

BEYOND DECODING

*The Behavioral and Biological
Foundations of Reading Comprehension*

Edited by

RICHARD K. WAGNER

CHRISTOPHER SCHATSCHNEIDER

CAROLINE PHYTHIAN-SENCE



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How Children Read for Comprehension

Eye Movements in Developing Readers

Ralph Radach, Christiane Schmitten,
Lisa Glover, and Lynn Huestegge

The use of eye movements to study reading dates back to the very beginning of psychology as an experimental science. In fact, many of the early discoveries about the very nature of eye movements were made in the context of reading (Wade, Tatler, & Heller, 2003). A textbook on reading that made frequent reference to eye movement data appeared as early as the beginning of the 20th century (Huey, 1908). Building on this tradition, the analysis of eye movements has become one of the most successful methodologies in the ongoing quest to understand the dynamics of normal and impaired reading (see Radach & Kennedy, 2004, for a recent introduction and Rayner, 1998, for a seminal review).

Much of the progress in this rapidly developing area of research is owed to advancements in recording technology. Current eye-tracking configurations allow monitoring of ongoing reading behavior with letter-level precision at high temporal resolution while preserving a relatively natural reading situation. From oculomotor data the nature and

time line of ongoing visual and linguistic processing can be inferred either for the purpose of testing specific psycholinguistic hypotheses or as a base for developing models of reading. In recent years, this productive tradition of research on information processing in normal reading has entered a new stage. A number of computational models have been developed that aim to simulate and explain key aspects of the reading process (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; McDonald, Carpenter, & Shillcock, 2005; Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2006). The existing models have proven quite successful in accounting for a large number of empirical observations in normal reading (Radach, Reilly, & Inhoff, 2007), but to date no such modeling approach has been adapted to accommodate characteristics of developing readers. Therefore, one of the goals of the present chapter is to provide a review on the state of empirical work in the area as a step toward extending contemporary models of dynamic reading into the developmental domain.

Looking at the vast number of publications using eye tracking to study reading, it is quite striking how little attention has been paid to developmental research in this context. This lack of work is rather surprising given the basic fact that normal reading development is a prerequisite of adequately developed literacy skills, which, in turn, are a necessary condition for leading a successful life in our society. As a consequence, considerable investment is being made to foster research into the search for causes and remedies for reading impairments. Although recent advances in this area of research have been impressive, no consistent causal explanation of developmental dyslexia has so far emerged (see Vellutino, Fletcher, Snowling, & Scanlon, 2004; Ramus et al., 2003, for discussions of competing accounts).

In our view, one reason for this problematic state of affairs is that the massive investment in work on developmental reading disabilities has not been backed by a thorough study of the development of normal reading during the first school years. We are convinced that knowing how successful reading evolves is a necessary precondition to a causal understanding of developmental delays and disabilities. This chapter first reviews studies that used oculomotor analyses to study reading development in general. We then examine in detail some important similarities and differences between silent and oral reading. Based on data recently collected in our group, a cross-linguistic perspective to this discussion is added that may help to illuminate how the context of a particular language codetermines the task of becoming a skilled reader.

Although our discussion focuses on eye movement data, we are aware that other important approaches to the study of reading development and its underlying mechanisms exist. There is a strong and successful tradition of psychometric assessments, using performance measures to examine the development of reading fluency and comprehension. Similarly, tasks that are considered component skills of reading are frequently examined to uncover cognitive mechanisms underlying normal and abnormal reading development. Both of these approaches are represented in this volume with chapters written by leading experts in the field. Looking at reading more from a basic science angle, vibrant fields of experimental research use single-word paradigms (now often combined with brain imaging techniques) to study word processing, asking in many cases questions that parallel those raised in oculomotor studies (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Jacobs & Grainger, 1994). At this point in the history of our field, these different theoretical traditions and methodological approaches are still largely in a state of friendly coexistence. We hope that the present volume will serve to help unite the field and that our chapter can make a contribution in this direction.

DEVELOPMENTAL STUDIES OF EYE MOVEMENTS IN READING

Important early studies of eye movements during reading were done with longitudinal designs by Buswell (1922) and Taylor, Frackenpohl, and Petee (1960). The Taylor et al. study is especially noteworthy, because it included more than 12,000 students from all grades, from elementary to high school, reading short passages of text. Despite the limitations of the recording techniques available to these authors, they were able to report consistent developmental trajectories with regard to a number of key oculomotor measures. These include a marked reduction of mean fixation duration and number of fixations during reading over the first 6 years in school. Interestingly, in all studies the developmental trend did not include leftward eye movements back to previously viewed text (regressions), which accounted for between 20 and 25% of all saccades until the sixth grade (see later discussion and Inhoff, Weger, & Radach, 2005, for a discussion). A serious technical limitation of these early studies is that, because of the insensitivity of recording, many small saccades were presumably overlooked, making the average values of both fixation durations and saccade amplitudes questionable.

More recent work using improved methodology and technology of data collection replicated these early results (see Rayner, 1985, for a discussion) but also advanced the field substantially by addressing more specific research questions. One central issue concerns the perceptual span in reading, the area around the current fixation position within which linguistic information of a certain kind (e.g., letter discrimination) can be acquired during a single fixation (e.g., Underwood & Zola, 1986). Rayner (1986) reported the span to be smaller for developing readers than for adults, but the typical asymmetry with more parafoveal processing occurring to the right of fixation was already present in very young readers. Very similar results were obtained in a recent follow up study by Haikio, Bertram, Hyona, and Niemi (2009), using a sample of Finnish readers. The letter identity span was found to be smaller than the span for identifying letter features. In addition, the letter identity span of slower readers turned out to be smaller than the one found for faster readers, suggesting that slower readers cannot allocate as much of their processing resources to words beyond the current fixation.

The first and so far only extensive longitudinal eye movement study of normal reading with letter-level accuracy of measurement was published by McConkie et al. (1991). They collected data from initially more than 200 children from the end of first to fifth grade. This study provided the first realistic estimation of what should be considered "normal" variability within a sample of readers performing within 1 year of grade level. These analyses indicated that, as could be expected, variability is much larger compared with adults and gradually reduces as young readers progress in their development. Another intriguing finding was that young children made many more small saccadic movements. As an example, 9% of all eye movements made by first graders were less than two characters in length. In contrast, students in fifth grade made such small saccades only 4% of the time. This striking difference is likely to reflect an emphasis on sublexical processing units in younger children, possibly related to mental effort in grapheme-to-phoneme conversion. Also interesting is that there is a much larger proportion of very short fixation durations—less than 120 ms—which are unlikely to be controlled directly by information acquired during the current fixation. The reason for this finding remains unclear.

Importantly, McConkie et al. closely investigated saccade landing positions within words and found that students at the end of first grade already show typical characteristics of adult saccade metrics. A Gaussian distribution of incoming saccade landing positions, commonly referred to as the preferred viewing position phenomenon (Rayner,

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1979), strongly supported the word-based nature of saccade control. The standard deviations of landing site distributions were not larger than those for adults, suggesting that the basic oculomotor targeting mechanism is well in place in normally developing readers by the end of first grade. Another interesting finding was a sharp reduction of the frequency with which a currently fixated word was immediately refixated, suggesting a greater automaticity of word recognition as development progresses. As an example, first graders refixated five letter words 57% of the time compared with 15% in a sample of adult readers (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989). Part of this difference is due to the fact the landing positions of incoming initial saccades are further to the left in younger children, leading to refixations, because landing on word initial-letter positions is less optimal for word processing (see Radach & McConkie, 1998, for a detailed discussion). However, even when this source of variance was controlled, the difference in refixation rate remained strong.

Overall, analyses of local saccade fixation patterns in the McConkie et al. study marked a new chapter in the history of oculomotor research with children. In prior research, interpretation of data was compromised by averaging over indicators reflecting qualitatively different mental processes. As one important example, the word-based analyses by McConkie et al. helped solve the mystery as to why the rate of regressions apparently stays more or less constant over the first 6 years of school. They reported that with progressing development of reading skill intraword regressions (regressive refixations) become less frequent while the percentage of interword regressions (saccades going back to the left of the current word) actually increases. The decrease in the number of regressive refixations reflects the overall tendency of reduced refixations, which tend to follow leftward within word saccades when the initial landing position was to the right of the word center (McConkie et al., 1989; O'Regan, 1990). Radach and McConkie (1998) and Inhoff, Weger, and Radach (2005) have demonstrated that interword regressions represent a distinct class of saccades based on different mechanisms of visuomotor control. Short-distance regressions back to the last one or two words may serve to catch up on missed lexical access or an ambiguous semantic role, whereas long-range regressions may be used to repair comprehension problems on the sentence and text levels. The fact that these operations become *more* frequent in older students may very well reflect an important (and so far overlooked) aspect of successful reading development.

Looking at fixation durations, it is important to note that the first

and second of two fixations made within a word are actually of shorter duration than a single fixation would be on the same word (Kliegl, Olson, & Davidson, 1983). As increases in cognitive workload during reading often lead to more refixations, reporting *average* fixation durations may obscure important differences in local text difficulty or reading ability (Inhoff & Radach, 1998). However, a difficulty in the interpretation of the McConkie et al. data arises, especially with respect to the more cognitively driven temporal measures such as fixation and gaze durations. Over several time points of assessment from first to fifth grades each student was asked to read "age-appropriate" texts, which are likely to differ on several levels, including vocabulary, syntactic complexity, and text coherence. Therefore, changes in the eye movement records are not clearly attributable to developmental factors but may also derive from differences in properties of texts.

Hyönä and Olson (1995) collected the first accurate oculomotor data while children were reading aloud and found that normally developing fourth graders exhibited typical word frequency and word length effects: They spent more time on infrequent compared with frequent words and on long compared with shorter words. However, these findings were based on a post hoc classification of words into frequency band that did not control for potentially confounding variables, especially the local visual configuration and the relevant linguistic context for the selected target words.

This problem was addressed more appropriately in a sentence-reading study by Huestegge, Radach, Corbic, and Huestegge (2009), who varied word frequency and length in a well-controlled two-factorial design. Eye movement data were collected during oral reading in 21 normally developing children during their second and fourth grades at a school in Aachen, Germany. The Huestegge et al. study is also unique in that it combined oculomotor methodology with the measurement of word-naming latencies. Word- and picture-naming performance was examined using the same items that served as target words in the reading experiment. This allowed the examination of performance in the processing of identical words outside the context of the dynamic reading situation. Huestegge et al. used identical sentence materials at second and fourth grades, thus avoiding the potential confounds with "age-appropriate" text. Comparing verbal responses with the respective pictures and words in the naming task allowed them to verify explicitly that participants at the second grade understood and adequately responded to all stimuli. In addition to the sentence-reading and naming tasks, psychometric tests were used that are relevant

for the assessment of reading development and may help to specify its underlying mechanisms. These included the Coloured Progressive Matrices (CPM; Raven, Raven, & Court, 1998) as a test of general cognitive abilities and several reading ability tests for German that are based on different methodological approaches, namely the Salzburger Leserechtschreibtest (SLRT; Landerl, Wimmer, & Moser, 2001), the Würzberger Leise Lese Probe (WLLP; Küspert & Schneider, 1998), and the Salzburger Lese Screening (SLS; Mayringer & Wimmer, 2003). In the fourth grade, measures of rapid automatized naming (RAN) and phonological awareness were also added.

Results from the sentence-reading task indicate that reading rate rose from 66 words/min ($SD = 28.08$) at the end of the second grade to 103 words/min ($SD = 16.92$) at the end of fourth grade, which represents an increase of about 36%. Interestingly, comprehension (as assessed using questions on sentence-level semantic relations) remained unchanged, suggesting that readers attempted to adjust the fluency of reading for a satisfactory level of comprehension. A second important observation is that variability between participants is much lower at fourth grade with respect to reading rate, gaze durations, and total reading times. This confirms similar observations by McConkie et al. (1991) and likely reflects the fact that individual reading skills substantially differ among younger children.

Looking at local word-based fixation patterns, as also found by McConkie et al., there was a marked decrease in the number of immediate refixations on the target words. A further interesting observation was that at second grade, readers did not send their eyes as far into target words. The difference in mean initial landing position amounted to 0.3, which may not appear large but the effect is very significant and in the order of what can be observed when comparing saccades into words with highly redundant versus irregular initial letter clusters (Hyönä & Olson, 1995; Radach, Heller, & Inhoff, 2002). Additional analyses indicated that the landing position effect held for a range of saccade launch distances to the left of the target word. This is quite remarkable because, everything else being equal, the inflated number of refixations on the word before the target (an adjective of controlled length) should actually have pushed the initial saccade landing position to the right (Radach & Kempe, 1993; Radach & McConkie, 1998). Perhaps the best explanation for this pattern of results is in terms of a more conservative or "careful" reading strategy (O'Regan, 1992) at second grade. Two components—shorter saccades into the next word and more refixations at any given resulting landing position—serve to provide optimal visual input for spatially distributed processing of sublexical and lexical information.

This kind of strategic difference is a top-down adjustment that, together with changes in local word-processing load, produces the observable developmental change in oculomotor reading behavior.

Figure 4.1 presents viewing duration data for all cells of the design at second and fourth grades. Word-viewing time measures decreased quite dramatically during 2 years of reading development. Apparent are the classic word length and frequency effects on gaze durations and total reading times (Rayner, 1998), while initial fixation durations were not affected by frequency. Effect sizes for gaze duration and total reading time were reduced at fourth grade, which may be explained in terms of a more automatic lexical access in more advanced readers where less familiar words no longer lead to excessive viewing durations. Note that the infrequent words were well known to the second graders, as suggested by low error rates of about 1% in the picture- and words-naming tasks. The decrease of word-viewing time from second to fourth grade was reflected in initial fixation durations, refixation time (additional fixations during the first pass over a word), and rereading time (fixations during later passes after first leaving the word). This strongly suggests that performance is enhanced across all word-processing stages, including decoding and contextual integration. In the naming task, a decrease in latency of about 9% for pictures and 15% for words from second to fourth grade was found. As in the reading task, word length and frequency effects were less pronounced at fourth grade.

A comparison of single-word naming and target word reading in the reading task indicated that naming times were generally longer than total reading times on the same items. In addition to the natural (and perhaps relatively constant) eye-voice lag, this may also be related to the dynamic nature of sentence reading, where the eyes do not have to remain on a word until it is fully processed (see, e.g., Kliegl, Nuthmann, & Engbert, 2006; Reichle et al., 2003). Subject-based correlations between word-naming latencies and total reading times were moderate: $.57 < r < .90$ for second graders and $.26 < r < .60$ for fourth graders (see Schilling, Rayner, & Chumbley, 1998, for data on adult readers). However, an analysis of item-based correlations of word-naming latencies with gaze durations and total reading times indicated that these correlations were significant at second grade but not fourth grade. Apparently, for a more developed reader, single word-naming latencies do not reliably predict the speed of word processing in normal reading. During the second grade, the common variance may reflect grapheme-phoneme conversion processes, whereas in the fourth grade this ability is already highly automatic, so that both tasks share fewer common components.

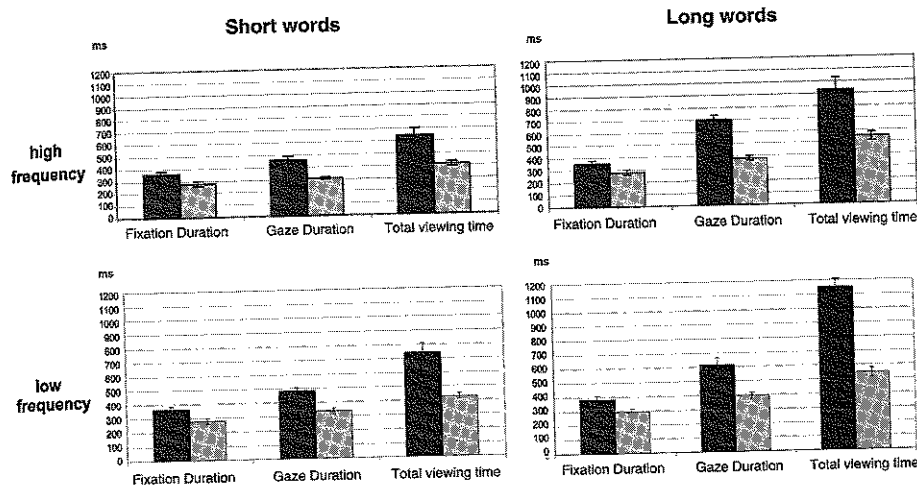


FIGURE 4.1. Word-viewing duration measures for sentence reading in children in second grade (dark gray) and fourth grade (light gray). Data are based on a longitudinal design with identical reading materials. Panels show effects on target words of varying word length (4–5 vs. 7–8 letters) and word frequency.

Saccade latencies for pro- and antisaccades and the amount of erroneous prosaccades in the antisaccade task decreased from second to fourth grade (see, e.g., Klein, 2001, for normative developmental data on these tasks). However, none of the oculomotor variables in the pro- and antisaccade tasks correlated significantly with any oculomotor measure of reading, including mean and initial fixation durations, for both second and fourth grade data. A regression analysis used a composite measure of oculomotor speed (mean latencies over several conditions in the pro- and antisaccade tasks), the number of erroneous prosaccades, and single word-naming latencies in second grade for the prediction of total reading times in fourth grade. Only naming latencies turned out to be a significant predictor, suggesting that linguistic, not oculomotor, skills were the driving force behind the acquisition of oral reading ability. Most likely, the limiting factor in the development of reading skills is the process of linguistic word decoding and integration and not any aspect of basic oculomotor development. The lack of any significant correlation between nonreading saccade parameters and reading performance appears quite discouraging for the view that simple saccade tasks remote from reading may contribute to a better understanding of developmental reading problems (see Biscaldi, Fish-

cer, & Hartnegg, 2000; see the more detailed discussion later in this chapter).

The additional assessments used at fourth grade revealed that phonological awareness measures correlated highly with measures related to the reading of single words (e.g., word naming) but not with measures reflecting the dynamic reading of words in the context of meaningful sentences like gaze durations and total reading times. In contrast, performance in a letter RAN task correlated highly with gaze durations and total reading times (see also Holland, McIntosh, & Huffman, 2004). In line with Neuhaus and Swank (2002), this corroborates the claim that the letter version of the RAN forms a basic reading test, comprising processes of phonological encoding, orthographic recognition, and articulation, all of which are fundamental prerequisites of normal oral reading.

COMPARING SILENT AND ORAL READING

Reading performance of children at the elementary level is usually assessed via oral reading. Reading aloud appears to provide an easy way to track errors, and many teachers generalize oral reading performance to provide a valid and reliable assessment for the general reading ability of a child. It is thus not surprising that oral reading fluency serves as a major benchmark in reading instruction and corresponding diagnostic assessments. However, in our opinion, it is rather unclear to what extent the ubiquitous extrapolation from oral to silent reading is really justified. Surprisingly little is known at this point about the precise nature of differences between reading aloud versus silently and their developmental dynamics. In the previous section, two oculomotor studies of reading development—McConkie et al. (silent) and Huestegge et al. (oral)—suggested that a number of similar developmental tendencies in silent and oral reading exist on a general level. In this section, we provide a more direct comparison after briefly addressing some relevant theoretical issues.

It is obvious that, for both the silent and oral mode, text comprehension is the eventual goal of the reading process (Anderson & Swanson, 1937; Karp, 1943; van Bon & Libert, 1997). However, beyond this basic commonality, the fundamental difference is that oral reading, via articulation and intonation, adds a language production component to the process. From this, fascinating issues arise regarding the degree to which this is merely an *addition* to the machinery of information processing active in silent reading and whether and how it also changes

operations within levels and modules of processing that are not obviously related to the sounding out of words. In the following discussion, we explore the commonalities and differences of both reading modes with respect to four key aspects: phonological recoding and "inner speech," reading speed, comprehension, and eye movements.

The first, and seemingly trivial, observation that can be made when comparing silent and oral reading is the slower speed in the oral mode. Buswell (1922) reported a speed of 250 words/min during reading aloud compared with up to 600 words during silent reading (see Juel & Holmes, 1981; Salasoo, 1986; and Sovik, Arntzen, & Samuelstuen, 2000, for more recent, similar estimates). Presumably, the major speed-limiting factors in oral reading in adults are the inherent physiological constraints. The pronunciation of words is only possible during exhalation and is also limited by the time course of the speech production system. On the other hand, it also makes sense to see the problem from the perspective of the recipient of the spoken language stream. As the ultimate goal in oral reading is the communication to a listener, the capacity of speech perception on the part of the listener is clearly a limiting factor, and in most situations there is no need to speed up the process beyond the pace of a convenient conversation.

However, the picture may be quite different in beginning and developing readers. As illustrated later, during the initial years of reading development the speed of reading aloud is much less different from silent reading. This is in line with the observation that inner speech or subarticulation is more salient in beginning readers, pointing to the possibility that speech production-related factors may impose limitations for oral reading speed in early readers (Aaronson & Ferres, 1986; Abramson & Goldinger, 1997). In the following sections, we briefly discuss the role of phonological recoding and inner speech in reading aloud and explore some relation between reading mode and comprehension. We then return to the issue of speed in more detail when considering eye movement analyses of dynamic reading in both silent and oral reading.

Phonological Recoding and Inner Speech

Early reading researchers made the observation that silent reading appears to include subarticulation. It appeared that silent reading is not possible without at least weak movements of tongue, vocal musculature, and lips (Pinter, 1913; Reed, 1916). This led to the assumption that some kind of "inner speech" is prominent, especially in early

readers, and becomes less salient and noticeable in more skilled readers (Huey, 1908). Modern reading research has produced solid evidence that processing operations related to sound properties of text are active in various ways during silent reading (see van Orden & Kluos, 2004, for a review).

1. It has been demonstrated that phonological properties of words play a substantial role in word recognition, even in very early phases long before any articulation-related processing could occur. Perhaps the most fascinating of these demonstrations have been made using eye movement-contingent display changes during silent sentence reading. Pollatsek, Lesch, Morris, and Rayner (1992) used the boundary technique (see Rayner & Slattery, Chapter 2, this volume) such that when their eyes crossed an invisible boundary, a preview word changed to the target word. As an example, this preview string can be (1) identical to the target word (*beach* used as a preview for *beach*), (2) a homophone of the target word (*beech* used as a preview for *beach*), (3) an orthographic control word (*bench* as a preview for *beach*), or (4) a completely unrelated consonant string (*jfzrp* as a preview for *beach*). Using this method, Pollatsek et al. demonstrated that a homophone of a target word, when presented as a preview in the parafovea, facilitated processing of the target word seen on the next fixation more than a preview of a word matched with the homophone in visual similarity to the target word (see Miellet & Sparrow, 2004, for converging evidence).

The related "fast priming paradigm" uses phonological priming during the first approximately 30 ms of target word-viewing time, using display changes during the first fixation on the target word (Lee, Binder, Kim, Pollatsek, & Rayner, 1999). Taken together, both techniques provided unequivocal evidence that knowledge about phonological word properties is activated extremely quickly in the time course of word recognition. From this and similar lines of work, it can be concluded that such fast sound processing may, in fact, be part and parcel of every act of word recognition. It is interesting to note that Chace, Rayner, and Well (2005) showed that the phonological preview benefit obtained using the boundary paradigm was present only in skilled readers, suggesting that less skilled readers may not be able to use this kind of sound code early during the time line of word recognition.

2. It is beyond doubt that in normal reading a division of labor exists between a direct route of word processing and an indirect route-based phonological recoding. Tracing the literature on phonological recoding during reading for meaning is far beyond the scope of this chapter (e.g.,

Coltheart, Laxon, Rickard, & Elton, 1988). The most prominent theoretical expression of this research tradition is the family of dual-route models of reading (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart et al., 2001; see Coltheart, 2000, for a brief overview). A beautiful demonstration of the interplay between these complementary sides of reading is a study by Coltheart and Doctor (1980), in which children misjudged the meaning of senseless sentences far more often if they were phonologically correct. It is quite clear that the phonological route of word recognition during reading is more important in young readers, because their knowledge of words and the automaticity of word processing are less developed. To our knowledge, there is no evidence on whether and how the balance between direct and indirect word processing differs between silent and oral reading.

3. A solid case can be made for effects of vocal length on word processing in silent reading (Abramson & Goldinger, 1997). To provide only a few examples, vocal length has an impact on response times in lexical decision tasks even if articulation is not necessary, and tongue twisters, appearing in sentences, increase semantic judgment times (Perfetti, 1982). Similar results have been reported by Ashby, Treiman, Kessler, and Rayner (2006) for gaze durations during sentence reading. These findings suggest that speech-like properties of phonological representation substantially modulate word processing during silent reading.

4. It has been shown in various ways that phonological working memory supports reading. To examine the time course of this type of working memory, Inhoff, Connine, and Radach (2002) developed the saccade contingent eye-speech paradigm. In this technique, a companion word is presented acoustically after the eye crosses an invisible boundary just before moving into a target word. Gaze duration on the target word increased drastically for all types of acoustic stimulation, including identical and dissimilar words. Critically, this increase persisted for gaze durations beyond the target word when the companion word was phonologically similar, indicating interference and thus reflecting the decay time of the memory trace (Inhoff, Connie, Eiter, Radach, & Heller, 2004). When Inhoff et al. (2001) partitioned their data between readers with longer versus shorter gaze durations, the effect was attenuated in less fluent readers, suggesting that a functioning phonological working memory is an essential component of efficient reading. Together with other data, these findings indicate that during silent reading for comprehension, phonological representations are activated at several stages during the time line of word processing. Moreover, at

least one of these forms of representation stays active for some time in the phonological compartment of working memory. These representations, in turn, help to store information for sentence processing and text comprehension (Baddeley, Thomson, & Buchanan, 1975).

Reading Comprehension

A review of the existing literature does not allow one to draw a clear conclusion regarding the influence of reading mode on comprehension. Some studies report better comprehension during oral reading (Collins, 1961; Schroiff, 1984), whereas others favor silent mode (Judd & Buswell, 1922; Poulton & Brown, 1967). To make the inconclusive picture complete, there are also quite a few studies that fail to find significant differences (Swalm, 1973; Juel & Holmes, 1981; Salasoo, 1986). The inconclusive findings of prior studies can perhaps partly be explained by methodological differences, such as the use of different age groups and inadequate specification of reading ability. As one important example, in the studies mentioned previously, the assessment approaches used to examine comprehension varied on a continuum between simple word verification to complex reasoning tasks (see Radach, Huestegge, & Reilly, 2008, for a recent discussion of task effects).

On a more theoretical level, there could be several reasons why one or the other reading mode might produce better comprehension. It is feasible to assume that oral reading supports comprehension because the reader benefits from the additional auditive input via "listening" to the ongoing speech production. Also, the conversion of graphemes into phonemic output is likely to demand more attention toward sub-lexical units of processing, which may benefit word recognition and comprehension (Swalm, 1973; Miller & Smith, 1990; Prior & Welling, 2001). Both arguments can be combined into the idea of a fundamental "mental economy," so that if a string of words is processed for a longer time in any part of the language-processing system, the build-up of a mental text representation should profit.

On the other hand, the possibility can be considered that in oral reading processing of a word may stop after its pronunciation and that the focus on the grapheme-to-sound route of reading may actually hamper access to more direct lexical and/or semantic information (Juel & Holmes, 1981). On a meta-level of cognitive control, it can also be argued that in the dual-task situation of (silently) reading for comprehension plus oral production (including speech planning and articulation), the oral production stream of processing occupies shared

resources that would otherwise be available for postlexical processing toward comprehension. A *prima facie* argument in favor of this view is familiar to every adult student of a foreign language: The actual task of reading aloud does not require the slightest bit of comprehension.

The situation has been clarified to a certain extent by Juel and Holmes (1981), who reported a longitudinal study on silent versus oral reading that attempted to take control for several potentially confounding factors. They concluded that beginning and especially struggling early readers show better achievement during oral reading, whereas third and fourth graders do not differ and skilled readers show better results during silent reading. A more detailed analysis of the third and fourth graders demonstrated that the reading comprehension of the more skilled readers among them were higher during silent reading. It is tempting to conclude from these results that the degree to which reading becomes more automatic and relies more on direct lexical access determines the relative advantage of silent versus oral reading for comprehension.

A related issue is whether factors can be specified that may help improve comprehension in either silent or oral reading. A conclusion that can be drawn from the prior discussion is that beginning and poor reader's comprehension should benefit more from oral reading, whereas more skilled readers may profit more from silent reading. It remains a challenge for future research to determine the turning point at which training in the silent reading mode becomes more effective. One important premise for this transition is apparently the internalization of the reading process (Kragler, 1995; Prior & Welling, 2001). Prior and Welling (2001) argue that "when reading is internalized, it is modified and constructed to serve a self-regulatory and self-guiding purpose. It is not simply a copy of the previous social reading now going on in the reader's head. It is transformed, and this change may explain why comprehension is typically superior after silent reading for advanced readers" (Prior & Welling, 2001, p. 4). Given that there was an obvious difference between third and fourth graders in the Juel and Holmes (1981) study, it is conceivable that this period describes the time window within which the hypothesized transformation process occurs for a majority of developing readers.

Eye Movements

As discussed, research on eye movements in reading can be divided into an early phase, during which summary measures are reported,

and a contemporary phase, which is dominated by precise analyses of word-based local fixation patterns (see Rayner, 1998, for a more elaborate discussion of the history of the field). In early research, it was found that oral reading is associated with a substantially larger number of fixations that are also of longer duration. The higher number of fixations while reading aloud has been assumed to be based on a higher probability to fixate every word. Judd (1918) and Buswell (1922) both suggested that in order to read aloud it is necessary to pay attention to every single word, while it is perfectly possible to skip words during silent reading and nevertheless comprehend the text. However, it was not known where these extra fixations are placed and which spatial and temporal parameter adjustments are made in the control system to implement the change from a silent to an oral mode of reading.

In addition to a higher number of fixations per line of text, Sovik, Arntzen, and Samuelstuen (2000) also found more regressions during oral reading. They suggested that more regressions may be needed to understand the main ideas of the text because oral reading is generally slower. It has also been suggested that the higher regression rate during oral reading is related to the complexity of text material. If the material is of high complexity (e.g., consisting of passive sentences), the oral-silent difference in the amount of regressions is elevated (Wanat, 1971, cited in Levin, 1979). The number of fixations and regressive saccades correlate with total reading speed ($r = .84$; Sovik et al., 2000). This correlation appears to support the assumption that these phenomena are related to the same source of variance in reading speed. As discussed previously, however, this type of account suffers from an inability to distinguish between regressive refixations and interword regressions and should, therefore, be seen with caution.

It is possible that reading mode also has an effect on the perceptual span in reading. In early research, it was often assumed that the perceptual span can be approximated based on the spatial distribution of fixations over a line of text. This indirect expression of the perceptual span, often referred to as the "recognition span," was believed to reflect the number of processed words during a fixation. As an example, Sovik et al. (2000) computed recognition span as the average number of words per fixation for a sample of 12-year-old readers and found a rather unsurprising correlation to reading speed. Concluding from this correlation that *recognition span* predicts the fluency of reading may be tempting, but it invites a rather serious lapse of reasoning. From a theoretical point of view, the logic behind the concept is flawed as long as it is unknown to what extent successive fixations reflect processing

of different versus identical words.¹ If in the absence of direct measurement of the perceptual span an approximation in terms of recognition span is taken to be valid, the data obviously suggest that the span is smaller for oral reading. However, this argument is again close to circular, because an increased number of fixations is usually assumed to be a consequence of the smaller span, which, in turn, is determined on the basis of the same increased fixation frequency.

To our knowledge, a study recently completed in our laboratory represents the first attempt to compare silent and oral reading using a methodology that includes analyses of word-based fixation patterns (Radach, Schmitten, Glover, & Vorstius, 2009). In this study, 20 fourth-grade elementary school students (age range, 9–10 years) were asked to read sentences for comprehension either silently or aloud. All students were reading at or near grade level, had English as their first language, and had normal or corrected-to-normal visual acuity. Materials included 120 relatively simple declarative sentences with recurring actors and recipients. To ensure reading for comprehension, 40 of the sentences were followed by comprehension questions targeting either simple (actor, object, location) or more complex (condition, causality) semantic relations. To allow for an orthogonal comparison of word length and word frequency, each experimental sentence contained either a low- or high-frequency target word of a short (four or five letters) or long (six or seven letters) length, respectively. In addition, the word familiarity was controlled using the *The Educators Word Frequency Guide* (Zeno, Ivens, Millard, & Duvvuri, 1995) to make sure that the determination of word frequency was adequate for children too.

Results indicated that in oral reading, not surprisingly, substantially more fixations are being made and interword saccades are of markedly smaller amplitudes. The size of word frequency effects on viewing duration measures remained approximately the same, even though gaze durations and total word-reading times were much longer in oral compared with silent reading. Here, in addition to sublexical and lexical word processing, these measures presumably also reflect post-word recognition speech planning and articulation processes, as found in research on delayed naming (e.g., Coltheart & Doctor, 1980; Inhoff & Topolski, 1994). It is interesting that, at least for good readers, such production-related components of oral reading appear equally sensitive to a word frequency manipulation as reflected in temporal eye movement parameters.

Figure 4.2 presents a comparison of viewing duration data for both silent and oral reading using a decomposition into initial fixation dura-

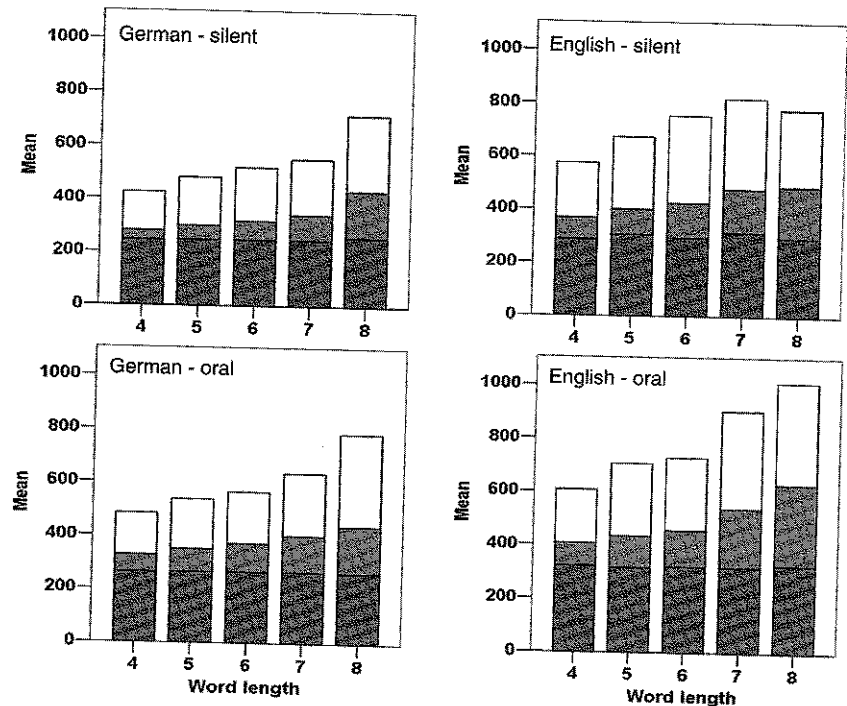
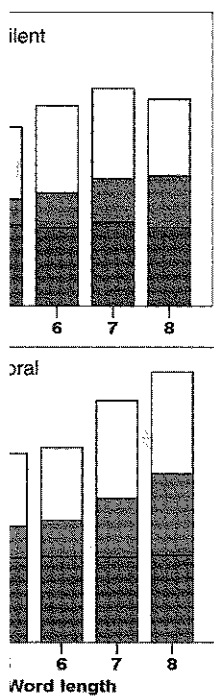


FIGURE 4.2. Decomposition of word-viewing durations into initial fixation durations (black), refixation time (gray), and rereading time (white). Panels represent data (in milliseconds) for words four to eight letters in length collected while U.S. versus German fourth-grade students were reading structurally identical sentences silently versus aloud.

tions, time for additional fixations during first-pass reading (refixations time), and time spent during later passes over the same word (rereading time; see also "Adding a Cross-Linguistic Perspective" for more details). Because fixation durations were only slightly longer, many of the observed prolonged word-viewing times when reading aloud were due to more refixations made within the same word. These extra refixations originate from two sources, with relative importance of both factors varying between individual readers. One source is a fixation position-independent increase in refixation frequency that manifests itself in a simple elevation of the u-shaped refixations curve describing the frequency of refixating the same word as a function of initial saccade landing position (McConkie et al., 1989). The second contributing



into initial fixation time (white). Panels letters in length col- re reading structur-

reading (refixations me word (reread- pective" for more ntly longer, many en reading aloud word. These extra mportance of both ource is a fixation cy that manifests s curve describing tion of initial sac- cond contributing

factor is a launch site-independent leftward shift of these incoming progressive interword saccade landing positions. This is a remarkable local adjustment, because the higher frequency of refixating the prior word causes a shortening of saccade launch distance, which, in turn, should have led to a rightward shift of subsequent saccade landing positions (Radach & McConkie, 1998). In sum, these patterns of intraword and interword saccades indicate how a global change in reading behavior is implemented in specific adjustments of local word fixation patterns.

ADDING A CROSS-LINGUISTIC PERSPECTIVE

Most research on reading development is conducted in English, and, as is the case in many other areas of cognitive and educational research, findings of these studies are often generalized to other languages. In doing so, it is (often implicitly) assumed that basic reading processes, at least in alphabetic writing systems using Roman script, are universal; therefore, studies in English are sufficient to provide an understanding of reading in general. However, investigations in languages other than English have shown that the linguistic environment and the writing system of a reader have a substantial impact on reading behavior (e.g., Frost, 1994; Hutzler & Wimmer, 2004; Aro & Wimmer, 2003; Caravolas, Volin, & Hulme, 2005; Eme & Golder, 2005).

Orthographies using Roman script vary widely in the consistency of their grapheme-phoneme and phoneme-grapheme correspondences. In consideration of this fact, languages can be placed on a continuum of consistency and transparency. The transparent (shallow) orthographies have consistent grapheme-phoneme mappings as, for example, in Italian, German, Spanish, and Serbo-Croatian. In contrast, in intransparent (deep) orthographies, like English, the same letter can represent different phonemes depending on its surrounding letters, and, vice versa, the same phoneme can be represented by different letters (Frost, Katz, & Bentin, 1987; Frost, 1994; Eme & Golder, 2005). Overall, the location of a language on that consistency continuum depends on the amount of grapheme-phoneme correspondence rules, which are necessary to read correctly. "The degree of irregularity is (then) defined as the percentage of words for which the rule pronunciation disagrees with the lexical pronunciation" (Ziegler, Perry, & Coltheart, 2000, p. 415).

Computational linguistic analysis of spelling body-rime correspondences showed that, for the English language, 31% of all monosyllabic words are feed-forward inconsistent, which means in the direction of spelling to pronunciation, and 72% are inconsistent backward,

from phonology to spelling. In German, the corresponding feed-forward inconsistency in monosyllabic words is only 16% and the backward inconsistency, 53%; for French, the forward inconsistency is 12% (Ziegler, Jacobs, & Stone, 1996; Wimmer & Mayringer, 2002). Within- and across-language research has shown that the consistency of orthography has substantial impact on the reading behavior in general and reading development in particular (e.g., Frost et al., 1987; Frost, 1994; Wimmer & Goswami, 1994; Aro & Wimmer, 2003; Ziegler & Goswami, 2005; Eme & Golder, 2005; Caravolas, Volin, & Hulme, 2005). When discussing results of such comparisons, some caution is warranted because there may be sources of variance that are very difficult to control, among them school systems, teacher quality, methods of reading instructions, amount of reading instruction within curricula, and demographic and socioeconomic characteristics.

With respect to the process of learning to read, a straightforward prediction can be derived from the prior discussion. Learning should be easier if the relationship between visual symbols (graphemes) and the corresponding sounds (phonemes) is more systematic. One important aspect of this general rule concerns the context sensitivity of pronunciation. As an example, in German the letter *a* is always pronounced /a/ like in *hand*, *garten*, or *ball*, whereas it is pronounced different in the English equivalents *hand*, *garden*, and *ball* (Hutzler & Wimmer, 2004). There is indeed substantial evidence indicating that children who learn to read in more consistent orthographies make faster progress in phoneme awareness, word recognition speed, spelling accuracy, and phonological recoding during the first years of schooling (e.g., Seymour, Aro, & Erskine, 2003; Wimmer & Goswami, 1994). In an attempt to quantify such differences, Ziegler and Goswami (2005) looked at the number of errors made when reading words or nonwords in various European languages. Whereas Italian second-grade students achieved an accuracy score of 94% in word reading and 82% in nonword reading, British children had scores of 70% and 45%, respectively. A cross-linguistic study in 14 European countries (Seymour et al., 2003) confirmed the advantage in learning to read in languages with more transparent orthographies. The development of grapheme-phoneme recoding skills took longer in less transparent languages, like English. Also, it appeared that the reading ability of English children depends less on phonological recoding because of the opaque relationship between graphemes and phonemes. Therefore, they have to learn more explicit rules, like reading new words via analogy to already known spelling patterns, during the process of reading acquisition instead of grapheme-

phoneme conversation rules (Wimmer & Goswami, 1994; Aro & Wimmer, 2003).

Converging evidence concerns the different types of reading errors made by German and English beginning readers. Misreading observed in German children most frequently involves nonsense words, whereas errors among the English readers primarily involve false real words. The nonsense word errors presumably occur because German children's reading depends on assembled pronunciation. In contrast, the English children use apparently direct access to the word, which results then in word errors (Wimmer & Hummer, 1990; Wimmer & Goswami, 1994). All these findings support the idea that, in languages with "shallow" orthography, the reader uses smaller chunks for computing phonology than in "deeper" orthographies. These smaller chunks are more regular and easier to learn; thus, the readers make fewer errors in nonword reading (Frost, 1994; Ziegler et al., 2000).

The findings discussed previously are based on research using single-word processing paradigms, like naming, lexical decision, and semantic priming. To our knowledge, there have been so far no studies directly comparing different languages with respect to corresponding dynamic reading situations in normal children. We recently completed a study including structurally similar sentences in English and German with fourth-grade readers. Most of the sentences were generated by directly translating from German into English (see "Comparing Silent and Oral Reading" for some aspects of methodology). Figure 4.2 presents a decomposition of total word-viewing time into three components: time spent during the initial fixation on the word, time used for immediate refixations within the first reading pass (refixation time), and time for reinspections of the same word during later passes (rereading time). This more compact way of reporting data was chosen here over directly plotting initial fixation durations, gaze durations, and total viewing times, as done in Figure 4.1, because it allows presenting more conditions in one figure.

Looking at Figure 4.2, it is apparent that there is not much difference between U.S. and German fourth-grade readers in the duration of initial fixations made on words during the reading of equivalent sentences. In contrast, the second component of word-viewing time, refixation duration, is strikingly longer among readers of English. This increased amount of time spent refixating is likely to reflect a higher mental effort necessary to achieve lexical access. In the absence of any traceable difference in target word frequency, this difference is presumably based on the intransparent nature of grapheme-phoneme corre-

spondence in English, as discussed previously for other methodologies. It is well known that increased difficulty in word processing on the lexical level translates primarily into an increase in the number of refixations (rather than inflating the initial fixation). As first shown by Kliegl, Olson, and Davidson (1983), the first of two fixations tends to be shorter than a single fixation, which means that the decision to refixate must be based on a fast educated guess about the to-be-expected mental effort associated with the processing of the current word.

The hypothesis of increased difficulty in lexical access works well in explaining the difference in refixation time. However, this is not the case for the second large difference apparent in Figure 4.2: a much higher rereading time in English. One could argue that English readers leave the target word more often prematurely and then have to return immediately for a completion of lexical processing. Even assuming that such a pattern of lexical spillover into subsequent fixations exists and is sometimes associated with returns to the target (Rayner & Duffy, 1986; Kliegl et al., 2006), a suboptimal processing strategy like this is unlikely in normal fourth-grade readers and can hardly account for the size of the observed difference. Moreover, syntactic processing difficulty can also be ruled out as the reason for the observed difference, because sentence structure was carefully held constant between the English and German versions of the sentence.

Our best candidate for an explanation of the increase in rereading time is a factor that, in our view, has not received enough attention in the existing literature on developing readers. Consider an English word like *exit*, which without context can be interpreted as a verb, noun, or adjective. There are also multiple ways to use it in compounds or equivalent phrases, such as "emergency exit" or "exit strategy." Virtually all of these possibilities are explicitly coded in German via inflection or productive compounding of nouns (Inhoff, Radach, & Heller, 2000), so that contextual processing is usually not needed to fully process the words meaning. Of course, the obvious advantage of explicit coding is partly offset by the fact that in many cases (but not in the study discussed here) words become longer or phrases have to include more words to convey the same message.² The resolution of lexical ambiguities during sentence reading in English is an established topic of experimental research (see Mason & Just, 2007; Sereno, O'Donnell, & Rayner, 2006, for recent examples).

From the prior discussions of significant differences between written languages like English and German, it should follow that the pattern of difficulties observed in struggling readers should also be language

dependent. Indeed, Hutzler and Wimmer (2004), in their (monolingual) study, suggested that the eye movement patterns of German students with developmental dyslexia differ from their counterparts in English. Common observations in English are frequent misreading of words when reading aloud, more regressions, and more and longer fixations compared with students reading at grade level. In contrast, German dyslexics make only slightly more fixations and shorter saccades regressions but show a larger effect of word length on viewing duration parameters. It appears that the key difference, more regressions, is in line with the increased rereading times for English in our direct cross-linguistic comparison. The larger impact of word length in German may reflect a greater reliance on phonological recoding in a more regular orthography (see De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002, for converging evidence on Italian readers with developmental dyslexia).

CONCLUSION

The present chapter attempted to sketch the state of the art in the area of developmental reading research based on analyses of oculomotor data. We have argued that this research is needed both as a contribution toward a better understanding of an important aspect of mental development in general but also as a baseline to evaluate performance in struggling or specifically impaired readers. After a brief introduction, we summarized basic developmental trends and then broadened the discussion to include comparisons between silent and oral reading with regard to several aspects of processing. Finally, a cross-linguistic perspective was introduced to illuminate the impact of language differences on how students master the task of reading. As we have seen, there are many interesting pieces of evidence addressing different angles of the problem. However, we are still lacking a comprehensive picture of the directions and determinants of development in dynamic reading and, to name just one major deficit, of the range of normal variability within such development.

The best way of addressing these complex and challenging issues will be in terms of well-controlled and comprehensive longitudinal research. The work by McConkie et al. (1991) has provided a promising first step in this direction, establishing the analysis of word-based saccade fixation patterns as the methodological standard in the field. As our own data have shown, advances in recoding technology now

permit precise measurement of eye movements during oral reading. Future research should aim to provide individual developmental trajectories for both silent and oral reading well into middle or even high school level. One important insight that such comparisons can deliver is to determine at which point in reading development (and why) silent reading becomes substantially more effective in terms of speed and comprehension. A related key question is which early indicators can predict specific aspects of success in silent and oral reading and to what extent growth in both modes of reading is interrelated.

This research will also have to address the tricky issue of age-appropriate reading materials. It is, of course, inadequate to ask students from first to fifth grade to reread identical materials throughout the course of a longitudinal project. However, using educational text materials that are at the "appropriate grade level" may introduce multiple combined changes in terms of vocabulary, sentence complexity, or even text coherence that are every experimenter's nightmare. Up to a certain point of proficiency, a developing reader can be matched at every grade level with more difficult text so that, at least on a global level of fluency, developmental changes are almost completely offset. Perhaps the best possible solution to this conundrum would be a careful combination of well-defined aspects of text difficulty that change from one point of measurement to the next, while other attributes or types of reading materials are held constant as a baseline throughout the entire time line of a longitudinal project.

Another key aspect of future research should be the combination of dynamic reading with psychometric assessments of reading ability and measures of component skills. From a cognitive science point of view, there are a number of good candidates for basic skills that may determine performance and developmental growth in reading such as working memory, phonological processing skills, word knowledge, attentional and visuomotor abilities, and general mental speed. In this context, it appears essential to prefer measures that do not themselves have a history of complex interrelation with multiple facets of performance. A good example would be RAN tasks, which have a well-established predictive utility, while the underlying cognitive processes are still quite controversial (see Wagner, Torgesen, & Rashotte, 1994; Vukovic & Siegel, 2006, for discussions).

For many potential component skills, a selection of valid and reliable measures has already been established. Interestingly, this is not the case for visuomotor abilities, so that it is currently difficult to substantiate the common anecdotic reports of reading problems related to

attention or spatial navigation. We are skeptical of attempts to capture such potential visuomotor problems in reading development with laboratory tasks that are remote from reading. Consequently, we are now developing a reading-like scanning task that incorporates much of the visuomotor dynamics of normal reading without imposing linguistic processing demands (Radach, Vorstius, & Günther, 2008). More generally, we strongly advocate the combination of experimental eye movement research with more psychometric and data analytic approaches as described in several chapters of the present volume. This will serve to broaden the scope of knowledge gained on both sides of the methodological spectrum. Moreover, combining the strengths of both approaches may also help eye movement-based developmental reading research establishing the educational credibility that is necessary to make an impact toward improving instructional practice and intervention for struggling readers.

NOTES

1. This discussion touches on the issue of sequential versus parallel word processing in reading. Positions on this issue range from strictly sequential word processing to limited parallel word processing within the limits of the perceptual span. It should be noted that the parallel position, although advocating temporal overlap in the processing of spatially adjacent words, is not necessarily in harmony with the idea of extrapolating a "recognition span" from the number of fixations on a line of text.
2. Looking at the problem more generally, there are several types of ambiguities on the lexical level that also exist in German but appear more frequent in English. Very common are homonyms, in which words have the same spelling but two or more meanings. An example is the word *mean*, which can describe an unkind person, an average, or the definition of a word. Another kind of lexical ambiguity is the heteronym, in which words are spelled the same but have different meanings and pronunciations. An example of this is *dove*, which can refer to a type of bird or can describe the action of jumping. The less frequent case of contronyms includes words that are spelled the same and pronounced the same but have two completely opposite meanings: for example, *Anxious*, where a person can be excited and eagerly looking forward to an event or might experience mental distress because of a perceived danger or misfortune. An experienced native reader of English may take all these decisions for granted but students in fourth grade might not be quite as efficient. Importantly, even a skilled reader is likely to spend more time with processing on a contextual level than is the case in a language that is less packed with lexical ambiguities (www.tesolcourse.com/tesol-course-articles/common-linguistic/article-01-mg.php; see

also Zhang, 2007, for a more detailed discussion from the perspective of foreign learners of English).

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