain how the eye movements of children come to resemble those of adults, it is necessary to understand how both linguistic processing and eye-movement control change with development. However, because of the inherent complexity of this third hypothesis (i.e., it entails interacting linguistic and oculomotor factors that change with reading skill), this article will focus on the linguistic-proficiency and oculomotor-tuning hypotheses.

In the sections of this article that follow, we will first review what is known about the various word-based variables that influence readers' eye movements and that provide some clues about what happens as children become skilled readers. The specific variables that will be discussed include word length, word frequency, and thematic role plausibility.[2] Word length is a variable that affects both where and when readers move their eyes. For example, consider what happens when a reader moves his/her eyes to a long vs. short word that happens to be located in the parafovea. Because the long word will be farther from the center of vision than the short word, a saccade directed towards the former will tend to be longer in length. And because the long word will have received less parafoveal processing than the short word, the former will tend to be fixated longer than the latter. Thus, one might gain a better understanding of how saccade targeting and programming change with development by examining how the effects of word length change with the development of reading skill. Similarly, word frequency is a variable that affects the rate and accuracy of lexical processing and, therefore, speaks to how this critical component of reading might develop with reading skill. Finally, thematic role plausibility is a variable that reflects linguistic processing and, more specifically, the use of both verb selection restrictions and world knowledge in relation to thematic assignment; the capacity to detect noun arguments that are either implausible or anomalous thus speaks to the development of the process of thematic role assignment in reading. Each of these three variables will now be discussed in their order of mention.

### *Word length and saccadic targeting*

It is generally known that a word's length (as measured in number of characters) affects both whether the word will be fixated and, if it is, the duration of the fixation. For example, longer words are more likely than shorter words to be fixated and to be the recipients of multiple fixations (Brysbaert & Vitu, 1998; McConkie & Rayner, 1976; Rayner & Fischer, 1996; Rayner & McConkie, 1976; Rayner, Sereno, & Raney, 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). And when longer words are fixated, they tend to be fixated for longer durations than shorter words, even when they are fixated only once (Rayner & Fischer, 1996; Rayner & McConkie, 1976; Rayner et al., 1996). All of these studies, however, used adult readers as subjects, and not children. To date, only five studies have explicitly examined how word length influences eye movements during reading in children.

Hyönä and Olson (1995) examined the eye movements of children (mean age = 10.5 years) reading aloud text that contained words of varying length. There were two key findings from this study. First, as the mean length of the words increased, so too did the mean *gaze duration*, or sum of first-pass

[2] Although there is also considerable evidence from studies of skilled reading that how predictable a word is from its preceding sentence context influences both how long a reader will look at the word and whether or not it is skipped (Rayner, 1998, 2009), word predictability will not be discussed in detail in this article because there are no studies examining how this variable influences beginning readers.

fixations, on those words. The second was that the mean *total-viewing time*, or the sum of all fixations on a word irrespective of whether they occurred during the first pass through the text, also increased with word length. However, despite this evidence that word length affects children's eye movements in a manner similar to what has been reported with adults, the study did not include adults to provide an explicit baseline of comparison. Furthermore, the effect of word length was assessed post hoc rather than by manipulating word length experimentally, thus introducing the possibility that some other factors confounded with word length (e.g., word frequency; Rayner & Duffy, 1986) were driving the effect.

The first of these two limitations of Hyönä and Olson's (1995) study was addressed by Vitu, McConkie, Kerr, and O'Regan (2001) in an experiment that examined the eye movements of children (mean age = 12 years) and adults, but again using post hoc analyses to examine the effects of word length. The results of these analyses again showed that children tend to make longer fixations on long than short words. In addition, measures of where the children actually looked were remarkably similar to those of the adults. For example, both groups tended to fixate longer words more often than shorter words. Both groups also tended to direct their initial fixations just to the left of the centers of the words, to the *preferred viewing location* (Rayner, 1979a). However, because of saccadic error, their fixation landing-site distributions resemble truncated Gaussians, with missing tails due to instances when the eyes under/overshot their intended targets (McConkie, Kerr, Reddix, & Zola, 1988; Rayner et al., 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). And finally, with both groups, the locations of the initial fixations also affected their durations, producing the *inverted optimal-viewing position* (*IOVP*) *effect*, or finding that single-fixation and first-fixation durations tend to be longest for fixations located near the centers of words (Nuthmann, Engbert, & Kliegl, 2005; Rayner & Fischer, 1996; Reingold, Reichle, Glaholt, & Sheridan, 2012; Vitu, McConkie, Kerr, & O'Regan, 2001). These results, therefore, suggest that word length affects the eye movements of children and adults in a very similar manner.[3]

More recently, Huestegge et al. (2009) also longitudinally assessed the development of word-length effects during oral reading in children from second to fourth grade. They found that the word-length effects decreased in magnitude from second to fourth grade. And finally, the most informative experiments showing how word length affects the eye movements of children vs. adults were reported by Joseph et al. (2009) and Blythe et al. (2011). In the experiment reported by Joseph et al., children (mean age = 10 years) and adults read the same set of sentences that were constructed to be appropriate for the children and that contained target words that were long vs. short but equated for frequency and predictability. The findings of this experiment were as follows: First, the adults read faster than the children, with the former group making longer saccades, fewer and shorter fixations, and fewer regressions than the latter group. Second, gaze durations were longer on the long than short words, but this effect of word length was more pronounced for children than adults. Similarly, both groups were more likely to refixate and less likely to skip long than short words, but these effects were again more pronounced with the children than the adults. Finally, both groups behaved very similarly with respect to where they moved their eyes: Their initial fixations were directed towards the preferred viewing locations and resulted in similar fixation landing-site distributions, and refixations were most likely to be initiated after initial fixations near the beginnings and endings of words (see also McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Rayner & Fischer, 1996; Rayner et al., 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). However, relative to the adults, the children were even more apt to making refixations following initial fixations near the ends of words, causing the refixation-probability curves to be more *U*-shaped for children than adults.

Similarly, in the experiment reported by Blythe et al. (2011), two groups of children (8–9 year-olds and 10–11 year-olds) and adult native Finnish speakers read sentences which contained 4- and 8-letter target words that were matched for both frequency and predictability in the disappearing-text paradigm. Again, the basic findings were that, in the conditions involving the normal text, both the children and adults exhibited word-length effects, with longer gaze durations and total-viewing times on the long than short words. These word-length effects were also more pronounced for the children

[3] McConkie et al. (1991) formed similar conclusions based on their analyses of children's eye movements taken from a data corpus collected by Grimes (1989).

than adults, resulting in both significant interactions between age and word length, and a marginally significant effect of word length on first-fixation durations in the youngest group of children.

The results of the experiments that were reviewed in this section thus collectively show that word length similarly affects *where* adults and children move their eyes, but that this variable had a larger effect on *when* children move their eyes. In other words, children seem to direct their eyes towards the preferred viewing locations and are more likely to initiate a refixation following initial fixations near the beginnings or endings of words, just like adults. And although children tend to fixate longer words more often and for longer durations than shorter words, these word-length effects are larger in children than adults, and larger in younger than older children.

### *Word frequency and cognitive control of fixation durations*

The frequency with which a word appears in printed text (as tabulated by various corpora; e.g., Baayen, Piepenbrock, & Gulikers, 1995; Brysbaert & New, 2009; Francis & Kucera, 1982; New, Pallier, Brysbaert, & Ferrand, 2004) is an important proxy measure for the difficulty associated with identifying a word, with another such variable being the age at which a word is first learned (Juhasz & Rayner, 2003, 2006). As such, a word's frequency of occurrence will on average strongly influence both whether it will be fixated, and, if it is, the duration of the fixation(s) on the word. For example, several eye-movement experiments have shown that high-frequency words are skipped more often and are the recipients of fewer, shorter fixations than low-frequency words (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Duffy, 1986; Rayner et al., 2004; Schilling, Rayner, & Chumbley, 1998) resulting in overall shorter fixation times on high-frequency than low-frequency words. These word-frequency effects are due to the fact that the lexical processing operations that are necessary to access a word's pronunciation and meaning from its printed form become more rapid and accurate with repeated exposure and practice (e.g., Joseph et al., in press; Taylor, Plunkett, & Nation, 2010; for a review, see Nation, 2009). By this account, as the forms and meanings of individual words become better represented in memory with practice, the words require fewer, shorter fixations for identification in printed text. However, this conclusion is based largely on studies that were completed using skilled adult readers. To reiterate, there have only been a few studies examining word-frequency effects, or indeed any lexical-level variable (although see van der Schoot, Vasbinder, Horsley, Reijntjes, & van Lieshout, 2009) in children.

One of these was the study by Hyönä and Olson (1995) that was reviewed in the previous section. In addition to examining the effects of word length, they also completed post hoc analyses to examine the effects of word frequency. These analyses indicated that the first-fixation durations, gaze durations, and total-viewing times decreased monotonically from high- to medium- to low-frequency words. In addition, the number of first- and second-pass fixations increased as word frequency decreased. However, because the words were sorted post hoc rather than being manipulated experimentally (e.g., by assigning length- and predictability-matched high- and low-frequency words to the same sentence frames; Rayner et al., 2004), these results must be interpreted with some caution because word frequency is typically confounded with other variables that influence fixation-duration measures (e.g., word length; Rayner & Duffy, 1986).

However, Blythe et al. (2009) subsequently examined how word frequency affects children's eye movements in their pair of experiments that were also discussed previously, in relation to the question of whether children and adults differ in their rate of visual information extraction. Remember that, in those experiments, a disappearing-text paradigm was used so that each word disappeared from view 40, 60, 80, or 120 ms after it was first fixated. This manipulation had negligible effects on the overall reading rate and comprehension in both children and adults. And furthermore, all three groups' eye movements were similarly affected by a manipulation of word frequency; that is, both older and younger children as well as adults tended to look at the length-equated high-frequency target words for shorter durations than the low-frequency target words, resulting in shorter single-fixations, first-fixations, and gaze durations on the high-frequency words. And interestingly, these frequency effects tended to be numerically larger for children than adults in both experiments (see Blythe et al., Table 4).

Finally, another more recent study by Joseph et al. (in press) also investigated frequency effects for target words embedded in sentences. In this experiment, Joseph et al. again compared the eye movements of adults and children (8–9 year-olds) on sentences containing high- and low-frequency target words, but using frequency counts based on child corpora and controlling for both adult frequency and age of acquisition. The most interesting aspect of Joseph et al.'s results is their finding of clear frequency effects in gaze duration for children, but not for adults. These results were interpreted as indicating that frequency counts for words will differ with age, and that the most effective manipulations of frequency in children will involve stimuli that are age specific in relation to this variable.

Taken together, these results are important because they suggest that the "decision" about when to move the eyes during reading is under cognitive control to a similar degree in both children and adults, as indicated by the fact that fixation durations are modulated by word frequency in both groups even under viewing conditions where visual information is only available for brief intervals of time. These results therefore strongly suggest that the rate of visual information extraction does not differ between children and adults, but that differences in the rate of lexical processing are instead important contributors to differences in their eye movements.

### *Thematic role plausibility and language processing*

Skilled readers are able to use both information inherent in the meanings of words (e.g., whether verbs are transitive or intransitive) and real-world knowledge to assign thematic roles to entities and objects in text. These roles include being the *agent* (i.e., whatever is doing the action described by the verb), the *instrument* (i.e., whatever is used to do the action described by the verb), the *patient* (i.e., whatever is the recipient of the action described by the verb), and so on. One demonstration that skilled readers rapidly use this thematic role information comes from an eye-movement experiment reported by Rayner, Warren, Juhasz, and Liversedge (2004). In this experiment, adult subjects read sentences containing target nouns (e.g., *carrots* in the examples below) that were either plausible patient arguments for the preceding instrument noun and verb (e.g., . . .*knife to chop*. . .), implausible patient arguments (e.g., . . .*axe to chop*. . .), or anomalous patient arguments (e.g., . . .*pump to inflate*. . .). Thus, whereas the first sentence (a) describes a completely plausible or normal situation, the second (b) describes one that is implausible (although certainly possible), and the third (c) describes one that is impossible or anomalous (at least outside of the context of some type of "cartoon world" scenario).

(a) John used a knife to chop the large carrots for dinner.
(b) John used an axe to chop the large carrots for dinner.
(c) John used a pump to inflate the large carrots for dinner.

Rayner et al. (2004) found that their subjects rapidly detected violations of both plausibility and possibility. That is, readers immediately detected violations of possibility during the first pass through the anomalous sentences, resulting in longer gaze durations on the target words in the anomalous (c) than plausible (a) sentences. And although readers also detected violations of plausibility, these effects were less immediate, manifesting as longer *go-past times* (i.e., the sum of all fixations from the first fixation on a word until the eyes move to the right of that word) for the target words in the implausible (b) than plausible (a) sentences. One explanation for this pattern of results is that adult readers are able to very quickly use thematic role information that is inherent in a verb's argument structure, along with knowledge about potential verb arguments, to construct a (quite shallow) semantic representation of a sentence, thus allowing them to rapidly detect situations that violate these verb restrictions because such situations are anomalous. However, adult readers are less facile using real-world information to help construct sentence representations, so that they are slower detecting situations that are not anomalous per se but that are instead implausible. Subsequent eye-movement experiments examining the time-course over which readers detect violations of semantic implausibility vs. anomaly have largely replicated these early findings (Warren & McConnell, 2007; Warren, McConnell, & Rayner, 2008; and for a review, see Warren, 2011), corroborating the conclusions about the differential rate with which adults can use verb selection restrictions vs. pragmatic knowledge to construct text representations.

More recently, the time-course over which readers use verb selection restrictions and pragmatic knowledge has also been examined using both children and adults (Joseph et al., 2008). Other than a very recent study investigating syntactic processing in children (Joseph & Liversedge, 2013), this experiment is currently the only published experiment examining the effects of a higher-level linguistic variable on the eye movements of both children vs. adult readers. In this experiment, children (mean age = 9.5 years) and adults read sentences like the following:

(d) Robert used a trap to catch the horrible mouse that was very scared.
(e) Robert used a hook to catch the horrible mouse that was very scared.
(f) Robert used a radio to play the horrible mouse that was very scared.

As with the example sentences that were used to explain the Rayner et al. (2004) experiment, the first sentence (d) describes a plausible situation, the second sentence (e) describes an implausible but possible situation, and the third sentence (f) describes a situation that is impossible and thus anomalous. An off-line normative study using children and adults who did not participate in the actual eye-movement experiment confirmed that both groups similarly rated the anomalous sentences as being less plausible than the implausible sentences, and that the latter were rated as being less plausible than the normal sentences. That being said, the basic findings from Joseph et al.'s (2008) eye-movement experiment were as follows.

First, the children were slower than adults at reading the sentences, exhibiting the typical pattern of making shorter saccades, more frequent and longer fixations, and more regressions. The pattern of eye movements of the adults was very similar to the one that was reported by Rayner et al. (2004), with inflated gaze durations on the target words (e.g., *mouse*) in the impossible sentences indicating rapid detection of semantic anomalies, and inflated go-past times in the post-target regions of the implausible sentences indicating that adults were slower at detecting violations of semantic plausibility. Finally, although the children also rapidly detected semantic anomalies, showing even longer gaze durations on the target words in the anomalous sentences than did the adults, the children were also much slower than the adults at detecting violations of semantic plausibility, only showing longer total-viewing times in the post-target regions of the implausible sentences. On the basis of these results, Joseph et al. (2008) concluded that, like adults, children are able to use thematic role information that is inherent within the lexical representation of a verb's argument structure to rapidly construct sentence representations, but that children are even less facile than adults at using pragmatic information to construct sentence representations.

With the brief overview of what is known about the basic characteristics of eye movements of children vs. adults and how three commonly studied word-based variables differentially affect the eye movements of the two groups, it is now possible to consider how developmental changes in the perceptual, cognitive, and/or oculomotor systems that support reading might mediate the concurrent development of eye-movement behavior and reading skill. Before doing this, however, it is first necessary to briefly describe the E-Z Reader model of eye-movement control during reading—the framework that will be used to evaluate the two hypotheses about how development mediates the changes in eye-movement behavior that occur as children become skilled readers. Recall that these hypotheses were that changes in eye-movement behavior reflect increasingly sophisticated language processing, or alternatively, that more highly tuned eye-movement behavior permits more efficient language processing.

## E-Z Reader

*E-Z Reader* is a computational model that describes how vision and cognition interact with the oculomotor system to produce the approximate patterns of eye movements that are observed during the first-pass reading of text. Because the model's theoretical assumptions are described and justified in great detail elsewhere (e.g., for the most recent version of the model, see Reichle, Pollatsek, & Rayner, 2012; for a detailed description of the model and its theoretical assumptions, see Reichle, 2011), it will only be described in enough detail here to make the simulations reported below intelligible.

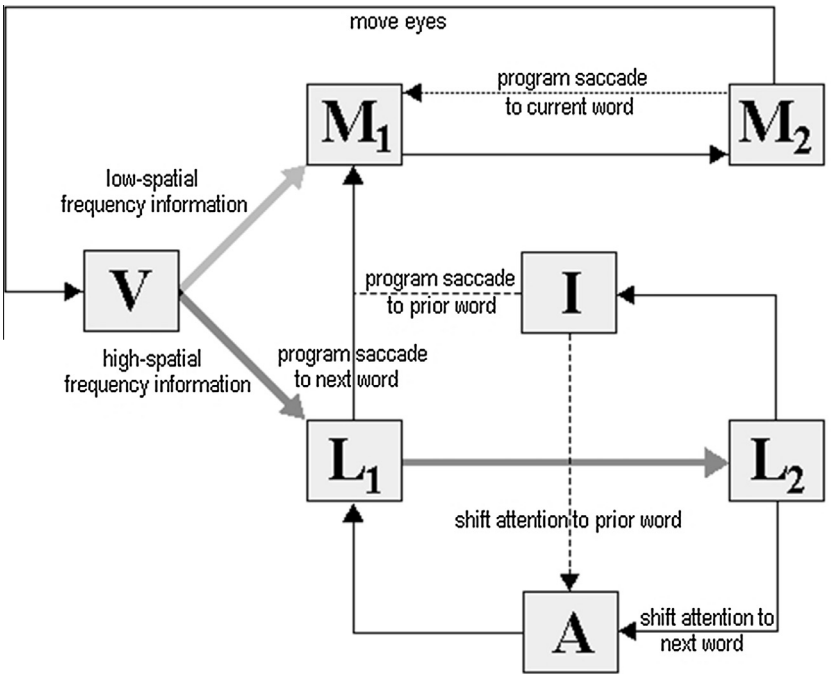


**Fig. 2.** A schematic diagram of the E-Z Reader model of eye-movement control during reading (Reichle, 2011). The components of the model are labeled as follows: (1) $V$ = pre-attentive stage of visual processing; (2) $L_1$ = familiarity check; (3) $L_2$ = lexical access; (4) $A$ = shift of attention; (5) $I$ = post-lexical integration; (6) $M_1$ = labile stage of saccadic programming; and (7) $M_2$ = non-labile stage of saccadic programming. The thick light-gray arrow represents low-spatial frequency information (e.g., word boundaries) that is used by the oculomotor system for selecting saccade targets, the thick dark-gray arrows represents high-spatial frequency information (e.g., letter identities) that is used by the word-identification system for lexical processing, the thin black arrows indicate how control passes between components of the model, and the thin dotted black arrows represent the transfer of control that occurs only probabilistically.

Fig. 2 is a schematic diagram of the model showing its functional components and how both information and the control of processing are passed among those components. The model does not provide a detailed or "mechanistic" account of any of the components shown in the figure, but instead provides a precise description of how those components dynamically interact to produce the approximate patterns of eye movements that are observed when readers initially move their eyes through text. As such, the model is—like all formal models of cognition—a simplification of the mental processes that it is used to simulate, but is for precisely that reason an extremely useful analytical tool for thinking about those mental processes.[4] (For an introduction to formal models of cognition, including a discussion of both why they are useful and their inherent limitations, see Hintzman, 1991.) Indeed, as we will demonstrate below, the results of our simulations using the E-Z Reader model provide novel predictions about which factors should and should not contribute to the developmental changes in eye movements that are observed as children become skilled readers.

The E-Z Reader model has been described as "a cognitive-control, serial-attention model" (Reichle, Pollatsek, & Rayner, 2006) because of its assumptions that: (1) cognition—or more specifically, an early stage of lexical processing called the *familiarity check*—controls the movement of the eyes through text

[4] Although the E-Z Reader model does not provide a mechanistic account of the component processes involved in reading, Heinzle, Hepp, and Martin (2010) recently implemented a biologically realistic model of eye-movement control during reading that is based on networks of spiking neurons and which shares two core assumptions with E-Z Reader—that attention is allocated in a strictly serial manner, and that the completion of an early stage of lexical processing initiates saccadic programming to move the eyes from one word to the next.

**Table 2**
The E-Z Reader parameters, their interpretation and relation to perception, cognition, and oculomotor control, and their default values.

| Type of processing | Parameter | Interpretation | Default values |
|---|---|---|---|
| Word identification | $\alpha_1$ | Mean maximum $L_1$ time (ms) | 104 |
| | $\alpha_2$ | Effect of frequency on $L_1$ time (ms) | 3.5 |
| | $\alpha_3$ | Effect of predictability on $L_1$ time (ms) | 39 |
| | $\Delta$ | Proportional difference between $L_1$ and $L_2$ | 0.34 |
| | $A$ | Mean attention-shift time (ms) | 25 |
| Language processing | $I$ | Mean integration time (ms) | 25 |
| | $p_F$ | Probability of integration failure | 0.01 |
| | $p_N$ | Probability of regression being directed to prior word | 0.5 |
| Saccadic programming and execution | $M_1$ | Mean labile programming time (ms) | 125 |
| | $\xi$ | Proportion of $M_1$ allocated to "preparatory" sub-stage | 0.5 |
| | $M_{1,R}$ | Additional time required for labile regressive programs (ms) | 30 |
| | $M_2$ | Mean non-labile programming time (ms) | 25 |
| | $\Psi$ | Optimal saccade length (character spaces) | 7 |
| | $\Omega_1$ | Effect of launch-site fixation duration of systematic error | 6 |
| | $\Omega_2$ | Effect of launch-site fixation duration of systematic error | 3 |
| | $\eta_1$ | Mean minimum random error (character spaces) | 0.5 |
| | $\eta_2$ | Effect of saccade length on random error (character spaces) | 0.15 |
| | $\lambda$ | Increase in refixation probability (character spaces) | 0.16 |
| | $S$ | Saccade duration (ms) | 25 |
| Visual processing | $V$ | Eye-to-brain transmission time (ms) | 50 |
| | $\varepsilon$ | Effect of visual acuity | 1.15 |
| Misc. | $\sigma_\gamma$ | Standard deviation of gamma distributions | 0.22 |

during reading; and (2) the type of attention that is necessary for lexical processing is allocated in a strictly serially manner, to only one word at any given time. There is thus a decoupling between the signal that initiates saccadic programming and the signal that causes attention to shift; whereas the completion of the familiarity check on word$_n$ initiates saccadic programming to move the eyes to word$_{n+1}$, the completion of lexical access on word$_n$ causes attention to move to word$_{n+1}$. The model therefore differs from other computational models that either assume that cognition has little or no immediate effect on eye movements during reading (Feng, 2006; McConkie & Yang, 2003; Yang, 2006) or that make different assumptions about how cognition affects eye movements during reading (McDonald, Carpenter, & Shillcock, 2005; Reilly, 1993; Reilly & Radach, 2003, 2006). For example, according to the *SWIFT* model, attention is allocated as a gradient that supports the concurrent processing of several words, and an autonomous timer that can be inhibited by lexical-processing difficulty determines when the eyes move (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Richter, Engbert, & Kliegl, 2006; for a review, see Engbert & Kliegl, 2011). (For a review of several current models of eye-movement control in reading, see the 2006 special issue of *Cognitive Systems Research*.)

According to the assumptions of the E-Z Reader model, the familiarity check is an early stage of lexical processing that corresponds to an overall "feeling" of familiarity (i.e., in the sense of dual-process theories of recognition; Yonelinas, 2002; see also Reichle & Perfetti, 2003) and/or a preliminary stage of word-form processing (e.g., orthographic processing; Reichle, Tokowicz, Liu, & Perfetti, 2011; Reingold & Rayner, 2006). Irrespective of the type(s) of information that might contribute to a word's familiarity, however, the functional significance of the familiarity check is that it indicates that lexical access is imminent, and thereby provides a "heuristic" that can be used to initiate saccadic programming so that the eyes leave a word right after its meaning has been accessed—neither sooner nor later (Liu & Reichle, 2010; Liu, Reichle, & Gao, in press; Reichle & Laurent, 2006; Reichle, Rayner, & Pollatsek, 2012). The mean time (in ms) required to complete the familiarity check on word$_n$ is denoted by $L_1$ and this time is modulated by a word's frequency of occurrence in printed text (as tabulated in various

corpora; e.g., Francis & Kucera, 1982) and its within-sentence cloze predictability (as tabulated by the mean proportion of subjects that correctly guess a word from its preceding sentence context; Taylor, 1953). More precisely, with some probability equal to a word's cloze predictability, word$_n$ is "guessed" from its context and the mean time to complete $L_1$ is set equal to 0 ms. However, in the vast majority of instances, the time needed to complete $L_1$ is set equal to a value specified by Eq. (1):

$$L_1 = \alpha_1 - \alpha_2 \ln(\text{frequency}_n) - \alpha_3 \text{predictability}_n \tag{1}$$

In Eq. (1), the values of the free parameter that controls the mean maximal time to complete $L_1$ (i.e., $\alpha_1$) and the parameters that control how this time is attenuated by both word frequency (i.e., $\alpha_2$) and word predictability (i.e., $\alpha_3$) are shown in Table 2.

During each Monte-Carlo simulation run of the model, the actual time to complete the familiarity check is a random deviate that is sampled from a gamma distribution with a mean specified by Eq. (1).[5] This time is then adjusted using Eq. (2) to simulate the slowing effect that visual acuity restrictions have on lexical processing; the exponent of Eq. (2) corresponds to the mean absolute spatial disparity (in character spaces) between each of the $N$ letters of the word being processed (indexed by $i$) and the fixation location, so that long words and/or words far from the center of vision require more time to process than short words and/or words close to the center of vision.

$$L_1 \leftarrow L_1 e^{\sum_{i=1}^{N} |\text{letter}_i - \text{fixation}|/N} \tag{2}$$

The mean time (in ms) required to complete lexical access, $L_2$, is given by Eq. (3) and is equal to some fixed proportion (specified by the parameter $\Delta$) of the mean time needed to complete the familiarity check (i.e., the time specified by Eq. (1)) under the assumption that the activation of a word's semantic codes requires some minimal amount of time to complete. For that reason, $L_2$ is not adjusted by eccentricity to simulate the slowing effect of visual acuity restrictions.

$$L_2 = \Delta L_1 \tag{3}$$

As indicated, the completion of lexical access causes attention to shift to the next word so that processing of it can begin. The mean time (in ms) required to do this is specified by parameter $A$, with the actual time during any given simulation also being a random deviate that is sampled from a gamma distribution. The completion of lexical access also causes post-lexical processing of that word to begin. This processing corresponds to the minimal amount of processing (in ms, as specified by the parameter $I$) that is required to "know" that there will probably be no problem integrating the word's meaning into the overall representation of the sentence that is being incrementally constructed. Importantly, this minimal integration can fail in two ways. The first is by failing to complete the integration of word$_n$ prior to the identification of word$_{n+1}$. The second is that, upon attempting to integrate word$_n$, there is some probability $p_F$ that this attempt will simply fail, and this probability reflects the difficulty of the linguistic structure of the sentence that is being processed, as might occur, for example, during the mis-parsing of a syntactically complex "garden-path" sentence (Frazier & Rayner, 1982) or when the meaning of a mis-identified word cannot be integrated into the meaning of the sentence (Levy et al., 2009; Slattery, 2009). However, irrespective of its actual cause, integration failure results in the cancelation of any pending saccadic programs, and thus a pause and/or a movement of the eyes and attention back to the source of processing difficulty. However, because the model does not provide a detailed account of linguistic processing, these regressions are directed back to where integration failed (i.e., word$_n$) with probability $p_N$ and to an earlier location (i.e., word$_{n-1}$) with probability $1 - p_N$. (This latter assumption is a proxy to mimic some of the variability that is observed in where regressions are directed under the assumption that readers may not always know precisely where the source of post-lexical processing difficulty is located.)

All of the remaining model assumptions are related to saccadic programming and execution. First, saccadic programs are completed in two successive stages: a *labile stage* that requires $M_1$ ms (on

[5] For the sake of simplicity, the durations of all of the stochastic processes in the model are sampled from gamma distributions with $\sigma = 0.22\ \mu$ (i.e., in Table 1, $\sigma_\gamma = 0.22$). It is therefore important to note that, as the mean durations of stochastic processes increase, so too does their overall variability.

average; see Footnote 5) to complete but that can be canceled by the initiation of a subsequent saccade; followed by a *non-labile stage* that requires $M_2$ ms (on average) to complete but that cannot be canceled. Furthermore, the labile stage is divided into two sub-stages: an initial stage in which the oculomotor system is "engaged" as a word target is selected, followed by a stage in which the spatial coordinates of the target are converted into a distance (or muscle force) metric. The proportion of the $M_1$ duration that is allocated to the former sub-stage is fixed by the parameter $\xi$. Finally, because of inhibition of return (e.g., see Rayner et al., 2003), regressive saccades require an additional $M_{1,R}$ ms to program.

Saccades are always directed towards the center of words, which is the *optimal-viewing position* (*OVP*) or the fixation location from where words that are displayed in isolation can be most rapidly identified (O'Regan & Lévy-Schoen, 1987). The length of any saccade that is actually executed, however, will be equal to the intended saccade length (i.e., a distance in character spaces that is represented by the variable *programmed* in Eqs. (4) and (5)), some amount of systematic error, and some amount of random error. The systematic error (in character spaces) is specified by Eq. (4), which causes programmed saccades that are longer/shorter than $\Psi$ character spaces in length to under/overshoot their intended targets. The amount of under/overshoot is also modulated by the duration of the fixation on the launch-site word (as specified by the $\Omega_1$ and $\Omega_2$ parameters in the right-most term of Eq. (4)), so that the systematic error becomes more pronounced for saccades from short fixations. Finally, the random error component of the saccade (in character spaces) is a random deviate that is sampled from a Gaussian distribution with $\mu = 0$ and $\sigma$ that increases linearly with the intended (programmed) saccade length, as specified by Eq. (5). Using Eqs. (4) and (5), the model can thus account for observations that fixation landing-site distributions on words tend to be approximately Gaussian in shape, with missing tails that reflect instances when the eyes presumably either under- or overshot their intended targets (McConkie et al., 1988; Rayner et al., 1996; Reingold et al., 2012; Vitu, O'Regan, Inhoff, & Topolski, 1995).

$$\text{systematic} = (\Psi - \text{programmed})[(\Omega_1 - \ln(\text{duration}))/\Omega_2] \tag{4}$$

$$\sigma = \eta_1 + \eta_2 \text{programmed} \tag{5}$$

The saccades themselves require $S$ ms to execute. During the actual saccades, lexical processing continues using whatever information was extracted from the page during the previous fixation and until information from the new viewing location becomes available (which requires $V$ ms, based on estimates of the eye-to-brain lag; e.g., Foxe & Simpson, 2002). Furthermore, after the eyes land on the new viewing location, there is some probability $p$ (specified by Eq. (6)) of immediately initiating a labile program to execute an "automatic" corrective saccade to rapidly move the eyes to a new viewing location—one that is typically closer to the center of the word. The rationale for this assumption is that such a saccade is more likely following an initial fixation near either end of a word because it will afford more efficient lexical processing from a better viewing location. The "decision" to refixate can be made immediately because it is presumably based on information available from an efference copy of the saccadic program that was generated to move the eyes to the word (Carpenter, 2000). Thus, according to Eq. (6), the probability of initiating a labile program to execute a corrective refixation, $p$, increases by an amount determined by the parameter $\lambda$ for each character space of absolute difference between the initial fixation on a word (i.e., *fixation* in Eq. (6)) and the intended target of that fixation—the center of the word (i.e., *OVP*).

$$p = \max[\lambda|\mathit{fixation} - \mathit{OVP}|, 1] \tag{6}$$

Another important aspect of Eq. (6) is that it allows the model to explain the IOVP effect, or the finding that fixations near the beginnings and endings of words tend to (on average) be shorter in duration than fixations near the centers of words (Vitu, McConkie, Kerr, & O'Regan, 2001): Because a fixation near either end of a word is more likely to cause the rapid initiation of a saccadic program to redirect the eyes towards the center of that word, a fixation near either end of a word will (on average) be shorter in duration than a fixation near the center of a word. This explanation of the IOVP effect is consistent with an error-correction account originally suggested by Nuthmann et al. (2005).

One final aspect of the model warrants discussion: Because attention shifts require less time than saccadic programming, lexical processing of word$_{n+1}$ usually begins when the eyes are still fixated on word$_n$, thus allowing the model to explain both parafoveal processing of upcoming words and how—on some occasions—easy-to-process parafoveal words are skipped (for an in-depth discussion of these issues, see Pollatsek et al., 2006; Reichle & Drieghe, in press). Furthermore, because the times required to both shift attention and move the eyes are (on average) constants (i.e., on average, saccades require 150 ms to program), but the time required to complete lexical access varies as a function of word-processing difficulty, the time that is available for parafoveal processing is modulated by the processing difficulty of the fixated word. The precise manner in which this happens is illustrated in Fig. 3, which shows the time course of lexical processing for a word that is being fixated and how this, in turn, modulates the amount of time that is available for parafoveal processing of the upcoming word. As the figure shows, more parafoveal processing can be completed from easy-to-process foveal words, thus allowing the model to explain how parafoveal processing is modulated by foveal load (e.g., Henderson & Ferreira, 1990; Rayner, 1986; White et al., 2005).

The preceding model assumptions are sufficient for E-Z Reader to simulate a wide variety of different reading-related phenomena, such as how eye movements might be affected by a reader's language and writing system (Chinese: Rayner, Li, & Pollatsek, 2007; French: Miellet, Sparrow, & Sereno, 2007), how older (age 70 and over) reader's eye movements differ from those of younger (college aged) readers (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006), the patterns of eye movements that are generated when readers encounter compound words (Pollatsek, Reichle, & Rayner, 2003), and how the presence vs. absence of biasing sentence context affects the patterns of eye movements that are observed when readers encounter lexically ambiguous words (Reichle, Pollatsek, & Rayner, 2007), to cite just a few examples (for a review, see Reichle, 2011). And more recently (e.g., see Reichle, Pollatsek, & Rayner, 2012; Reichle et al., in press), the model has been used to examine whether its core assumptions about serial-attention allocation and cognitive control of saccadic programming are sufficient to explain the patterns of eye movements that are observed in a variety of non-reading tasks (e.g., scanning linear arrays of Landolt *C*s to detect *O*s; Williams & Pollatsek, 2007). This work has collectively demonstrated the model's utility as a framework for examining the possible relationship between perception, cognition, and eye-movement control, and it is in exactly this spirit that the simulations reported below were completed. In other words, the model has been productively used to generate novel predictions about theoretical issues related to reading and non-reading tasks, and in the present article it is again being used in exactly this capacity to make precise predictions about the factors that are (and are not) important in the development of eye-movement control during reading.

## Simulations

As with our introductory discussion of eye movements in children vs. adults, our discussion of the simulations using E-Z Reader are organized into four sections respectively corresponding to the more global characteristics of the eye movements, and how these behaviors might be affected by oculomotor, lexical, and post-lexical (linguistic) variables. All of the reported simulations were completed using the Schilling et al. (1998) sentence corpus, 1000 statistical subjects per simulated condition, and unless otherwise indicated, all of the model's default parameter values (see Table 2 and Reichle et al., 2012).[6]

[6] The Schilling et al. (1998) sentences were used for two reasons. First, because they are relatively simple declarative sentences containing 8–14 words for which all of the lengths, frequencies, and cloze-probabilities (which are difficult to obtain) are known. And second, because the model's default parameter values were selected to maximize the goodness-of-fit between various empirical eye-movements measures collected from these sentences and the same measures as generated by the model. Although one might object that using this corpus limits the degree to which the simulation results reported in this article generalize to other subjects and/or materials, this objection can be countered as follows: First, all of our simulations are of general patterns of results that are themselves quite robust, having been demonstrated across several studies; second, the effects of specific word-based variables (e.g., word frequency) tend to be localized on specific target words and can thus be simulated using the sentences as "frames" in which properties of those target words can be embedded and manipulated; and finally, although there will be discrepancies in word-frequency estimates based on children's versus adult text corpora (cf., Joseph et al., in press), our simulations only provide qualitative demonstrations of which factors are important determinants of reading skill development, and as such our conclusions are not dependent upon accurate estimates of word frequency.

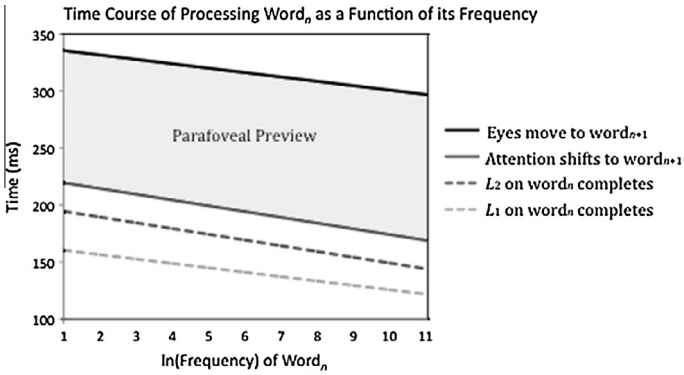


**Fig. 3.** The time course of processing word$_n$ as a function of its frequency of occurrence, and how this in turn modulates the amount of time that is available (represented by the gray region) for the parafoveal processing of word$_{n+1}$.

Because one of the main purposes of the simulations is to formally evaluate the two hypotheses that have been offered to explain the developmental patterns of eye movements that are observed in reading, it was first necessary to instantiate these hypotheses within the framework of the E-Z Reader model. Because the model has 22 free parameters, however, the task of evaluating how well various combinations of parameter values affect different measures of when and where the eyes move is a non-trivial task because the many parameters provide many degrees of freedom that can be used to "fit" the model to the observed data (for a discussion of this problem, see Myung, 2000; Zucchini, 2000). Therefore, to make this task manageable, it was necessary to consider both the range of parameter values that were plausible on a priori grounds, as well as how the values of those parameters might be predicted to change with development based on what is already known about how the patterns of eye movements actually change with increasing reading skill.

For example, consider the two parameters that control how long it takes to program a saccade—$M_1$ and $M_2$ (see Table 2). In the model, increasing the value of either of these parameters will increase the time required to program a saccade, which in turn increases the time available for parafoveal processing (see Fig. 3), modulates the probability of making "corrective" refixations (see Eq. (6)), and thereby interacts with other aspects of the model's performance in complex ways. However, on the basis of prior research using both reading (Reingold et al., 2012) and non-reading tasks (Becker & Jürgens, 1979; Molker & Fisher, 1999; Rayner, Slowiaczek, Clifton, & Bertera, 1983), it has been estimated that adults require a minimum of 100–175 ms to program eye movements. That being the case, the parameters that determine how long it takes to program a saccade in the model are constrained in that they must be set equal to values within this range. Furthermore, given the model's estimates for how long it takes adults to program a saccade (150 ms; see Table 2), and given that only an assumption that children are less rapid than adults at saccadic programming could (by itself) explain why fixations are *longer* in children than adults (e.g., Rayner, 1986), the choice of saccadic-programming parameter values that one might use to explain the observation of longer fixation durations in children is not completely arbitrary. The choice of parameter values is instead fairly tightly constrained—the values must be increased, but probably not by more than 50–75 ms if the minimal saccadic latencies of children are not to be so long as to be implausible.

Such a consideration and others (e.g., differences in the rate of lexical processing in children vs. adults) result in a fairly circumscribed set of assumptions about how the model's default parameter values (which were selected to simulate the eyes movements of adult readers) might be adjusted to explain the overall pattern of eye movements that is observed with children. These hypothetical adjustments and their justification (or alternatively, their theoretical implications) are listed in Table 3, where they are organized according to the two general hypotheses that were discussed earlier and that were proposed to explain how eye movements change with reading skill. (A detailed exposition of these hypotheses and the method that was used to evaluate them is provided below.) It is important

**Table 3**
How three developmental hypotheses are instantiated within the framework of the E-Z Reader model: Relevant parameters, their adult (default) values, and their hypothetical values for children and the implications of these values.

| Hypotheses | Parameters | Adult values | Child values | Theoretical implications of children's parameter values |
|---|---|---|---|---|
| Linguistic-proficiency | $\alpha_1$ | 104 | >104 | Slower overall rate of lexical processing |
| | $\alpha_2$ | 3.5 | ? | Lexical processing rate is more/less modulated by word frequency and/or predictability |
| | $\alpha_3$ | 39 | ? | Lexical processing rate is more/less modulated by word frequency and/or predictability |
| | $\Delta$ | 0.34 | <0.34 | Less able to use word familiarity to initiate saccadic programming |
| | $I$ | 25 | >25 | Slower construction of linguistic structures from text |
| | $p_F$ | 0.01 | >0.01 | Less accurate construction of linguistic structures from text |
| Oculomotor-tuning | $M_1$ | 125 | >125 | Slower saccadic programming |
| | $M_2$ | 25 | >25 | Slower saccadic programming |
| | $\Psi$ | 7 | ? | Oculomotor system is not "tuned" to prefer 7-character saccades |
| | $\Omega_1$ | 6 | ? | Systematic error is more/less modulated by launch-site fixation duration |
| | $\Omega_2$ | 3 | ? | Systematic error is more/less modulated by launch-site fixation duration |
| | $\eta_1$ | 0.5 | >0.5 | Saccades more prone to random error |
| | $\eta_2$ | 0.15 | >0.15 | Saccades more prone to random error |

to acknowledge, however, that our a priori predictions about how the model's parameter values might be adjusted to accommodate the patterns of eye movements observed with children vary in terms of their specificity. For example, the value of $L_1$, the parameter that controls the overall rate of lexical processing (see Eq. (1)), would a priori have to be increased if differences in this parameter value are to explain differences between children and adults, while predictions about $L_2$, the parameter that controls how word frequency modulates the rate of lexical processing, are much less clear. Thus, whereas some of the simulations reported below evaluate the effect of selectively increasing *or* decreasing parameter values to test specific hypotheses, other simulations were completed twice to evaluate the effect of both increasing *and* decreasing parameter values to test non-directional hypotheses.

Finally, because the E-Z Reader model's numerous parameters can interact in complex ways, it was also important to exhaustively examine all of its parameters to determine if some non-intuitive adjustments of the model's parameter values might also be sufficient to account for the main developmental patterns that are observed in readers' eye movements. This exhaustive evaluation was completed for two reasons. The first was to avoid possible criticisms of having "cherry picked" specific parameters to evaluate—parameters that might lend themselves to simulating children's eye movements in a manner that confirms our collective intuitions about factors that should be important. The second was that it provides a more rigorous "test" of the model's assumptions by allowing for the possibility that some non-obvious—and possibly demonstrably false—adjustments of the model's parameters are also sufficient to simulate children's eye movements. To facilitate the exposition of our simulation results, they are discussed in three sections, corresponding to parameters related to the linguistic-proficiency hypothesis (see Tables 4 and 5), parameters related to the oculomotor-tuning hypothesis (see Table 6), and the remaining model parameters that are not specifically related to either language processing or saccadic programming/execution (see Table 7).

### *Simulating the basic characteristics of eye movements during reading*

As indicated previously, the most basic difference between children and adults is that the former read more slowly than the latter and, as such, tend to make shorter saccades, more frequent and longer fixations, and more regressions. Any explanation of the concurrent development of reading skill and eye-movement behavior during reading must therefore be able to account for this basic pattern of differences between children and adults. That being said, our first simulation was intended to adjudicate

between two general accounts of these differences—the linguistic-proficiency vs. oculomotor-tuning hypotheses.

This was done by examining the model's overall performance in reading the Schilling et al. (1998) sentences with each of the two hypotheses instantiated within the framework of the model. Six dependent measures of this performance were examined: (1) Mean number of fixations per sentence (mean sentence length = 11.17 words); (2) mean fixation duration (in ms); (3) mean forward saccade length (in characters); (4) mean proportion of saccades that were regressions; (5) mean reading rate (in wpm); and (6) mean perceptual span. As indicated earlier, a large number of studies (see Blythe & Joseph, 2011) have independently shown that, relative to adult readers, children tend to make more fixations that are longer in duration, shorter saccades, and more regressive saccades, resulting in a slower overall rate of reading and a smaller perceptual span.

Because it is not possible to simulate the moving-window paradigm using the E-Z Reader model,[7] in our simulations we estimated the efficiency of parafoveal processing using an alternative method—by measuring the amount of benefit that accrues from having a valid as compared to an invalid parafoveal preview of an upcoming target word, as measured using the *boundary paradigm* (Rayner, 1975). In this gaze-contingent paradigm, either a valid preview of a target word (i.e., the target itself) or an invalid preview (e.g., a string of *X*s or random letters) is displayed in a target location until the subject's eyes cross an invisible boundary immediately to the left of the target, at which point the target word replaces the invalid preview in the invalid-preview condition. By comparing fixation-duration measures on the target word in valid- vs. invalid-preview conditions, it is possible to determine how much processing of the target word occurs prior to it actually being fixated (i.e., from the parafovea). On average, gaze durations are 40–50 ms shorter on the target word when it is preceded by a valid as compared to invalid preview (Schotter, Angele, & Rayner, 2012). This *preview benefit* indicates that attention shifts from the pre-target word to the target word rapidly enough to allow 40–50 ms of processing of the target (Hyönä, Bertram, & Pollatsek, 2004). If parafoveal processing in children is less efficient than that of adults, then children should show less preview benefit than adult readers. Therefore, in the simulations reported below, the preview benefit on the Schilling et al. (1998) target words is our measure of parafoveal processing efficiency.

Finally, to implement and evaluate possible instantiations of the linguistic-proficiency vs. oculomotor-tuning hypotheses using E-Z Reader, we adopted the simple strategy of independently manipulating the values of those model parameters that are related to lexical and language processing, on the one hand, and saccadic programming and execution, on the other. (And as already indicated, the remaining model parameters were also manipulated for the purposes of exhaustively evaluating the model's capacity to explain developmental patterns of eye movements during reading.) The value of each parameter was incrementally varied across a range of at least five plausible values using equal-sized increments. Tables 4, 6 and 7 show the results of these simulations, organized by the individual parameters (in rows) and the basic phenomena being simulated (column). The top row shows the dependent measures for each of the phenomena that are predicted using the model's default (adult) parameter values. Each subsequent row then shows the dependent measures that are predicted by the model using a range of values that, on a priori consideration of the data being simulated, might explain those data. Finally, the last column provides a qualitative evaluation of each simulation: Simulations that are qualitatively consistent with what has been observed with children are indicated with pluses and those that are inconsistent are indicated with minuses.[8] (Values that are neither consistent nor inconsistent are unmarked.) The sections that follow provide an explanation of each of the simulations and the extent to which changes in their corresponding parameter values are sufficient to

[7] This limitation stems from the fact that the model does not provide a detailed account of lexical processing, and as such does not explain how the rate of lexical processing is affected when only some portion of a word's letters are available for processing (as occurs when a moving window exposes some portion of an upcoming word).

[8] Our metric for deciding whether adjusting a parameter value affected a dependent variable in a manner consistent with what is observed with children is somewhat arbitrary but is simple and consistent—a 5% change in the correct direction (e.g., longer fixation durations) for number of fixations per sentence, fixation durations, saccade lengths, and reading rate resulted in a plus symbol in Tables 4, 6 and 7, as did a 50% increase in the probability of making a regression and a 10% decrease in parafoveal processing efficiency. Similarly, changes in each of the respective dependent variables of the same magnitude but in the incorrect direction resulted in a minus symbol in Tables 4, 6 and 7.

**Table 4**
Results of simulations to evaluate how changing default (adult) parameter values associated with the linguistic-proficiency hypothesis about age-related differences in reading (see Table 2) affect six dependent measures diagnostic of children's eye-movement behavior during reading.

| Sim. # | Parameters | Range of values tried (increments) | Mean # fixations per sentence | Mean fixation duration (ms) | Mean saccade length (characters) | Mean probability of making Regression | Reading rate (wpm) | Parafoveal processing efficiency (mean preview benefit; ms) | Simulated results consistent w/observations? |
|---|---|---|---|---|---|---|---|---|---|
| Default (adult) parameter values | | | 7.28 | 215 | 6.28 | 0.04 | 315 | 43 | N/A |
| 1 | $\alpha_1$ | 104–208 (4) | 7.28–9.03 (+) | 215–319 (+) | 6.28–5.93 (+) | 0.04–0.09 (+) | 315–177 (+) | 43–23 (+) | Yes |
| 2a | $\alpha_2$ | 3.5–0 (0.5) | 7.28–7.81 (+) | 215–235 (+) | 6.28–6.12 | 0.04–0.05 | 315–271 (+) | 43–37 (+) | ? |
| 2b | $\alpha_2$ | 3.5–7 (0.5) | 7.28–6.32 (−) | 215–202 (−) | 6.28–6.87 | 0.04 | 315–384 (−) | 43–45 | No |
| 3a | $\alpha_3$ | 39–0 (3) | 7.28–7.41 | 215–217 | 6.28–6.24 | 0.04 | 315–307 | 43–42 | No |
| 3b | $\alpha_3$ | 39–60 (3) | 7.28–7.22 | 215–214 | 6.28–6.31 | 0.04 | 315–319 | 43–42 | No |
| 4a | $\Delta$ | 0.34–0 (0.02) | 7.28–6.97 | 215–209 | 6.28–6.44 | 0.04 | 315–338 (−) | 43–48 (−) | No |
| 4b | $\Delta$ and $\alpha_1$ | See Table 5 | 7.28–7.77 (+) | 215–239 (+) | 6.28–6.17 | 0.04–0.06 (+) | 315–268 (+) | 43–41 | ? |
| 5 | $I$ | 25–125 (10) | 7.28–8.8 (+) | 215–212 | 6.28–5.82 (+) | 0.04–0.05 | 315–264 (+) | 43–52 (−) | No |
| 6 | $p_F$ | 0.01–0.15 (0.01) | 7.28–8.59 (+) | 215–217 | 6.28–6.09 | 0.04–0.1 (+) | 315–264 (+) | 43–42 | No |

*Note:* "+" Indicates simulated values that are (qualitatively) consistent with children's data;
"–" indicates simulated values that are (qualitatively) inconsistent with children's data (see Footnote 8).

**Table 5**
Values of $\alpha_1$ and $\Delta$ used to equate total lexical-processing times to examine how increasing the disparity between the familiarity check vs. lexical access affects eye movements in Simulation 4b (see Table 4).

| $\alpha_1$ | $\Delta$ | Mean familiarity check time [$t(L_1)$ ms] | Mean lexical access time [$t(L_2)$ ms] | Mean total lexical-processing time [$t(L_1) + t(L_2)$ ms] | Prop. of total lexical-processing time required for familiarity check |
|---|---|---|---|---|---|
| 104 | 0.34 | 104 | 35.36 | 139.36 | 0.75 |
| 139.36 | 0 | 139.36 | 0 | 139.36 | 1 |

explain children's eye movements. As indicated, this discussion will be organized around the linguistic-proficiency and oculomotor-tuning hypotheses.

*Linguistic-proficiency hypothesis*

By this hypothesis, changes in the values of one or more of the lexical- and/or language-processing parameters should be sufficient to account for the observed changes in the basic patterns of eye movements that are observed when children become skilled adult readers. The first attempt to evaluate this hypothesis involved the independent manipulation of four parameters that control the rate of lexical processing in E-Z Reader: (1) $\alpha_1$, the parameter that determines the overall (intercept) rate of lexical processing; (2) $\alpha_2$, the (slope) parameter that controls the degree to which lexical processing is modulated by word frequency; (3) $\alpha_3$, the (slope) parameter that controls the degree to which lexical processing is modulated by word predictability; and (4) $\Delta$, the parameter that controls the proportion of the total lexical-processing time that is required to complete the familiarity check.

Because larger values of $\alpha_1$ slow the rate of lexical processing by increasing the time required to complete the familiarity check (see Eq. (1)), increasing the value of this parameter increased the mean fixation duration (see Table 4, Sim. 1). Larger values of $\alpha_1$ also generated more fixations because the automatic refixations that are initiated following mis-located fixations (Eq. (6)) were less likely to be canceled by the rapid completion of the familiarity check on a word following its initial fixation. The fact that there were more refixations in turn caused both a decrease in the mean length of the forward saccades and an overall increase in the proportion of regressive saccades. All of these factors contributed to reduce the overall rate of reading. And finally, because larger values of $\alpha_1$ also increased the time required to complete lexical access (Eq. (3)), there was less time available for parafoveal processing of upcoming words, which caused the parafoveal processing efficiency (as measured by preview benefit) to decrease to approximately half of its normal (adult) value. Thus, as Table 4 shows, according to the model, a simple decrease in the overall rate of lexical processing is sufficient to account for all of the differences in eye movements that have been observed between children and adult readers (Blythe & Joseph, 2011). However, this result should not be taken to suggest that a slower rate of lexical processing has no other effect on reading ability; for example, less efficient lexical processing might also cause less efficient (post-lexical) linguistic processing if the latter is dependent upon the former. What the simulation does show, however, is that a decreased rate of lexical processing is by itself all that is necessary to explain the differences (listed in Table 4) that have been reported between the eye movements of children and skilled adults readers.

As Table 3 indicates, there is more uncertainty about how the values of the next two lexical-processing parameters ($\alpha_2$ and $\alpha_3$) should be adjusted to account for children's eye movements: On the one hand, decreasing the values of these parameters should slow the rate of lexical processing, resulting in a pattern very similar to the one that resulted from increasing the value of $\alpha_1$; on the other hand, the fact that children are slower at processing words might exaggerate any differences due to word frequency and/or predictability, thus justifying larger values for these two parameters. To examine both of these possibilities, the effects of using both smaller (Sims. 2a and 3a) and larger values (Sims. 2b and 3b) were examined. As Table 4 shows, neither type of change produced the pattern of eye movements observed with children. For example, although smaller values of $\alpha_2$ (Sim. 2a) increased the mean number and duration of fixations, slowed the overall rate of reading, and decreased

**Table 6**
Results of simulations to evaluate how changing default (adult) parameter values associated with the oculomotor-tuning hypothesis about age-related differences in reading (see Table 2) affect six dependent measures diagnostic of children's eye-movement behavior during reading.

| Sim. # | Parameters | Range of values tried (increments) | Mean # fixations per sentence | Mean fixation duration (ms) | Mean saccade length (characters) | Mean probability of making regression | Reading rate (wpm) | Parafoveal processing efficiency (mean preview benefit; ms) | Simulated results consistent w/observations? |
|---|---|---|---|---|---|---|---|---|---|
| Default (adult) parameter values | | | 7.28 | 215 | 6.28 | 0.04 | 315 | 43 | N/A |
| 1 | $M_1$ | 125–175 (5) | 7.28–6.31 (−) | 215–261 (+) | 6.28–6.71 | 0.04–0.02 (−) | 315–305 | 43–58 (−) | No |
| 2 | $M_2$ | 25–75 (5) | 7.28–7.03 | 215–244 (+) | 6.28–6.38 | 0.04 | 315–291 (+) | 43–63 (−) | No |
| 3a | $\Psi$ | 7–3 (0.5) | 7.28–7.62 | 215–217 | 6.28–5.78 (+) | 0.04–0.02 (−) | 315–298 (+) | 43–47 (−) | No |
| 3b | $\Psi$ | 7–11 (0.5) | 7.28–7.23 | 215–209 | 6.28–6.86 | 0.04–0.07 (+) | 315–326 | 43–30 (+) | No |
| 4a | $\Omega_1$ | 6–5.3 (0.1) | 7.28–7.23 | 215–218 | 6.28–6.33 | 0.04 | 315–313 | 43–46 | No |
| 4b | $\Omega_1$ | 6–8.3 (0.1) | 7.28–8.44 (+) | 215–198 (−) | 6.28–6.55 | 0.04–0.09 (+) | 315–293 (+) | 43–25 (+) | No |
| 5a | $\Omega_2$ | 3–0.7 (01) | 7.28–8.98 (+) | 215–198 (−) | 6.28–6.93 | 0.04–0.14 (+) | 315–275 (+) | 43–22 (+) | No |
| 5b | $\Omega_2$ | 3–15 (1) | 7.28–7.17 | 215–218 | 6.28 | 0.04 | 315 | 43–46 | No |
| 6 | $\eta_1$ | 0.5–1 (0.05) | 7.28–7.46 | 215–211 | 6.28–6.34 | 0.04–0.05 | 315–312 | 43–37 (+) | No |
| 7 | $\eta_2$ | 0.15–0.5 (0.05) | 7.28–8.68 (+) | 215–198 (−) | 6.28–7.18 (−) | 0.04–0.16 (+) | 315–285 (+) | 43–31 (+) | No |
| 8a | $\lambda$ | 0.16–0 (0.02) | 7.28–6.65 (−) | 215–236 (+) | 6.28–6.33 | 0.04–0.01 (−) | 315–317 | 43–42 | No |
| 8b | $\lambda$ | 0.16–0.3 (0.02) | 7.28–7.94 (+) | 215–200 (−) | 6.28–6.24 | 0.04–0.07 (+) | 315–308 | 43–38 (+) | No |
| 9a | $M_{1,R}$ | 30–0 (5) | 7.28–7.3 | 215 | 6.28–6.27 | 0.04 | 315–314 | 43–44 | No |
| 9b | $M_{1,R}$ | 30–60 (5) | 7.28–7.27 | 215–216 | 6.28–6.29 | 0.04 | 315–314 | 43–44 | No |
| 10a | $p_N$ | 0.5–0 (0.05) | 7.28–7.33 | 215 | 6.28–6.27 | 0.04 | 315–312 | 43–44 | No |
| 10b | $p_N$ | 0.5–1 (0.05) | 7.28–7.24 | 215 | 6.28 | 0.04 | 315–316 | 43–42 | No |
| 11a | $\xi$ | 0.5–0 (0.05) | 7.28–7.11 | 215–229 (+) | 6.28–6.36 | 0.04–0.03 | 315–304 | 43–44 | No |
| 11b | $\xi$ | 0.5–1 (0.05) | 7.28–7.41 | 215–210 | 6.28–6.23 | 0.04 | 315–316 | 43–44 | No |
| 12 | $S$ | 25–50 (5) | 7.28–7.18 | 215–204 (−) | 6.28–6.35 | 0.04 | 315–301 | 43–59 (−) | No |

*Note:* "+" Indicates simulated values that are (qualitatively) consistent with children's data;
"−" indicates simulated values that are (qualitatively) inconsistent with children's data (see Footnote 8).

**Table 7**
Results of simulations to evaluate how changing default (adult) parameter values associated with no specific hypotheses about age-related differences in reading affect six dependent measures diagnostic of children's eye-movement behavior during reading.

| Sim. # | Parameters | Range of values tried (increments) | Mean # fixations per sentence | Mean fixation duration (ms) | Mean saccade length (characters) | Mean probability of making regression | Reading rate (wpm) | Parafoveal processing efficiency (mean preview benefit; ms) | Simulated results consistent w/observations? |
|---|---|---|---|---|---|---|---|---|---|
| Default (adult) parameter values | | | 7.28 | 215 | 6.28 | 0.04 | 315 | 43 | N/A |
| 1 | $V$ | 50–100 (5) | 7.28–7.54 | 215–228 (+) | 6.28–6.27 | 0.04–0.05 | 315–289 (+) | 43–60 (−) | No |
| 2 | $\varepsilon$ | 1.15–1.3 (0.01) | 7.28–8.29 (+) | 215–268 (+) | 6.28–6.09 | 0.04–0.07 (+) | 315–227 (+) | 43–2 (+) | ? |
| 3 | $A$ | 25–50 (2.5) | 7.28–6.23 (−) | 215–223 | 6.28–6.72 | 0.04 | 315–373 (−) | 43–33 (+) | No |
| 4 | $\sigma_\gamma$ | 0.22–0.38 (0.04) | 7.28–7.13 | 215–216 | 6.28–6.46 | 004–0.05 | 315–320 | 43–40 | No |

*Note:* "+" Indicates simulated values that are (qualitatively) consistent with children's data;
"−" indicates simulated values that are (qualitatively) inconsistent with children's data (see Footnote 8).

parafoveal processing efficiency, it did not increase either the mean saccade length or the rate of regressions. And what is perhaps even more problematic is that smaller values of $\alpha_2$ would presumably reduce the size of the word-frequency effect in children, contrary to the finding that such effects actually tend to be larger with children than adults (Blythe et al., 2009). Finally, changing the value of the parameter that modulates the effect of word predictability, $\alpha_3$, had very little effect on any of the dependent measures because predictable words also tend to be short and frequent and are thus likely to be rapidly processed irrespective of how their lexical processing rate is modulated by predictability.

The last parameter directly related to lexical processing is $\Delta$, the parameter that controls the difference in the amount of time required to complete the familiarity check vs. lexical access (see Fig. 3). The results of a recent series of simulations (Reichle et al., 2012) using the E-Z Reader to examine several non-reading tasks (e.g., scanning arrays of Landolt-*C* to find an *O* target letter; Williams & Pollatsek, 2007) suggest that, relative to these tasks, reading affords more of a decoupling between the signal to initiate saccadic programming (i.e., the familiarity check) and the signal to shift attention (i.e., lexical access). This suggests that the familiarity check might emerge through extensive practice, as a reader learns to use cues that are rapidly available and that are predictive of lexical access to initiate saccadic programming. Given that children have much less reading experience than adults, this hypothesis about how readers might learn to use the familiarity check suggests that children may be less reliant on the familiarity check during reading, and that a smaller value of the $\Delta$ parameter might be necessary to account for children's eye-movement behavior. Contrary to this prediction, however, smaller values of $\Delta$ actually had little effect on the dependent measures reported in Table 4 (Sim. 4a). This null finding is largely due to the fact that, although decreasing the value of $\Delta$ increased the proportion of the completed lexical-processing time required to initiate saccadic programming, it also reduced the overall lexical-processing time. And as Table 4 shows, smaller values of $\Delta$ also *increased* parafoveal processing efficiency because more time was available between when lexical access of a word finished and when the eyes moved to the next word. This last finding is contrary to what is observed with children, and thus suggests that smaller values of $\Delta$ are not sufficient to explain children's eye movements.

However, one might argue that this evaluation of the $\Delta$ parameter was not a fair test because the value of $\alpha_1$ was held constant, which meant that, as $\Delta$ decreased from 0.34 to 0, so too did the overall word-identification latencies [i.e., $t(L_1) + t(L_2)$]. Thus, whatever processing loss might result from triggering the saccade relatively late in the course of lexical processing (i.e., by using smaller values of $\Delta$) was offset by the fact that words required less time to identify. To address this potential limitation, a second simulation was completed (Sim. 4b) to evaluate how changing values of $\Delta$ might influence eye movements. In this simulation, the values of $\Delta$ and $\alpha_1$ were manipulated concurrently so that the overall lexical-processing latencies could be held constant (139.36 ms). Table 5 shows the precise parameter values that were used and how these values modulated the familiarity check and lexical access durations. Importantly, as the value of $\Delta$ now decreased from 0.34 (i.e., the optimal value for simulating adults) to 0, the familiarity check became increasingly slower, consuming a larger portion of the total time needed to complete lexical processing of words. And as Table 4 shows, this produced many of the effects that one would expect if children rely less upon the familiarity check for saccadic programming: As the value of $\Delta$ decreased from 0.34 to 0 and the familiarity check consumed more of the total lexical-processing time, both the mean number and duration of fixations increased, the proportion of regressions increased, and the overall reading rate decreased. The results of this simulation thus suggest that increasing reliance upon word familiarity (as simulated by using increasingly large values of $\Delta$) might explain some of the changes that occur in children's eye movements as they learn to read. However, for this variant of the linguistic-proficiency hypothesis to be viable, it would have to be one of two or more factors that contribute to the developmental pattern of eye movements (cf., Sims. 4a vs. 4b). For example, an increasing reliance upon familiarity (i.e., larger values of $\Delta$) in conjunction with a general speed up of lexical processing (i.e., smaller values of $\alpha_1$) would be sufficient to explain the full pattern of eye-movement results that are observed as children become adult readers.

Finally, the last two parameters that might in principle differ between children and adults if the linguistic-proficiency hypothesis is correct are $I$ and $p_F$, the parameters that respectively modulate the time needed to complete post-lexical integration and the probability that this process will result in some type of integration failure. Because children have less experience reading than adults, it is only reasonable to assume that integration will take longer and/or be more prone to error in children than

adults. Both of these possibilities were examined, but as Table 4 (Sims. 5 and 6) shows, neither was sufficient to account for the complete pattern of children's data. Although increasing the value of $I$ (Sim. 5) increased the number of fixations, decreased the saccade length, and slowed reading, it did not affect the fixation durations or the proportion of regressions, and actually increased the parafoveal processing efficiency. Similarly, although increasing the value of $p_F$ (Sim. 6) increased the number of fixations, the proportion of regressions, and slowed reading, it did not affect fixation durations, saccade length, or parafoveal processing efficiency. Thus, although the model suggests that problems associated with higher-level (i.e., post-lexical) linguistic processing might also contribute to some of the differences that are observed between the eye movements of children and adults, these problems are not likely to explain all of those differences (e.g., the smaller perceptual span of children).

Based on these results, it is unlikely that increasingly efficient post-lexical processing is the primary cause of the differences that are observed in the eye movements of children vs. adults. These differences seem to instead reflect a simple speed up in the overall rate of lexical processing, as demonstrated by the fact that these changes can actually be simulated by increasing the value of the $\alpha_1$ parameter in the E-Z Reader model. However, it is worth emphasizing once again that efficient post-lexical processing may be critically dependent upon efficient lexical processing. That is, although differences in the rate and accuracy of post-lexical processing do not seem to be sufficient to explain the full pattern of differences between the eye movements of children vs. skilled adults, a decreased rate of lexical processing (which does appear to be sufficient to explain such differences) might also result in slower and/or less accurate higher-level processing if the latter is critically dependent upon the former. For example, although the lexical processing that is associated with a mis-identified word still might be sufficient to move the eyes forward, the meaning of that word would presumably cause post-lexical integration to fail, resulting in pauses and/or regressions (Levy et al., 2009; Slattery, 2009). And it is reasonable to assume that these problems with comprehension would occur more often with children than adults to the extent that the former group is more likely to mis-identify words.

Given that the simulations reported in this section provide some preliminary support for this simple version of the linguistic-proficiency hypothesis, we now turn to the alternative explanation and evaluate the plausibility of the oculomotor-tuning hypothesis. Before doing so, however, it is again worth emphasizing that our conclusions about the sufficiency of the linguistic-proficiency hypothesis are not established fact, but instead should be viewed as a hypothesis that has been made more precise and garnered additional support by having been shown to be feasible when instantiated within the framework of a well-established formal model of eye-movement control during reading, E-Z Reader.

*Oculomotor-tuning hypothesis*

Another possible explanation for the observed differences between the eye movements of children vs. adults is that children are slower and/or less accurate at moving their eyes during reading. By this account, slower and/or less accurate eye movements play a causal role in reading comprehension. For example, inaccurate saccades might cause the eyes to move to poor viewing locations, which in turn might be predicted to slow lexical processing and possibly increase the probability of misidentifying words. A slower rate of lexical processing would obviously translate into a slower overall rate of reading, but an increased propensity to misidentify words might also result in problems with higher-level (post-lexical) language processing, increasing fixation durations and making regressions more likely. Thus, in contrast to the linguistic-proficiency hypothesis, in which poor language-processing skills cause the patterns of eye movements that are observed with children, the oculomotor-tuning hypothesis would maintain that problems associated with the movement of the eyes are what cause language processing difficulty.

The simplest variant of the oculomotor-tuning hypothesis is that children require more time to program saccades. To evaluate this hypothesis, simulations were completed using larger values of $M_1$ and $M_2$, the parameters that specify the mean times required to complete the labile and non-labile stages of saccadic programming, respectively. As Table 6 shows, increasing the values of $M_1$ (Sim. 1) and $M_2$ (Sim. 2) did not produce the correct pattern of results; although larger values of these parameters did increase the mean fixation duration, they had little effect on most other measures, and actually increased the perceptual span. These last finding is completely contrary to what is observed with

children and, as such, it suggests that the hypothesis that children require more time to program saccades—at least as implemented within the E-Z Reader model—is unlikely to explain thedifferences that are observed between the eye movements of children vs. adults.

The next variant of the oculomotor-tuning hypothesis is that whatever "tuning" of the oculomotor system occurs and is ultimately responsible for the systematic portion of saccadic error (see Eq. (4)) is not completely established in children. For example, adults show a preference to make 7–8 character saccades, with shorter/longer saccades tending to over/undershoot their intended targets by about half a character space for each character space of deviation between the preferred saccade length and the intended saccade length. And with adult readers, this systematic error is also modulated by the fixation duration on the launch-site word. In the E-Z Reader model, these characteristics of the systematic error are controlled by three parameters: $\Psi$, the parameter that controls the preferred saccade length, and $\Omega_1$ and $\Omega_2$, the parameters that control how the launch-site fixation duration modulates the size of the systematic error. Therefore, to evaluate this hypothesis, simulations were completed using a range of values that were less than and greater than the default (adult) values (see Table 6, Sims. 3–5). As Table 6 shows, none of these simulations were sufficient to explain the full pattern of differences between children and adults. For example, although smaller values of $\Omega_2$ did increase the mean number of fixations, increase the proportion of regressions, slow the rate of reading, and decrease parafoveal processing efficiency, they also decreased the mean fixation duration. This suggests that possible developmental changes associated with the systematic range error—as implemented in E-Z Reader model—are not sufficient to explain the full pattern of differences that are observed in children's vs. adults' eye movements.

A third variant of the oculomotor-tuning hypothesis is that children's eye movements are simply more prone to (random) motor error. By this account, children lack the fine motor skills that are necessary to accurately move their eyes in that manner that is required to support optimal reading. In the E-Z Reader model, the amount of random motor error is controlled by two parameters (see Eq. (5)): $\eta_1$, the (intercept) parameter that determines the minimal amount of error, and $\eta_2$, the (slope) parameter that determines how much the error increases as a function of the intended saccade length. According to this third version of the oculomotor-tuning hypothesis, the values of these two parameters should be larger in children than adults. Therefore, to evaluate this hypothesis, two simulations (Sims. 6 and 7) were completed using a range of parameter values that were larger than the default (adult) values. As Table 6 shows, these simulations were not successful in accounting for the developmental changes in children's eye movements. Although larger values of $\eta_2$ (Sim. 7) increased the mean number of fixations and rate of regressions and reduced the reading rate and parafoveal processing efficiency, they also decreased the mean fixation duration and increased the mean saccade length. Thus, it is unlikely that reduced saccade accuracy can by itself explain all of the differences that are observed between the eye movements of children vs. adult readers.

The final "variant" of the oculomotor-tuning hypothesis was not a specific hypothesis per se, but was instead a series of simulations that were completed to exhaustively evaluate the consequences of adjusting each of the remaining model parameters that are in some way related to saccadic programming and/or execution: (1) $\lambda$, the parameter that controls the propensity to initiate "automatic" corrective refixations (see Eq. (6)); (2) $M_{1,R}$, the additional time that is required to complete the labile stage of programming for regressive saccades; (3) $p_N$, the probability of directing regressive saccades back to the preceding word; (4) $\xi$, the proportion of the labile programming stage that is required to "engage" the oculomotor system; and (5) $S$, the durations of the actual saccades. With the exception of one of those parameters (i.e., $S$), a pair of simulations was completed to evaluate the consequences of using values of each parameter that were smaller and larger than their default (i.e., adult) values. As Table 6 shows (see Sims. 8–12), the values of these parameters had little effect on the majority of the dependent measures. As such, the simulations demonstrate that these aspects of saccadic programming and execution—as implemented within E-Z Reader—are not sufficient to explain developmental changes in readers' eye movements.

The results of the simulations reported in this section thus collectively demonstrate that adjustments to the values of the parameters that control saccadic programming and execution in E-Z Reader are not sufficient to simulate the full pattern of developmental changes that are observed in eye movements as children become skilled adult readers. Therefore, to the degree that the model provides a

valid description of the perceptual, cognitive, and motor processes that control readers' eye movements, the preceding simulation results provide some evidence against the oculomotor-tuning hypothesis. It is worth pointing out, however, that these conclusions are not meant to imply that saccadic programming and execution do not play important roles in eye-movement control during reading; to the contrary, recent simulations also completed using the E-Z Reader model suggest that the parameters that determine the preferred saccade length (i.e., $\Psi$; see Eq. (4)) and the propensity to make corrective refixations (i.e., $\lambda$; see Eq. (6)) play important roles in the language-related differences in eye movements that are observed between native readers of Chinese, English, and Finnish (Reichle, Drieghe, Liversedge, & Hyönä, in preparation).

*Miscellaneous parameters*

The final set of simulations were completed to examine the consequences of adjusting the remaining E-Z Reader parameters in an exhaustive fashion, irrespective of the fact that there was no a priori reason to assume that the processes that are described by these parameters play important roles in the developmental changes that are observed in readers' eye movements. As Table 7 shows, we completed four simulations to examine the consequences of increasing: (1) *V*, the parameter that controls the duration of the pre-attentive stage of visual processing: (2) $\varepsilon$, the parameter that modulates how visual acuity limitations attenuate the rate of lexical processing (see Eq. (2)); (3) *A*, the parameter that controls the mean time needed to shift attention from one word to the next; and (4) $\sigma_\gamma$, the parameter that controls the overall variability of the gamma distributions that are used in our Monte-Carlo simulations (see Footnote 5).

As Table 7 shows, with one notable exception, increasing the values of these miscellaneous parameters was not sufficient to reproduce the basic developmental pattern of eye movements; the exception was the parameter that modulates the rate of lexical processing as a function of foveal eccentricity, $\varepsilon$ (Sim. 2). As the table shows, increasing the value of this parameter increased the number and duration of fixations and the rate of regressions, but also decreased the saccade length, reading rate, and parafoveal processing efficiency. Although these results suggest an alternative account of the basic differences between the eye movements of children and adults, it is important to point out that, by this account, one would have to posit that the delimiting effects of visual acuity become less pronounced with age, so that adults become better able to identify peripheral words than children due to changes in visual acuity. This possibility seems implausible (e.g., see Atkinson, 2000) and is contrary to results that were discussed earlier indicating that children are as facile as adults at extracting briefly displayed visual information from the printed page (Blythe et al., 2009, 2011). For that reason, the hypothesis that the eye movements of children differ from those of adults due to differences in visual acuity will not be consideredfurther.

*Interim summary*

The preceding simulations provide some support for a fairly strong version of the linguistic-proficiency hypothesis—that developmental change in lexical-processing efficiency is the primary determinant of why children's eye movements change in the way that they do as children become skilled adult readers. Although this conclusion remains tentative because it is based on a model which may ultimately turn out to be invalid in some important way and because it is entirely possible that some combination of changes in linguistic processing and oculomotor control will ultimately provide a more precise account of these developmental changes, the simple linguistic-proficiency account is both parsimonious and consistent with other behavioral changes that have been observed as children learn to read (e.g., see Perfetti, 1985). That being said, the next three sections of this article provide more rigorous tests of the specific hypothesis that larger values of the $\alpha_1$ parameter are sufficient to explain what is currently known about children's eye movements during reading and how they differ from those of adults. Therefore, the simulations reported next are intended to evaluate the model's account of important "benchmark" phenomena using two different values of $\alpha_1$: (1) $\alpha_1 = 104$ ms, the default value for simulating adult performance (Reichle et al., 2012); and (2) $\alpha_1 = 208$ ms, the value that will be used to simulate children's performance. Note that the decision to use a value of 208 ms to simulate children's performance was fairly arbitrary but does correspond to the maximum value that was used in our first set of simulations (see Table 4) and thus should provide a good

contrast between the dependent measures predicted using the two parameter values. In addition, using this value gives a maximum mean word-identification latency of 329 ms for children, which is not implausibly long considering that the mean time is 189 ms for adults according to the model.[9]

### *Simulating word-length effects and saccadic targeting*

Our second set of simulations examined the effect of word length and the manner in which children and adults target their saccades during reading. To accomplish these objectives, we examined four different dependent measures on 4- to 9-letter words in the Schilling et al. (1998) corpus. The mean probabilities of making initial fixations in each possible viewing position are shown in Fig. 4, as are the mean probabilities of making refixations as a function of the initial fixation position. As Panels A and B of the figure show, the simulations of adults and children produced very similar fixation-landing site distributions, indicating that slowing the overall rate of lexical processing does not affect the basic nature of saccadic targeting. Similarly, Panels C and D indicate that the two simulations also produced similar patterns of refixation probabilities, although the simulation of children did result in higher rates of refixations after initial fixations near the ends of words, consistent with what has actually been observed with children (see Joseph et al., 2009, Fig. 2). It is important to emphasize that this last result was not necessarily anticipated prior to running the simulation, but instead emerged as a consequence of the fact that slower lexical processing make it less likely that any "automatic" refixation saccades initiated from the ends of words are canceled by the completion of the familiarity check on those words. The model and our assumption that lexical processing is slower in children is therefore sufficient to explain this observed difference between children and adults.

Fig. 5 shows two other measures of saccadic targeting: the mean IOVP effects for single fixations and the first (of one or more) fixations using the adult and child values of the $\alpha_1$ parameter. A comparison of Panels A vs. B and C vs. D indicates that both age groups were similarly affected by word length and initial landing position: As word length increased, so too did the mean single-fixation and first-fixation durations, and both measures were longer for fixations located near the centers of words and shorter for fixations near the beginnings and ends of words. However, the effect of word length was actually more pronounced for the simulation of children than adults, resulting in longer overall fixation durations in children than adults and causing the simulated IOVP effects to be more pronounced in the former group. All of these findings have been reported previously (e.g., see Vitu, McConkie, Kerr, & O'Regan, 2001, Fig. 11) and thus provides additional support for our claim that slowing the overall rate of lexical processing does not affect the basic nature of saccadic targeting. That being the case, we now turn to discuss simulations of the word-frequency effect.

### *Simulating word-frequency effects and cognitive control of fixation durations*

As indicated in the Introduction, a word's frequency of occurrence in printed text is one of the main lexical variables that predicts whether that word will be fixated, and if so, for how long (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl et al., 2006; Rayner & Duffy, 1986; Rayner et al., 1996, 2004; Schilling et al., 1998). There have also been several demonstrations that word frequency similarly affects the eye movements of adults and children (Blythe et al., 2009; Huestegge et al., 2009; Hyönä & Olson, 1995; Joseph et al., in press), although these frequency effects tend to be more pronounced with children (see Blythe et al., Table 4). To examine whether our assumption that lexical processing is slower in children is compatible with these results, a simulation was completed using both the adult and child values of the $\alpha_1$ parameter to examine how the frequency of the Schilling et al. (1998) target words affected first-fixation and gaze durations on those words. These simulations were completed using the actual Schilling et al. (1998) materials, with the high- and low-frequency target words respectively having mean frequencies of 141 vs. 2 counts per million (as tabulated by Francis and Kucera (1982)). Table 8 shows the results of this

[9] The maximal mean word-identification latency for children is 329 ms, or the sum of $V$ (=50 ms), $t(L_1)$ (=208 ms), and $t(L_2)$ (=71 ms). Note, however, that this value of $t(L_1)$ ignores any additional time that results from limited visual acuity (see Eq. (2)). Similarly, the maximal mean time for adults is 189 ms, or the sum of $V$ (=50 ms), $t(L_1)$ (=104 ms), and $t(L_2)$ (=35 ms).

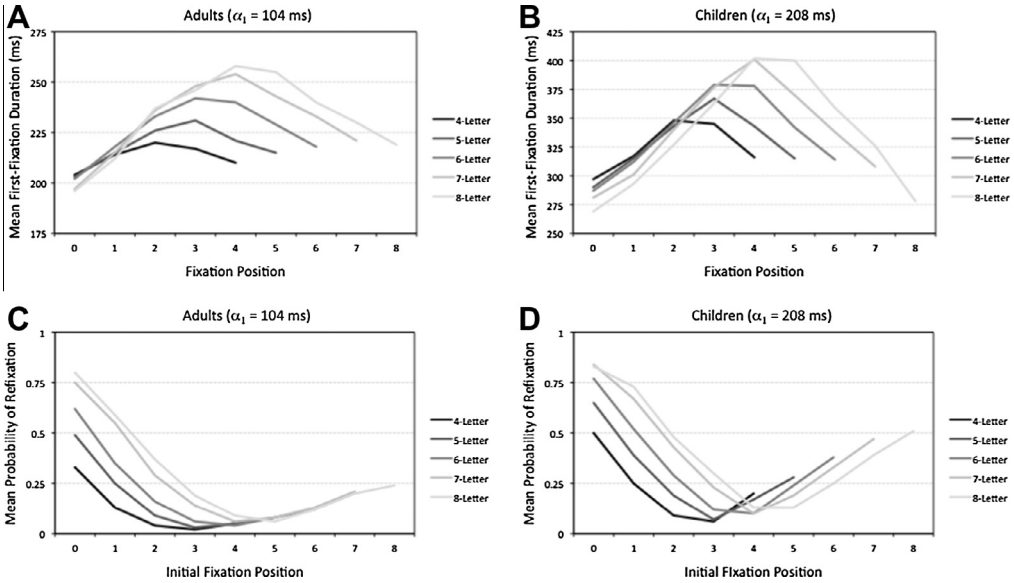


**Fig. 4.** Two simulated measures of saccadic targeting. Panels A and B respectively show the first-fixation landing site distributions using the adult (default) vs. child values of the $\alpha_1$ parameter. Similarly, Panels C and D show the probabilities of making refixations as a function of the initial fixation locations using both values of $\alpha_1$. (In the figure, fixation position 0 on the *x*-axis represents the blank space immediately to the left of each word of a given length.)

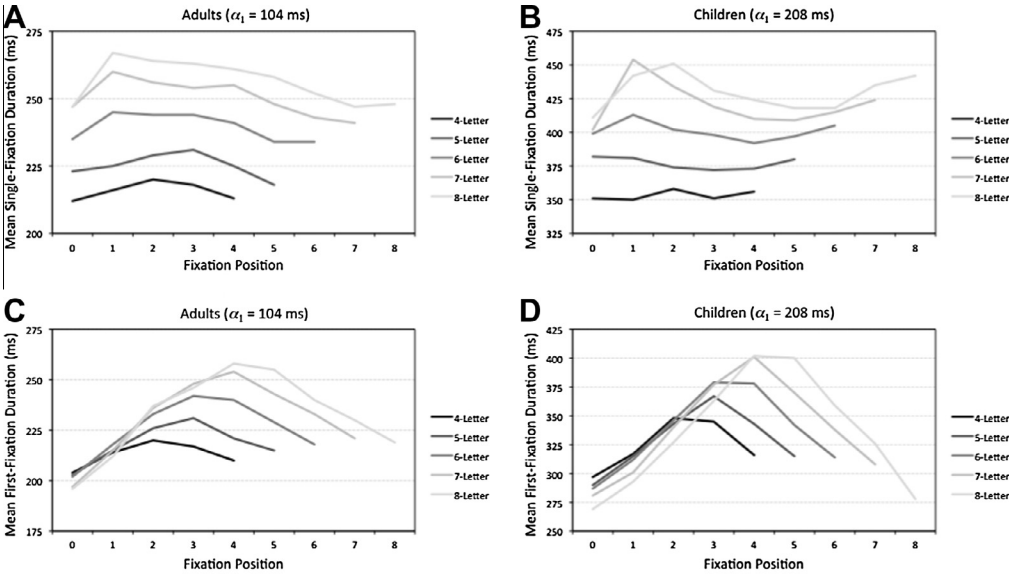


**Fig. 5.** Two simulated measures showing the interaction between saccadic targeting and fixation durations. Panels A and B respectively show the single-fixation durations as a function of their locations using the adult (default) vs. child values of the $\alpha_1$ parameter. Similarly, Panels C and D show the durations of the first (of one or more) fixation durations as a function of their initial locations using both values of $\alpha_1$. (In the figure, fixation position 0 on the *x*-axis represents the blank space immediately to the left of each word of a given length.)

**Table 8**
Simulations examining how word frequency affects first-fixation and gaze durations in adults ($\alpha_1$ = 104 ms) and children ($\alpha_1$ = 208 ms).

| Age group | Condition | Dependent measures | |
|---|---|---|---|
| | | FFD | GD |
| Adults ($\alpha_1$ = 104 ms) | LF | 239 | 305 |
| | HF | 227 | 269 |
| | Frequency effect | 12 | 36 |
| Children ($\alpha_2$ = 208 ms) | LF | 358 | 476 |
| | HF | 343 | 431 |
| | Frequency effect | 15 | 45 |

*Note:* "FFD" = first-fixation duration and "GD" = gaze duration.

simulation. As the table shows, frequency affected both dependent measures in both age groups, but resulted in numerically longer measures and larger frequency effects with the children. This indicates that, despite a slower overall rate of lexical processing, the frequency of a word still modulates how long a word is looked at, lending additional support to the feasibility of the hypothesis that the main differences between the eye movements of children and adults reflects underlying differences in lexical processing efficiency. We therefore now turn to our last simulation, which examined the role of thematic role plausibility and how this important linguistic variable might differentially affect the eye movements of children vs. adults.

### *Simulating thematic role plausibility and languageprocessing*

Up to this point, our hypothesis about the underlying basis for the observed differences between the eye movements of children vs. adults has been an extremely simple variant of the linguistic-proficiency hypothesis—that children are less proficient at lexical processing than adults. Because this account makes only one assumption (and in the context of the E-Z Reader model, can be simulated by changing one free parameter value), this account is a strong version of the linguistic-proficiency hypothesis. A weaker version might therefore be one in which some aspects of the observed differences between children and adults reflect some other underlying differences in how the two groups process higher-level language. For example, one obvious possibility is that children are also less efficient at integrating the meanings of words into the representations of the sentences that they construct from the text. By this account, differences between the eye movements of children and adults in experiments involving the manipulation of linguistic variables (e.g., thematic role plausibility; Joseph et al., 2008) might require assumptions besides the one that children are simply slower at lexical processing. Therefore, to test this possibility, one final set of simulations was completed using two values of $\alpha_1$ (104 vs. 208 ms) to determine if this assumption is also sufficient to explain the different patterns of eye movements that have been reported when children vs. adults read sentences containing thematic role violations. However, before the results of these simulations are reported, one important caveat is necessary.

Because the E-Z Reader model does not provide a detailed account of either language processing or how it fails (e.g., what actually happens cognitively when a reader encounters a semantic anomaly), the simulations reported below are by necessity very simple, and are intended only to demonstrate some basic limitations of a strong linguistic-proficiency hypothesis. Although a detailed model of language processing and how such processing interacts with other systems involved in reading (e.g., attention, lexical processing, etc.) will be necessary for a more rigorous test of whether or not a slower rate of lexical processing is sufficient to account for the types of results reported by Joseph et al. (2008), it is still possible to use the model in a productive manner to make general inferences about the role of higher-level language processing and how it influences readers' eye movements without having to know all of the details.

For example, the simulations reported next were completed using the values of the $\alpha_1$ parameter that were previously used to examine the performance of adults vs. children. To simulate the effects of a semantic implausibility in these two age groups, the model parameter that causes integration failure, $p_F$, was increased from its default value of $p_F = 0.01$ (simulating the low probability of failing to integrated a very easy-to-integrate word) to a value of $p_F = 0.1$ (simulating a ten-fold increase in the probability of failing to integrate a word that is difficult to integrate) for the Schilling et al. (1998) target words. (The parameter $p_F$ was set equal to its default value for the other words in the sentences, consistent with the assumption that the types of plausibility violations studied by Joseph et al., 2008 can be localized to specific words.) However, the value of the parameter that controls the time that is required to complete post-lexical integration (irrespective of whether it succeeds or fails) was set equal to its default value: $I = 25$ ms.

The results of this first simulation are shown in Table 9. As the table shows, an increased failure to integrate an implausible word ($p_F = 0.1$) increased the first-fixation duration on that word very little relative to the normal integration condition ($p_F = 0.01$), but increased the gaze duration modestly and the total-viewing time fairly significantly. However, as Table 9 also shows, this pattern was evident with the simulation of both adults (i.e., using $\alpha_1 = 104$) and children ($\alpha_1 = 208$). (Table 9 shows that, if anything, the simulated effect of implausibility was actually slightly larger with the children.) The simulation thus demonstrates that, within the framework of the E-Z Reader model, any linguistic manipulations that (by assumption) increase the probability of integration failure will increase both gaze duration and total-viewing time, but that the magnitude of these effects will not be significantly influenced by differences in the overall rate of lexical processing. For example, if semantic plausibility violations of the type studied by Joseph et al. (2008) result in post-lexical integration difficulty, and if the only difference between children and adults is that the children process words more slowly than the adults, then the model will predict that the effects of semantic implausibility on eye movements should be approximately the same size in children and adults. Clearly this prediction is wrong, indicating either that: (1) the model is in some manner wrong and/or that (2) the hypothesis that only the rate of lexical processing is different between adults and children is wrong.

However, if one assumes that the model provides a more-or-less accurate description of how cognition (and in particular, both lexical and post-lexical processing) influence eye-movement behavior during reading, then it is possible to evaluate other hypotheses about the reasons why the eye movements of adults and children differ. One relatively simple alternative hypothesis is that the two groups also differ in their rate of *post*-lexical processing. By this account, children might also be slower than adults at integrating the meaning of individual words into sentence representations, thereby causing any problems that might occur due to integration failure to be delayed. To test this idea, the previous simulation of the children's data was repeated using a different value of the parameter that controls

**Table 9**
Simulations examining how the accuracy and time required to complete post-lexical integration affect first-fixation durations, gaze durations, and total-viewing times in adults ($\alpha_1 = 104$ ms) and children ($\alpha_1 = 208$ ms). The semantic-implausibility effects are the mean differences (in ms) between each of the dependent measures in the normal vs. implausible conditions.

| Age group | Condition | Parameters | | Dependent measures | | |
|---|---|---|---|---|---|---|
| | | $I$ | $p_F$ | FFD | GD | TVT |
| Adults ($\alpha_1 = 104$ ms) | Normal | 25 | 0.01 | 233 | 287 | 293 |
| | Implausible | 25 | 0.1 | 237 | 301 | 312 |
| | Semantic-implausibility effects (i.e., differences) | | | 4 | 14 | 19 |
| Children ($\alpha_1 = 208$ ms) | Normal | 25 | 0.01 | 348 | 452 | 481 |
| | Implausible | 25 | 0.1 | 354 | 473 | 513 |
| | Semantic-implausibility effects (i.e., differences) | | | 6 | 21 | 32 |
| | Normal | 25 | 0.01 | 348 | 452 | 481 |
| | Implausible | 125 | 0.1 | 347 | 449 | 512 |
| | Semantic-implausibility effects (i.e., differences) | | | −1 | −3 | 31 |

*Note:* "FFD" = first-fixation duration; "GD" = gaze duration; and "TVT" = total-viewing time.

the time required to complete integration—one that increased the duration on integration to $I = 125$ ms. Although this value of $I$ is arbitrary, it is sufficient to simulate the consequences of slow integration that might be predicted to occur with children. The results of this second simulation are also shown in Table 9. As can be seen there, this slowing of integration caused the effect of the semantic plausibility violation to be delayed; the difference between the normal and implausible conditions is no longer evident in first-pass measures (e.g., first-fixation and gaze durations), but instead only appears in the measure that includes regressive fixations—total-viewing times.

The results of these simulations thus suggest that a strong version of the linguistic-proficiency hypothesis—one in which *all* of the observed differences between the eye movements of children and adults are due to slower lexical processing in the former group—is probably not viable. The simulations instead suggest that a weaker version of the hypothesis—one in which the rate of lexical *and* post-lexical processing account for differences between children and adults—is more likely to be correct. A few of the more important theoretical implications of this possibility will now be discussed in the final section of this article.

## General discussion

Our main goal in completing the simulations that were reported in this article was to use the framework of an existing model of eye-movement control in reading, E-Z Reader (Pollatsek et al., 2006; Rayner et al., 2004; Reichle, 2011; Reichle, Rayner, & Pollatsek, 1999; Reichle et al., 1998, 2003, 2006, 2009), to interpret the patterns of eye movements that are observed as children become skilled adult readers and to thereby gain a better understanding of what actually develops with reading ability. To meet this goal, we completed a series of simulations in which key aspects of two hypotheses—the linguistic-proficiency and oculomotor-tuning hypotheses—were instantiated within the framework of E-Z Reader so that we could determine how the specific assumptions of these hypotheses fared in explaining developmental trends in eye-movement control during reading.

The results of these simulations were informative. First of all, the basic pattern of eye movements exhibited by children (i.e., longer fixations and shorter saccades with more regressions) could not be generated by varying the values of any of the model's parameters that control either the timing and/or accuracy of saccadic programming and/or execution. This suggests that the differences that are observed between the eye movements of children vs. adults cannot be explained by difference in how the oculomotor system has been "tuned" (presumably through years of practice) in adults—at least not in terms of how that "tuning" is specified within the framework of our model, where the initiation of saccadic programming is tightly coupled to serial lexical processing.

However, the basic pattern *could* be generated by simply reducing the overall rate of lexical processing in children (i.e., by increasing the value of the $\alpha_1$ parameter). Based on this result, one might conclude that a strong version of the linguistic-proficiency hypothesis is correct, and that an increase in lexical processing efficiency causes the eye movements of children to eventually resemble those of skilled adult readers. Additional simulations supported this conclusion: Simulations in which the rate of lexical processing was slowed indicated that various metrics of saccade targeting were largely unaffected, consistent with findings that children and adults make similar "decisions" about where to move their eyes (Vitu, McConkie, Kerr, & O'Regan, 2001), but that lexical variables (e.g., word length and frequency) influence the fixation durations of children more than adults (Blythe et al., 2009; Joseph et al., 2009, in press). However, the final simulations showed that this simple account could not fully explain the effects of certain post-lexical variables (e.g., thematic role anomalies; Joseph et al., 2008); an explanation of these effects instead required the additional assumption that, relative to adults, children are also less proficient at post-lexical processing. Thus, the simulations collectively suggest that an understanding of the development of language-processing skill in its entirety may be necessary to fully understand the concurrent development of eye-movement behavior during reading.

From a pedagogical perspective, these simulation results are interesting because they suggest that most of the variance in reading ability stems from differences in language processing skill, with very little or none of the variance being due to differences in the basic mechanics of programming and

executing eye movements. On some level this should not be too surprising given the simple fact that, in teaching children how to read, teachers spend a considerable amount of effort teaching their students basic lexical (e.g., decoding) and other language-related skills, but virtually no effort teaching children how to move their eyes (apart from perhaps occasionally pointing at a grapheme or word that is being read). Rather, children seem to learn to move their eyes on their own, in a manner that presumably supports maximally efficient reading and that is sensitive to local processing difficulty. The fact that even young children with minimal reading experience (e.g., 8–9 year-olds) target their saccades in a manner very similar to skilled adult readers supports this assertion, and suggests that readers' eye movements are "tuned" through learning so that they come to afford optimal text processing given the various physiological (e.g., limited visual acuity) and psychological (e.g., limited attention capacity) constraints imposed by the perceptual, cognitive, and motor systems, as well as the linguistic constraints imposed by both the language being read and its system of writing (Liu & Reichle, 2010; Liu et al., in press; Reichle & Laurent, 2006). That being said, our evidence supporting a weak form of the linguistic-proficiency hypothesis also speaks directly to two other, related areas of inquiry— the question of how older readers come to differ from younger, college-aged readers, and the long-standing question of what makes one reader more skilled than another.

Two recent eye-movements experiments have examined how the eye movements of older readers differ from those of college-aged adults (Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner et al., 2006). The results of these two experiments were remarkably consistent, showing the same pattern of differences between the two age groups. Relative to the younger readers, the older readers tended to make fewer fixations that are longer in duration, but seem to compensate for this slow-down by more often skipping predictable words, but then also making more regressions back to the words that are skipped. To explain these differences, both studies reported simulations of their findings and the main differences between college-age and older readers, using very different models and theoretical assumptions to do so.

For example, Laubrock, Kliegl, and Engbert (2006) provided an account of the Kliegl et al. (2004) results using the *SWIFT* model of eye-movement control in reading (Engbert et al., 2002, 2005; Richter et al., 2006; for a review, see Engbert & Kliegl, 2011). According to this model, attention is allocated as a gradient to support the concurrent processing of several (typically 3–4) words. As the activation level for any given word in the gradient first increases and then decreases, so too does the probability that it will be selected as the target of a saccade. The actual decision about when to move the eyes, however, is determined by an autonomous timer that initiates saccadic programming at random intervals, but whose activity can be inhibited (after some amount of delay) if the word being fixated is difficult to process. The model thus explains all of the "benchmark" findings that can be explained by the current eye-movements models (for a review, see the 2006 special issue of *Cognitive Systems Research*). To explain the pattern of results observed with older readers, Laubrock et al. simply assumed that older readers have a smaller gradient of attention, but that this gradient is also more asymmetrical to the right of fixation. The first assumption is sufficient to explain the longer fixations observed in older readers because fewer attentional resources are available to support lexical processing, making lexical processing more difficult, thereby inhibiting the autonomous timer and inflating fixations. The second assumption is likewise sufficient to explain the increased rate of skipping because the greater asymmetry in the older readers' attention gradient increases the probability that words far to the right of fixation will be selected as saccade targets, thus causing any intervening words to be skipped.

Rayner et al. (2006) provided a very different account of the same pattern of behavioral results using the E-Z Reader model as their theoretical framework. The basic logic of their account was that, because older readers exhibit a general cognitive slowing, they tend to rely more upon their knowledge of language and discourse and/or sentence context to "guess" the identities of predictable words. But because this heuristic is not always successful, older readers are more prone to making errors (e.g., misidentifying words) that require regressions back to earlier parts of the text. The feasibility of this "risky" reading strategy was evaluated via simulations in which the overall rate of lexical processing was slowed (i.e., the value $\alpha_1$ of was increased relative to its default value), the propensity to "guess" predictable words was increased (i.e., the value $\alpha_3$ of was also increased relative to its default value), but this increased propensity to "guess" words was also made prone to error, leading to the

misidentification of some proportion of words and thus more frequent regressions.[10] These assumptions were sufficient to simulate the general pattern of eye movements observed with elderly readers. However, it provides a very different account of the life-long developmental "trajectory" of reading skill than the account based on SWIFT (Laubrock et al., 2006).

That is, according to the account based on E-Z Reader, two basic factors work to increase reading skill across a reader's lifespan—the increasing ability to identify printed words in a rapid, automatic manner, and the ability to use prior reading experience to rapidly integrate the meanings of words and to make inferences about upcoming linguistic structure and/or content. Both factors increase markedly during the first few years of a reader's experience, but with lexical-processing skill probably increasing more rapidly and reaching asymptote sooner than the skills associated with higher-level linguistic analysis and prediction. And in the later years, these increases in reading skill that come from enhancements in lexical and linguistic proficiency are offset by a generally slowing in the rate of cognitive processing, which decreases the rate of lexical processing. Skilled older readers therefore come to rely upon their greater linguistic skill to compensate for this general slowdown, resulting in greater rates of both skipping and making regressions. Thus, by this account, age-related differences in reading skill and eye-movement behavior reflect underlying age-related differences in the skills that are necessary to identify printed words and perform other linguistic operations; that is, the changes in eye-movement behavior are caused by the changes in the skills that support reading.

Now, if one extrapolates from the SWIFT account of why older readers differ from college-aged readers to explain how reading skill changes across the entire lifespan, then it would seem reasonable to assume that the differences between children and adults also reflect underlying differences in how the attention gradient is distributed. Such an account might, for example, claim that the size of the attention gradient increases in size and becomes more asymmetrical to the right of fixation as children become skilled adult readers, thus providing an account of why both the overall reading rate and the span of perception increase with reading skill (Rayner, 1986). In the latter years, however, the attention gradient begins to shrink in size and to become even more asymmetric, thus both slowing the rate of lexical processing and increasing propensity to skip words. The critical point to note about this account, however, is that it says nothing about the development of lexical and/or linguistic skill per se, but instead says that age-related changes in reading ability reflect changes in the capacity to allocate attention and/or the manner in which attention is allocated (e.g., the degree of gradient symmetry). Thus, according to this account, age-related changes in reading skill and eye-movement behavior may also reflect age-related changes in lexical- and linguistic-processing skills, but these latter changes are themselves caused by even more basic age-related changes in the capacity to allocate attention. That being said, the two basic accounts of how reading skill and eye-movement behavior change with age make very different predictions about the etiology of those changes—that they reflect either the development of linguistic skill or the skilled deployment of attention. Future research will be necessary to adjudicate between these two very different accounts.

Another basic question related to the work reported in this article has to do with individual differences in reading ability, and the question of why some readers are better able to understand text than others. This question has also been examined using eye-movement experiments, and the results of two of these experiments are particularly relevant here. For example, an experiment by Schilling et al. (1998) examined the performance of skilled and less-skilled readers in the identification of length-matched high- and low-frequency target words using three different dependent measures: (1) gaze durations on the target words in the sentences; (2) response latencies for deciding that the target words were words rather than non-words in a lexical-decision task; and (3) response latencies for pronouncing the words aloud in a naming task. Perhaps not too surprisingly, all three measures were affected by word frequency, with shorter gaze durations and response latencies for high- than

[10] The version of E-Z Reader that was used to complete these simulations (i.e., version 9; Pollatsek et al., 2006) was a precursor to the current version (i.e., version 10; Reichle et al., 2009) and did not explain how higher-level language processing and its failures might affect the movement of the eyes and attention during reading. Consequently, the simulations required an ad hoc parameter that determined the probability of "misidentifying" words that were "guessed". In the current version of the model, this kludge would be unnecessary because the increased propensity for older readers to make such errors would be simulated by increasing the default value of the $p_F$ parameter (see Table 2), thereby increasing the probability of rapid integration failure.

low-frequency words. More interesting, however, was that subjects' overall performance tended to be stable across tasks, so that, for example, a subject who responded rapidly on one measure tended to respond rapidly on the others. These findings are important because they indicate that some aspect of lexical processing (which was being measured by both the lexical decision and naming tasks) also modulated gaze durations during reading, and that individual differences in this underlying ability also mediated—at least to some degree—the observed, between-individual differences in reading ability. One theoretical implication of this conclusion is that a significant portion of the variability associated with individual differences in reading ability might be readily explained by differences in the speed and/or accuracy of lexical processing, consistent with the hypothesis about lexical quality (see Footnote 1).

A second important eye-movement study examining individual differences in reading ability was reported by Ashby, Rayner, and Clifton (2005; see also van der Schoot et al., 2009). This study compared the eye movements of two groups of college-level readers: average readers who scored below the 70th percentile on the Nelson–Denny standardized reading test (mean = 40th percentile) vs. skilled readers who scored above the 74th percentile on the same test (mean = 88th percentile). Both groups read sentences containing length-matched high- and low-frequency targets words that were embedded in neutral contexts (Experiment 1) or contexts in which the words were either unpredictable vs. highly predictable (Experiment 2). Although the pattern of results across the two experiments was complex, the overall pattern indicated that the average readers made longer fixations and more regressions that the skilled readers, and that the average readers were slowed even more by the low-frequency words than were the skilled readers, producing a larger frequency effect with average readers. The size of the frequency effect was also not modulated by predictability with the skilled readers, but was modulated by this variable with the average readers. Together, these results suggest that skilled readers are less reliant upon sentence context to facilitate lexical processing, and that differences in both lexical processing efficiency and—to a lesser degree—higher-level language processing contribute to the differences between skilled and average readers.

This conclusion is remarkably consistent with the linguistic-proficiency hypothesis and suggests a common account of differences in reading ability both between individuals of differing ability and within individuals across their lifespan. As Huey (1908) indicated, the "astounding complexity" that is reading is "built up slowly, and by an immense amount of practice"; our contribution in this article is to suggest that what is being practiced to become a skilled reader is largely the identification and subsequent linguistic processing of printed words.

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## References

Ashby, J., Rayner, K., & Clifton, C. Jr., (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *The Quarterly Journal of Experimental Psychology, 58A*, 1065–1086.

Atkinson, J. (2000). *The developing visual brain*. New York, NY: Oxford University Press.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX lexical database (CD-ROM)*. Philadelphia: Linguistic Data Consortium, University of Pennsylvania.

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research, 19*, 967–983.

Blythe, H. I., Häikiö, T., Bertram, R., Liversedge, S. P., & Hyönä, J. (2011). Reading disappearing text: Why do children refixate words? *Vision Research, 51*(84), 92.

Blythe, H. I., & Joseph, H. S. S. L. (2011). Children's eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 643–662). Oxford, England: Oxford University Press.
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., 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.
Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure of American English. *Behavior Research Methods, Instruments, & Computers, 41*, 977–990.
Brysbaert, M., & Vitu, F. (1998). Word skipping: Implication for theories of eye movement control in reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 125–147). Oxford: Elsevier.
Buswell, G. T. (1922). *Fundamental reading habits: A study of their development*. Chicago, IL: University of Chicago Press.
Carpenter, R. H. S. (2000). The neural control of looking. *Current Biology, 10*, R291–R293.
Cohen, M. E., & Ross, L. E. (1977). Saccade latency in children and adults: Effects of warning interval and target eccentricity. *Journal of Experimental Child Psychology, 23*, 539–549.
Cohen, M. E., & Ross, L. E. (1978). Latency and accuracy characteristics of saccades and corrective saccades in children and adults. *Journal of Experimental Child Psychology, 26*, 517–527.
Engbert, R., & Kliegl, R. (2011). Parallel graded attention models of reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 787–800). Oxford, England: Oxford University Press.
Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42*, 612–636.
Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112*, 777–813.
Feng, G. (2006). Eye movements as time-series random variables: A stochastic model of eye movement control in reading. *Cognitive Systems Research, 7*, 70–95.
Foxe, J. J., & Simpson, G. V. (2002). Flow of activation from V1 to frontal cortex in humans: A framework for defining "early" visual processing. *Experimental Brain Research, 142*, 139–150.
Francis, W. N., & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston: Houghton Mifflin.
Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14*, 178–210.
Fukushima, J., Hatta, T., & Fukushima, K. (2000). Development of voluntary control of saccadic eye movements: I. Age-related changes in normal children. *Brain & Development, 22*, 173–180.
Grimes, J. (1989). *Where first grade children look in words during reading*. Unpublished master's thesis. University of Illinois.
Groll, S. L., & Ross, L. E. (1982). Saccadic eye movements of children and adults to double-step stimuli. *Developmental Psychology, 18*, 108–123.
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.
Häikiö, T., Hyönä, J., & Bertram, R. (2010). Development of parafoveal processing within and across words in reading: Evidence from the boundary paradigm. *Quarterly Journal of Experimental Psychology, 63*, 1982–1998.
Heinzle, J., Hepp, K., & Martin, K. A. C. (2010). A biologically realistic cortical model of eye movement control in reading. *Psychological Review, 117*, 808–830.
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, and Cognition, 16*, 417–429.
Hintzman, D. L. (1991). Why are formal models useful in psychology? In W. E. Hockley & S. Lewandowsky (Eds.), *Relating theory and data: Essays on human memory in honor of Bennet B. Murdock*. Hillsdale, NJ: Erlbaum (pp. 39–56).
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.
Huey, E. B. (1908). *The psychology and pedagogy of reading*. New York: Macmillan.
Hyönä, J., Bertram, R., & Pollatsek, A. (2004). Do frequency characteristics of nonfixated words influence the processing of fixated words during reading? *European Journal of Cognitive Psychology, 16*, 104–127.
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.
Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40*, 431–439.
Joseph, H. S. S. L., Nation, K., & Liversedge, S. P. (in press). Using eye movements to investigate word frequency effects in children's sentence reading. *School Psychology Review*.
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*, e54141. http://dx.doi.org/10.1371/journal.pone.0054141.
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. *The 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.
Juhasz, B. J., & Rayner, K. (2003). Investigating the effects of a set of intercorrelated variables on eye fixations in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 1312–1318.
Juhasz, B. J., & Rayner, K. (2006). The role of age of acquisition and word frequency in reading: Evidence from eye fixations. *Visual Cognition, 13*, 846–863.
Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*, 329–354.

Kennison, S. M., & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 68–81.
Kirkby, J. A., Blythe, H. I., Drieghe, D., & Liversedge, S. P. (2011). Reading text increases binocular disparity in dyslexic children. *PLoS ONE, 6*, 1–7.
Klein, C., & Foerster, F. (2001). Development of prosaccade and antisaccade task performance in participants ages 6 to 26 years. *Psychophysiology, 38*, 179–189.
Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of word on eye movements in reading. *European Journal of Cognitive Psychology, 16*, 262–284.
Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General, 135*, 12–35.
Kowler, E., & Martins, A. J. (1982). Eye movements in preschool children. *Science, 215*, 997–999.
Laubrock, J., Kliegl, R., & Engbert, R. (2006). SWIFT explorations of age differences in eye movements during reading. *Neuroscience and Behavioral Reviews, 30*, 872–884.
Levy, R., Bicknell, K., Slattery, T., & Rayner, K. (2009). Eye movement evidence that readers maintain and act on uncertainty about past linguistic input. *Proceedings of the National Academy of Sciences, 106*, 21086–21090.
Liu, Y., Reichle, E. D., & Gao, D. -G. (in press). Using reinforcement learning to examine dynamic attention allocation during reading. *Cognitive Science*.
Liu, Y., & Reichle, E. D. (2010). The emergence of adaptive eye movements in reading. In S. Ohlsson & R. Catrabone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 1136–1141). Austin, TX: Cognitive Science Society.
Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kintridge, R. W. (2004). Eye movements when reading disappearing text: Is there a gap effect in reading? *Vision Research, 44*, 1013–1024.
Luna, B., & Velanova, K. (2011). Development from reflexive to controlled eye movements. In: S. P. Liversedge, I. D. Gilchrist, & S.Everling (Eds.), Oxford handbook on eye movements (pp. 621-642). Oxford, England: Oxford University Press.
Matin, E. (1974). Saccadic suppression: A review. *Psychological Bulletin, 81*, 899–917.
McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial fixations on words. *Vision Research, 28*, 1107–1118.
McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics, 46*, 245–253.
McConkie, G. W., & Rayner, K. (1975). The span of effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578–586.
McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8*, 365–368.
McConkie, G. W., & Yang, S.-N. (2003). How cognition affects eye movements during reading. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 413–427). Oxford, UK: Elsevier.
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. F. Stein (Ed.), *Vision and visual dyslexics* (pp. 251–262). London: MacMillan.
McDonald, S. A., Carpenter, R. H. S., & Shillcock, R. C. (2005). An anatomically constrained, stochastic model of eye movement control in reading. *Psychological Review, 112*, 814–840.
Miellet, S., Sparrow, L., & Sereno, S. C. (2007). Word frequency and predictability effects in reading French: An evaluation of the E-Z Reader model. *Psychonomic Bulletin & Review, 14*, 762–769.
Miller, L. K. (1969). Eye-movement latency as a function of age, stimulus uncertainty, and position in the visual field. *Perceptual and Motor Skills, 28*, 631–636.
Molker, A., & Fisher, B. (1999). The recognition and correction of involuntary prosaccades in an antisaccade task. *Experimental Brain Research, 125*, 511–516.
Myung, I. J. (2000). The importance of complexity in model selection. *Journal of Mathematical Psychology, 44*, 190–204.
Nation, K. (2009). Form-meaning links in the development of visual word recognition. *Philosophical Transactions of the Royal Society, B, 364*, 3665–3674.
New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers, 36*, 516–524.
Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research, 45*, 2201–2217.
O'Regan, J. K., & Lévy-Schoen, A. (1987). Eye-movement strategy and tactics in word-recognition and reading. In M. Coltheart (Ed.). *Attention and performance* (Vol. XII, pp. 363–384). Hillsdale, NJ: Erlbaum.
Perfetti, C. A. (1985). *Reading ability*. New York, NY: Oxford University Press.
Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading, 11*, 357–383.
Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. Vehoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors to functional literacy* (pp. 189–213). Amsterdam, Holland: John Benjamins.
Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language, 14*, 174–180.
Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology, 52*, 1–56.
Pollatsek, A., Reichle, E. D., & Rayner, K. (2003). Modeling eye movements in reading: Extensions of the E-Z Reader model. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eyes: Cognitive and applied aspects of oculomotor research* (pp. 361–390). Oxford, England: Elsevier.
Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7*, 65–81.
Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85*, 618–660.
Rayner, K. (1979a). Eye guidance in reading: Fixation locations with words. *Perception, 8*, 21–30.

Rayner, K. (1979b). Eye movements and cognitive psychology: On-line computer approaches to studying visual information processing. *Behavior Research Methods & Instruments, 11*, 164–171.
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). The Thirty Fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology, 62*, 1457–1506.
Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 720–732.
Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science, 206*, 468–469.
Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 14*, 191–201.
Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: Eye movements during reading and scanning are different. *Perception & Psychophysics, 58*, 734–747.
Rayner, K., Foorman, B. F., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interest, 2*, 31–74.
Rayner, K., Foorman, B. F., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2002). How should reading be taught? *Scientific American, 286*, 84–91.
Rayner, K., Juhasz, B. J., Ashby, J., & Clifton, C. Jr., (2003). Inhibition of saccade return in reading. *Vision Research, 43*, 1027–1034.
Rayner, K., Li, X., & Pollatsek, A. (2007). Extending the E-Z Reader model of eye movement control to Chinese readers. *Cognitive Science, 31*, 1021–1033.
Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research, 46*, 310–323.
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., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16*, 829–837.
Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Englewood Cliffs, NJ: Prentice Hall.
Rayner, K., Pollatsek, A., Ashby, J., & Clifton, C. Jr., (2012). *Psychology of reading* (2nd ed.). New York, NY: Psychology Press.
Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effects of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging, 21*, 448–465.
Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1188–1200.
Rayner, K., Slowiaczek, M. L., Clifton, C., & Bertera, J. H. (1983). Latency of sequential eye movements: Implications for reading. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 912–922.
Rayner, K., Warren, T., Juhasz, B. J., & Liversedge, S. P. (2004). The effect of plausibility on eye movements in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, 1290–1301.
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*, 214–223.
Reichle, E. D. & Drieghe, D. (in press). Using E-Z Reader to examine word skipping during reading. *Journal of Experimental Psychology: Learning, Memory and Cognition*.
Reichle, E. D., Drieghe, D., Liversedge, S. P., & Hyönä, J. (in preparation). A comparative analysis of eye movements during reading of Chinese, English, and Finnish using E-Z Reader.
Reichle, E. D., Rayner, K., & Pollatsek, K. (in press). Eye movements in reading versus non-reading tasks: Using E-Z Reader to understand the role of word/stimulus familiarity. *Visual Cognition*.
Reichle, E. D., & Laurent, P. A. (2006). Using reinforcement learning to understand the emergence of "intelligent" eye-movement behavior during reading. *Psychological Review, 113*, 390–408.
Reichle, E. D. (2011). Serial attention models of reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 767–786). Oxford, England: Oxford University Press.
Reichle, E. D., & Perfetti, C. A. (2003). Morphology in word identification: A word experience model that accounts for morpheme frequency effects. *Scientific Studies of Reading, 7*, 219–237.
Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105*, 125–157.
Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E-Z Reader: A cognitive-control, serial-attention model of eye-movement control during reading. *Cognitive Systems Research, 7*, 4–22.
Reichle, E. D., Pollatsek, A., & Rayner, K. (2012). Using E-Z Reader to simulate eye movements in non-reading tasks: A unified framework for understanding the eye-mind link. *Psychological Review, 119*, 155–185.
Reichle, E. D., Pollatsek, A., & Rayner, K. (2007). Modeling the effects of lexical ambiguity on eye movements during reading. In R. P. G. Van Gompel, M. F. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 271–292). Oxford, England: Elsevier.
Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research, 39*, 4403–4411.
Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26*, 445–476.
Reichle, E. D., Tokowicz, N., Liu, Y., & Perfetti, C. A. (2011). Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check. *Psychophysiology, 48*, 993–1003.
Reichle, E. D., Warren, T., & McConnell, K. (2009). Using E-Z Reader to model the effects of higher-level language processing on eye movements during reading. *Psychonomic Bulletin & Review, 16*, 1–21.

Reilly, R. (1993). A connectionist framework for modeling eye-movement control in reading. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 193–212). Amsterdam, Holland: Elsevier.
Reilly, R., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research, 7*, 34–55.
Reilly, R., & Radach, R. (2003). Foundations of an interactive activation model of eye movement control in reading. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 429–456). Oxford, UK: Elsevier.
Reingold, E. M., & Rayner, K. (2006). Examining the word identification stages hypothesized by the E-Z Reader model. *Psychological Science, 17*, 742–746.
Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from survival analysis of fixation durations. *Cognitive Psychology, 65*, 177–206.
Richter, E. M., Engbert, R., & Kliegl, R. (2006). Current advances in SWIFT. *Cognitive Systems Research, 7*, 23–33.
Salman, M. S., Sharpe, J. A., Eizenman, M., Lillakas, L., Westall, C., To, T., et al (2006). Saccades in children. *Vision Research, 46*, 1432–1439.
Schilling, H. E. H., Rayner, K., & Chumbley, J. I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory & Cognition, 26*, 1270–1281.
Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysics, 74*, 5–35.
Seymour, P. K. H., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94*, 143–174.
Slatery, T. J. (2009). Word misperception, the neighbor frequency effect, and the role of sentence context: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 35*, 1969–1975.
Taylor, W. L. (1953). Cloze procedure: A new tool for measuring readability. *Journalism Quarterly, 30*, 415–433.
Taylor, S. E. (1965). Eye movements while reading: Facts and fallacies. *American Educational Research Journal, 2*, 187–202.
Taylor, J. S. H., Plunkett, K., & Nation, K. (2010). The influence of consistency, frequency, and semantics on learning to read: An artificial orthography paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 60–76.
van der Schoot, M., Vasbinder, A. L., Horsley, T. M., Reijntjes, A., & van Lieshout, E. C. D. M. (2009). Lexical ambiguity resolution in good and poor comprehenders: An eye fixation and self-paced reading study in primary school children. *Journal of Educational Psychology, 101*, 21–36.
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.
Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: Eye-movement characteristics are similar in scanning letter strings and reading text. *Perception & Psychophysics, 57*, 352–364.
Warren, T. (2011). The influence of implausibility and anomaly on eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 911–924). Oxford, England: Oxford University Press.
Warren, T., & McConnell, K. (2007). Disentangling the effects of selectional restriction violations and plausibility violation severity on eye-movements in reading. *Psychonomic Bulletin & Review, 14*, 770–775.
Warren, T., McConnell, K., & Rayner, K. (2008). Effect of context on eye movements when reading about plausible and impossible events. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 1001–1010.
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.
Williams, C. C., & Pollatsek, A. (2007). Searching for an O in an array of Cs: Eye movements track moment-to-moment processing in visual search. *Perception & Psychophysics, 69*, 372–381.
Yang, S.-N. (2006). A oculomotor-based model of eye movements in reading: The competition/activation model. *Cognitive Systems Research, 7*, 56–69.
Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441–517.
Zucchini, W. (2000). An introduction to model selection. *Journal of Mathematical Psychology, 44*, 41–61.