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The Influence of Past, Present, and Future Words on Fixation Durations

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Abstract

Reading requires the orchestration of visual, attentional, language-related, and oculomotor processing constraints. This study replicates previous effects of frequency, predictability, and length of fixated words on fixation durations in natural reading and demonstrates new effects of these variables related to previous and next words. Results are based on fixation durations recorded from 222 persons, each reading 144 sentences. Such evidence for distributed processing of words across fixation durations challenges psycholinguistic immediacy-of-processing and eye-mind assumptions. Most of the time the mind processes several words in parallel at different perceptual and cognitive levels. Eye movements can help to unravel these processes.

Keywords: eye movements, fixation duration, gaze, word recognition, reading

Tracking the Mind During Reading:
The Influence of Past, Present, and Future Words on Fixation Durations

Reading is a fairly recent cultural invention. The perceptual, attentional, and oculomotor processes enabling this remarkable and complex human skill had been in place for a long time before the first sentence was read. Of course, reading also fundamentally presupposes language, reasoning, and memory processes. If we want to understand how internal processes of the mind and external stimuli play together in the generation of complex action, reading may serve as an ideal sample case, because, despite its complexity, it occurs in settings that are very amenable to experimental control. In addition, the measurement of eye movements yields high-resolution time series that have proven to be very sensitive to factors at all levels of the behavioral and cognitive hierarchy. Most importantly, we already know or can determine basic perceptual, attentional, and oculomotor constraints which any theory of reading and any computational model implementing such a theory at a behavioral microlevel must respect.

Looking at the eyes, reading proceeds as an alternating sequence of fixations (lasting 150 to 300 ms) and saccades (30 ms). Information uptake is largely restricted to fixations. For example, fixation durations reliably decrease with the printed frequency of words and with their predictability from prior words of the sentence. Beyond these uncontroversial facts, however, much still needs to be learned about perceptual and attentional processes and properties of words that guide the eyes through a sentence. Starr and Rayner (2001, p. 156) highlighted the following three issues as particularly controversial:

> “(1) the extent to which eye-movement behavior is affected by low-level oculomotor factors versus higher-level cognitive processes; (2) how much information is extracted from the right of fixations; and (3) whether readers process information from more than one word at a time.”

In this article, we report new empirical results relating to each of these issues. We also present a data-analytic framework within which these issues can be addressed simultaneously and propose a set of theoretical principles which account for a complex set of experimental observations. Basically, in our analysis of reading fixations we show that most of the time the mind processes several words in parallel at different perceptual and cognitive levels. Similar dynamical and parallel effects of perceptual and attentional modulation guide human gaze control during real-word scene perception and interpretation (e.g., Henderson, 2005). A future challenge is to utilize the potential of eye movements as prime indicators of these general cognitive and behavioral dynamics.

Theoretical Background

Many students of reading still endorse the following two assumptions dating back at least to Just and Carpenter (1980). The first is the *immediacy-of-processing assumption,* which states that readers try to interpret words as they are encountered, that is without deferring processing until visual, lexical, or semantic ambiguities are resolved; they do so at the risk of guessing the wrong word at times. The second assumption is the *eye-mind assumption*: Readers retain fixation on a word as long as the word is processed. This assumption implies that gaze duration, defined as the sum of all fixations on a word when it is first encountered during reading (i.e., during first-pass reading), is diagnostic of processing time. Indeed, gaze duration has been used as the preferred dependent variable in much psycholinguistic research using eye-movement measures (see Rayner, 1998, for a review). According to these assumptions, there is no distributed processing of words across fixations on different words.

The complexity of the reading process quickly revealed serious limits of the eye-mind assumption; it could not explain, for example, how readers link a pronoun to its proper noun mentioned earlier in the sentence (Ehrlich & Rayner, 1983). Consequently, it was replaced with the *process-monitoring assumption* which restricted the eye-mind assumption to the interface of lexical access and initiation of saccade programs (Morrison, 1984). The basic idea of this assumption is that during reading we look up only one word at a time in the mental lexicon (i.e., lexical access). The mind monitors this lexical-access process and programs the next eye movement contingent upon its completion.

The process-monitoring assumption postulates a fundamental link between language-related and oculomotor processes. This assumption of strictly *sequential word-to-word shifts of attention contingent on lexical access* has also been implemented in the E-Z Reader model of eye-movement control during reading (Pollatsek, Reichle, & Rayner, in press, Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2003). This model, however, allows a limited form of distributed processing of words across fixations, because it also assumes that saccade programs are triggered by an initial stage of lexical access and, therefore, the eyes may move before or after the completion of lexical access. Distributed processing is limited, however, because the start of saccade programs is linked to serial lexical processing. For example, this assumption implies that a fixation duration can be influenced by the difficulty of the previous word but not by the difficulty of the next word.

Kolers (1976, also Bouma and deVoogd, 1974) had formulated a very different perspective on reading. They thought fixations lasting between 150 and 300 ms were too short to account for comprehension on top of visual processing. Therefore, they postulated an eye-mind span in silent reading analogous to the eye-voice span in oral reading (Buswell, 1920). Kolers argued that the irregularity of eye movements suggests that the eyes move largely at their own pace, that process monitoring can intervene when necessary, and that the mind sorts out the serial word order quite independently of the order in which words are fixated by the eyes. According to this *cognitive-lag hypothesis* (Rayner, 1977, 1978), linguistic processing of a word still occurs while the eyes already have moved on to the next word, just as in oral reading the eyes tend to run ahead of the voice.

In the present article, we propose that Kolers's (1976) proposal deserves a serious re-evaluation: Distributed lexical processing of a word across two or three fixations appears to be the rule rather than the exception, very much in agreement with the *cognitive-lag* hypothesis (e.g., Bouma & de Voogd, 1974; Kolers, 1976). Moreover, fixation durations are simultaneously sensitive to lexical, visual, and oculomotor levels of processing. Thus, the evidence presented here favors a much looser coupling between these processes than envisioned by Just and Carpenter's (1980) immediacy and eye-mind assumptions as well as subsequent assumptions of process monitoring (e.g., Ehrlich & Rayner, 1983) and sequential attention shifts (Morrison, 1984, Reichle et al., 1998). Our results challenge strong versions of these assumptions and, consequently, warrant a re-evaluation of the use of eye-movement statistics in psycholinguistic research. Unraveling the dynamics of distributed processing across reading fixations requires appropriate methods of statistical control which will lead to refined tests of the role of perception, attention, language-related, and even memory processes during reading.

Experimental Evidence for Distributed Processing

Over the last years, eye-movement research has uncovered a varied, controversial, and sometimes also confusing set of influences on fixation durations from neighboring words. Most of this research originates in experiments where a few target words were manipulated with a limited number of independent variables, rarely more than two or three. Our goal here is to test simultaneously the influence of twelve variables. These are the frequency, predictability, and length of currently fixated, preceding, and next word, the amplitudes of incoming and outgoing saccades, and the position of the fixation within the current word. We assess the effects of these variables for all fixation durations in first-pass reading rather than restricting the analysis to fixations on one or two target words per sentence which is the typical procedure in experimental reading research. We will refer to reading without experimental manipulations of target words and reading without gaze-contingent display changes as *natural reading*.

The simultaneous consideration of twelve effects in natural reading requires an integrative review of much related experimental research; it also requires a consistent terminology. To this end, we refer to the word currently fixated as word *n,* to the word to the left of it as word *n*-1, and to the word to the right of it as word *n*+1. Likewise, we refer to the current fixation as fixation *n*, the preceding fixation as *n*-1, and the next fixation as *n*+1. Note that the fixation *n*-1 need not be on word *n*-1, and fixation *n*+1 need not be on word *n*+1, because sometimes words are skipped. The only dependent variable is the duration of fixation *n*.

We start with a short synopsis of generally agreed-upon influences of word *n* on the duration of fixation *n*. These on-line measures of fixation times serve as the primary dependent variable of much experimental psycholinguistic research. Then, we present three predictions for influences of word *n*-1 (i.e., *lag effects*) and three predictions for influences of word *n*+1 (i.e., *successor effects*) on the duration of fixation *n*.

Immediacy of processing

Frequency, predictability, and word length. As pointed out above, much of psycholinguistic research is based on the assumption that properties of the fixated word *n* are the primary determinant of fixation or gaze durations (Just & Carpenter, 1980; Rayner, 1998, for a review). The "big three" properties are frequency, predictability, and length. Frequency and predictability correlate negatively and length correlates positively with fixation duration. In a previous report on part of the data reported here, we documented independent effects of these variables in separate analyses of first-fixation durations, single-fixation durations, and gaze durations as well as analogous effects on the probabilities of skipping, single-fixation, multiple-fixations, and regression (Kliegl, Grabner, Rolfs, & Engbert, 2004; see also Calvo & Meseguer, 2002; Rayner, Ashby, Pollatsek, & Reichle, 2004a, for simultaneous assessment of frequency and predictability).

Inverted optimal viewing position effect. The position of the fixation within a word has been identified as another variable with a large impact on fixation durations. Vitu, McConkie, Kerr, & O'Regan (2001; see also O'Regan, Vitu, Radach, & Kerr, 1994) reported an inverted optimal viewing position (IOVP) effect, meaning that fixations at the edges of a word are shorter than those occupying a middle position. At first glance, this effect appears to be difficult to interpret because the middle position seems to be the optimal viewing position for a word–it is associated with minimum refixation probability (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989) and requires the least presentation time in single-word recognition (see Brysbaert & Nazir, 2005, for a review). We replicated and modeled this IOVP effect on two assumptions (Nuthmann, Engbert, & Kliegl, 2005): (1) Some of the fixations hitting the edges of a word are the results of misguided saccades that were aimed toward the neighboring word. (2) These cases immediately trigger a new saccade program. Interestingly, the IOVP effect appears to be largely independent of word frequency (i.e., the curve is simply elevated for low-frequency words; Nuthmann et al., 2005; Rayner, Sereno, & Raney, 1996; Vitu et al., 2001) and, therefore, represents a comparatively confined contribution of oculomotor errors to fixation durations.

Lag Effects

Lag effects refer to the influence of properties of word *n*-1 or the position of fixation *n*-1 on the fixation on word *n*. Previous research suggests two main sources which relate (a) to limits of visual acuity, that is how close the last fixation *n*-1 was to the current fixation on word *n*, and (b) the difficulty of word *n*-1, that is how likely it is that processing of the last word *n*-1 is still going on during fixation *n*. Combinations of these explanations lead to additional predictions. Lag effects have been established for target words in experimental research but there have been no simultaneous assessments of lag and immediate effects for natural reading. We review four theoretical proposals.

Lag effect due to limits of visual acuity. One of the experimentally best-established facts about eye movements in reading is that masking of words outside the fovea (i.e., parafoveal masking) increases subsequent fixation durations relative to unconstrained reading (e.g., Balota, Pollatsek, & Rayner, 1985; Binder, Pollatsek, & Rayner, 1999; McConkie & Rayner, 1975; Rayner, 1975; Rayner & Bertera, 1979; Underwood & McConkie, 1985). Therefore, by inference, parafoveal preview of the upcoming words should benefit reading in general. On average, a fixation on a long word *n-1* will be further away from word *n,* and, consequently, preview benefit for word *n* will be reduced due to the drop-off in visual acuity and associated lateral inhibitions. Therefore, the length of word *n*-1 predicts the duration of fixation *n*. For the same reason, the distance between the locations of fixation *n* and fixation *n*-1, that is the amplitude of the incoming saccade, should have a similar effect: We expect long fixations after long saccades because the previous fixation yielded less preview of the current word compared to fixations after short saccades. Indeed, Radach and Heller (2000) and Vitu et al. (2001) reported strong effects of launch-site distance on subsequent fixation duration (see also Heller & Müller, 1983; Pollatsek, Rayner, & Balota, 1986).

Lag effect due to incomplete processing of word n-1. Processing of word *n*-1 may also influence the duration of the fixation on word *n* if the eyes moved from word *n-1* to word *n* before lexical processing of word *n*-1 was finished (Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999). In this case, fixation durations on word *n* are said to reflect a *spillover* from incomplete processing of word *n*-1. Incomplete processing is more likely for low-frequency words and, indeed, experimentally manipulated low-frequency words *n*-1 cause longer fixations on words *n*

(Rayner & Duffy, 1986). To our knowledge, this effect has not been documented for natural reading.

Lag effect due to dynamical modulation of the perceptual span. An alternative explanation to *spillover* can be derived from Henderson and Ferreira's (1990) *foveal-load hypothesis* which assumes that the perceptual span decreases with the difficulty of the foveal word, for example, when fixating low-frequency words (see also Balota et al., 1985; Inhoff, Pollatsek, Posner, & Rayner, 1989; Inhoff & Rayner, 1986; Rayner & Pollatsek, 1987). A low-frequency word *n*-1 is assumed to narrow the focus of attention during fixation on word *n*-1. This reduces the preview benefit for word *n,* which translates into the prediction that low-frequency words *n*-1 should be followed by longer fixations *n.* In addition, this hypothesis predicts that the frequency effect of word *n* should be stronger if the frequency of word *n*-1 is low, because there is less parafoveal processing of word *n* in this case.

Successor effects

Some properties of the not yet fixated word *n*+1 must become available during fixation *n.* Research on the perceptual span established that parafoveal visual information extending about ten characters in reading direction can influence the fixation duration on word *n* (McConkie & Rayner, 1975; Rayner, 1975). This information is used for selecting the next saccade target and for determining the amplitude of the next saccade. However, it is not clear to what extent such *parafoveal processing* modulates durations of fixation *n*: Is the influence restricted to visual and sublexical information of parafoveal words (i.e., only overall word shape and the initial letters) or does it also extend to their lexical and semantic properties? These questions relate to an active and controversial field of current experimental research (e.g., Kennedy & Pynte, 2005; Vitu, Brysbaert, & Lancelin, 2004). Here we restrict ourselves to two lexical influences of parafoveal lexical frequency. In addition, in anticipation of a key result of this article, we propose that the predictability of upcoming words *n*+1 may exert their influence on the duration of fixation *n* not only via parafoveal preprocessing but also via memory retrieval triggered by the prior sentence context.

Successor effect due to lexical preprocessing (frequency or relatedness of word n+*1*). There is disagreement about the existence of lexical parafoveal-on-foveal effects, that is, whether lexical properties of the not yet fixated parafoveal word (in particular, the frequency of word *n*+1) influence the current fixation duration (see Inhoff, Radach, Starr, & Greenberg, 2000a; Kennedy, Pynte, & Ducrot, 2002; Rayner, White, Kambe, Miller, & Liversedge, 2003, for comprehensive reviews of this issue). Recently, Kennedy and Pynte (2005) reported an effect of frequency of word *n+1* on durations of single fixations on short foveal words *n.* Their data were based on fixations of selected words measured during natural reading of newspaper articles. Evidence based on experimentally manipulated target words in sentences mostly does not show such an effect (e.g., Altarriba, Kambe, Pollatsek, & Rayner, 2001; Henderson & Ferreira, 1993; Starr & Inhoff, 2004; but see Inhoff, Starr, & Shindler, 2000b; Vitu et al., 2004). Proponents of parallel lexical processing interpret this pattern by assuming that parafoveal words are processed in parallel only if they fit into the current perceptual span, as illustrated in the top panels of Figure 1 for a fixation on a short and a long foveal word (Kennedy & Pynte, 2005). The main counter argument is that results in support of such parafoveal processing may be due to a small percentage of "erroneous" assignments of eye position to word *n* instead of word *n*+1 because of calibration error (i.e., machine error) or saccade error (i.e., a reader undershot the intended word *n*+1; Rayner, Warren, Juhasz, & Liversedge, 2004b).

Successor effect due to dynamical modulation of the perceptual span. One can also deduce a successor effect from Henderson and Ferreira's (1990) proposal of dynamical attention modulation described above in the context of lag effects. Specifically, if the foveal word *n* is of low frequency, the focus of attention should be narrower, and therefore there should be less of an influence of the parafoveal word *n*+1 on the duration of fixation *n* (White, Rayner, & Liversedge, 2005; but see also Henderson & Ferreira, 1993, Kennison & Clifton, 1995, for some negative evidence). This hypothesis is illustrated in the bottom panels of Figure 1 with different processing rates for high-frequency and low-frequency foveal words. The attention-modulation hypothesis predicts that the frequency effect of parafoveal word *n*+1 should be larger for high-frequency than low-frequency foveal words *n*.

Successor effect due to plausibility and predictability. Finally, parafoveal words can also be identified or guessed *without* direct fixation if they are strongly suggested by the preceding sentence context (e.g., *mouse* given *The cat chases the* ...*),* as documented by increases in skipping rates with word predictability and frequency (O'Regan, 1979, 1980), predictability (Ehrlich & Rayner, 1981; Rayner & Well, 1996), and plausibility (Rayner et al., 2004b). The eyes also land further into words that could be predicted from semantic context (Lavigne, Vitu, & d'Ydevalle, 2000) and visually similar nonwords are almost as effective parafoveal previews as real words (Balota et al., 1985). Fixation durations, in contrast, were not influenced by plausibility and predictability. Since we have predictability norms for all words of our sentences, we re-evaluated this issue with much better statistical power than previous studies. To foretell a key result: We will report a very strong inverted effect of predictability of word *n*+1 on the duration of fixation *n.* Thus, counter to the usual result that high predictability implies easy processing and consequently *short* fixations, we find that the more predictable the next word *n*+1, the *longer* the fixation on word *n.* We will interpret this result (1) as evidence for memory retrieval of upcoming words with prior sentence context as retrieval cue and (2) as evidence for processing of these retrieved words *n*+1 during fixation *n*.

Reading patterns: Single fixations and gaze durations

Single fixations occurring in a stream of forward between-word saccades represent the most frequent type of reading pattern (Hogaboam, 1983). They are a special case of gaze durations (i.e., the sum of consecutive fixations on a word). So far all arguments have applied to the case of single-fixation reading. Do we need to qualify our reasoning if word *n* is the target of two or more successive fixations?

First, refixations might reflect a lexical-processing difficulty for word *n*. If refixations are correlated with a focusing of attention on this word, that is if they indicate an increase in foveal load (Henderson & Ferreira, 1990), then the properties of word *n* should be more influential than those of word *n-1* and word *n*+1. Also, for a simple statistical reason, properties of word *n* should have a larger influence on gaze durations arising from refixation patterns than on single-fixation durations: Multiple fixations are multiple measures and averaging (or summing) suppresses noise. Thus, in general, gaze durations should be more reliable measures than individual fixation durations.

Second, refixations might provide a pause for the mind to catch up with processing of a lexically difficult word *n*-1 (see also Bouma & de Voogd, 1974, for an elaboration of this buffer concept). If so, the difficulty of word *n*-1 should spill over into the fixation durations on word *n*.

Third, multiple fixations, in particular regressive refixations, might simply be indicative of an oculomotor difficulty, which triggers an adjustment of the fixation position within the word, irrespective of the lexical status of the fixated word (O'Regan, 1990). In this case, lexical effects as well as lag and successor effects should not differ much between single-fixation durations and gaze durations. Taken together, these three considerations suggest that single-fixation and gaze durations may well exhibit different patterns of distributed processing during reading.

Summary

In summary, in addition to the well-known immediate influences of word-*n* properties on fixation durations in reading, on which much psycholinguistic research is based, we consider (1) influences from properties of the previous word *n*-1 (i.e., lag effects), (2) potential influences of properties of the upcoming word *n*+1 (i.e., successor effects), and (3) the influence of the relative fixation location in word *n* and of previous and next fixation locations (i.e., incoming and outgoing saccade amplitude) on the duration of fixation on word *n*. We tested these effects with single-fixation durations and gaze durations of first-pass reading as dependent variables. Lag effects have been established with manipulations of experimentally defined target words but are close to undocumented for natural reading. Successor effects relating to properties of frequency and predictability are the subject of current controversies in experimental reading research and are also undocumented for natural reading. The third topic is of great relevance for an understanding of the relative weight of contributions from perceptual span and lexical and oculomotor processing, respectively.

Progress on these issues is critical for the further development of current computational models of reading (e.g., Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; McDonald, Carpenter, & Shillcock, 2005; Pollatsek, Reichle, & Rayner, in press; Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2003; Yang & McConkie, 2001) because none of these models contains an adequate model of visual word recognition in sentence context (see commentaries to Reichle et al., 2003). These models are productive, however, because they differ in core assumptions about serial versus distributed word recognition in the perceptual span and about how strongly stages of word recognition determine the programming of saccades. In this context, two goals of this article are (1) to provide new benchmark data for the further development and evaluation of such computational models and (2) to facilitate the integration of reading and word-recognition research (see Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004, for a complementary agenda for visual recognition of isolated single-syllable words). Finally, we hope to show that prior sentence context and parafoveal visual information serve as effective memory-retrieval cues for the anticipation of upcoming words.

METHOD

Participants

Data from nine experimental and quasi-experimental samples, that is, from a total of 222 readers ranging in age from 16 to 84 years, were pooled for the following analyses. Table 1 provides information about age (i.e., mean, standard deviation, and range), experimental conditions, and sampling rate (250 Hz = EyeLink I; 500 Hz = EyeLink II) of the nine samples. Sessions lasted 45 to 60 minutes. Participants received 5 to 7 € or study credit. The experiment was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki; participants gave their informed consent prior to their inclusion in the study. Some data from samples 1 and 9 were reported in Kliegl et al. (2004).

Apparatus

Single sentences (see next paragraph) were presented on the center line of a 21-inch EYE-Q 650 Monitor (832 x 632 resolution; frame rate 75 Hz; font: regular New Courier 12) controlled by an Apple Power Macintosh G3 computer. Participants were seated in front of the monitor with the head positioned on a chin rest. Eye movements of four samples were recorded with an EyeLink I system (SR Research, Toronto) with a sampling rate of 250 Hz and an eye position resolution of 20 sec-arc; for the remaining five samples we used the EyeLink II system with a 500 Hz sampling rate. All recordings and calibration were binocular. Data were collected in two laboratories with identical equipment and setup.

The Potsdam Sentence Corpus

Word length. The Potsdam Sentence Corpus (PSC) comprises 144 German sentences (1138 words). They were constructed with the goal to represent a large variety of grammatical structures around a set of target words (one or two per sentence; see below) for which length and frequency are uncorrelated across the sentences. Sentences range from 5 to 11 words (M=7.9; SD=1.4). Excluding the first word of each sentence which was never used in the analyses, the number of words for lengths 2 to 13 and more letters are: 54, 222, 134, 147, 129, 92, 72, 66, 20, 25, 16, and 17. (The category *13 and more letters* contains seven words of length 14 to 20.)

Printed frequency. CELEX Frequency Norms (Baayen, Piepenbrock, & Rijn, 1993) are available for the 1138 words. Excluding the first word of each sentence, word frequencies range from 0 to 25,153 per million; the mean (standard deviation) log frequency (incremented by 1) is 2.1 (1.3). The CELEX corpus is based on approximately 5.4 million words.

Predictability. Predictability norms were collected in an independent study with 272 native speakers of German ranging in age from 17 to 80 years yielding 83 complete predictability protocols for each word of the PSC. Participants were high-school students, university students, and older adults (see samples 10, 11, and 12 in Table 1 for age-related statistics). Predictability was measured as probability of predicting a word after knowing the preceding part of the sentence. Excluding the first word of each sentence, word predictabilities range from 0 to 1 with a mean (standard deviation) predictability of 0.20 (0.28). These probabilities were submitted to a logit transformation. Logits are defined as .5*ln(pred/(1-pred)); predictabilities of zero were replaced with 1/(2*83)=-2.55 and those of the five perfectly predicted words with (2*83-1)/(2*83)=+2.53, where 83 represents the number of complete predictability protocols (Cohen & Cohen, 1975); the mean (standard deviation) logit predictability is -1.35 (1.18). For a word with predictability .50, the odds of guessing are one and the log odds of guessing are zero. Thus, words with predictability larger than .50 yield positive logits, those with predictabilities smaller than .50 negative logits. Further procedural details on the norming study and 32 example sentences are provided in Kliegl et al. (2004).

Procedure

Participants were calibrated with a standard nine-point grid for both eyes. They were instructed to read the sentence for comprehension and fixate a dot in the lower right corner of the monitor to signal the completion of a trial. After validation of calibration accuracy, a fixation point appeared on the left side of the center line on the monitor. If the eye tracker identified a fixation on the fixation spot, a sentence was presented so that the midpoint between the beginning and the center of the first word was positioned at the location of the fixation spot. Therefore, each sentence-initial word was read from a word-specific optimal viewing position (e.g., O'Regan & Levy-Schoen, 1987). Sentences were shown until participants looked to the lower right corner of the screen. Then, the sentence was replaced (a) by a three-alternative multiple choice question pertaining to the current sentence on 27% of the trials, which the participant answered with a mouse click, (b) a fixation spot indicating the beginning of the next trial which participants then initiated by fixating the fixation point or (c) a complete recalibration with the nine-point grid after every 15 sentences. In addition, the experimenter carried out an extra calibration if the tracker did not detect the eye at the initial fixation point within two seconds. Figure 2 shows sample traces.

Analyses

The data set. Eye movement data were screened for loss of measurement and blinks. Data of sentences without problems were reduced to a fixation format after detecting saccades as rapid binocular eye movements, using a binocular velocity-based detection algorithm which was originally developed for the analyses of saccades in attention-shifting experiments (Engbert & Kliegl, 2003). This first level of screening led to a pool of N = 238,185 binocularly defined fixations. In a second level of data screening, we excluded first and last fixations in sentences (2*28,112), fixations on first or last words of sentences (first word : 33,339, last word: 26,405), fixations shorter than 30 ms (n=7,212) or longer than 1000 ms (n=27), and fixations preceded or followed by microsaccades (i.e., within-letter saccades; n=2*5,283). This second level of screening left us with 159,888 valid within-sentence reading fixations. The difference between the total *N* and this valid number of fixations was mostly due to "first" and "last" fixations; only 5.4% of fixations were too short, too long, or bordered by a microsaccade. Relaxing these criteria or enforcing even stricter ones did not change the results to be reported below in any substantive manner. We analyzed only fixations in first-pass reading. Our "first-pass" constraint excludes fixations prior to and after regressions to previous words irrespective of whether these words had been skipped or fixated before.

Repeated-measures multiple regression analysis (rmMRA). With a rmMRA as described by Lorch and Myers (1990; method 3), we tested effects of log frequency, logit predictability, and length (using the reciprocal value of 1/length) of current, last, and next word (predictors 1 to 9), the amplitudes of the incoming and outgoing saccade (predictors 10 and 13), and the effect of the fixation location in the current word (linear and quadratic polynomial contrasts; predictors 11 and 12) on fixation duration. Fixation locations within words (coded in absolute fixation position, *afp*, with respect to the fixated letter) were rescaled to relative fixation positions (range: 0 to 1, *rfp*) by dividing *afp* by word length (i.e., *rfp* = *afp/wl*). As we used *1/wl* as predictor for word length (see above), *rfp* effectively also coded the multiplicative interaction of absolute letter position and word length.[1] In a second set of analyses, we included additional multiplicative interaction terms in the regression equation to test specific predictions of lag and parafoveal-on-foveal effects outlined in the introduction.

Binocular control analyses. Since we had recorded binocularly, we could restrict analyses to those fixations that were assigned to the same word in both eyes. As discussed in the Introduction, any erroneous assignment of fixations to neighboring words due to limits of spatial resolution of the eye tracker or inaccuracies associated with its calibration could generate parafoveal-on-foveal effects (see Rayner et al., 2004b, for a cautionary note along those lines). Therefore, analyses of parafoveal-on-foveal interactions are based on the 77% binocularly defined first-pass fixations that were assigned to the same word.

RESULTS

Most our analyses focus on first-pass single-fixation and gaze durations. The presentation of results is organized into two main sections. In the first section, we document how representative first-pass fixations are of all fixations. In the second section, we present results about tests of the influence of fixated and neighboring words on single-fixation and gaze durations. In this section, we report a series of analyses relating to (a) the theoretical issues of distributed processing across fixation durations and (b) differences between single-fixation and gaze durations.

Descriptive statistics for fixation patterns in first-pass reading

First-pass single-fixation cases comprise 54% of all valid reading fixations in our data base; first-pass two-fixation cases comprise 18% of all valid fixations, with a 2:1 ratio of intraword forward to intraword backward patterns (12% vs. 6%); 2723 “gazes” with at least 3 fixations contribute 5.6% of valid fixations (see Table 2). The remaining fixations concern fixations prior to regressions and all fixations of second-pass reading. Table 2 lists means and standard deviations of eye-movement statistics (i.e., duration, fixation position, last and next saccade amplitude) of all valid fixations in the data base for comparison with cases of first-pass single-fixation, first-pass two-fixation, and first-pass multiple-fixation (i.e., gaze>=3).

Single fixations constitute the majority of valid fixations; their descriptive statistics differ only in minor ways from the entire data set. In comparison to all valid fixations, amplitudes of associated saccades are about half a letter longer and the length of the fixated word is half a letter shorter for single fixations. No discrepancies are related to word statistics of frequency and predictability. In the left column of Table 2 we also list mean and standard deviation for length, frequency, and predictability of the full set of words of the Potsdam Sentence Corpus. Again, these statistics are very similar to those of the words that received single fixations.

Major differences are observed between valid fixations and two-fixation cases, quite in agreement with previous research (e.g., Rayner et al., 1996). (a) Second fixation durations are shorter than first fixation durations, (b) fixations in two-fixation cases are towards the beginning and end of words, (c) saccade amplitudes coming into and leaving words with a left-directed refixation are especially long, and (d) words with right-directed refixations are longer, less frequent, and less predictable compared to those with other fixations.

Finally, words that attracted at least three fixations in first-pass reading are at least one standard deviation longer, less frequent, and less predictable than words with single fixations. Manipulations of text material often induce multiple fixations on target words. Obviously, such multiple-fixation cases are less representative of natural reading than single-fixation cases.

Tests of distributed processing

In this section we present results of various rmMRAs to test the effects of frequency, predictability, and length as well as of fixation position and incoming and outgoing saccade amplitude on fixation and gaze durations. First, we focus on right-eye single-fixation durations. Then, we restrict the analyses to fixations that were identified on the same word in both eyes. For this analysis we also extend the rmMRA model with multiplicative interaction terms to test specific hypotheses about predicted lag and successor effects. In a third and fourth set of analyses we repeat these analyses for gaze durations and for the special case of two-fixation patterns.

Single-fixation durations

Figure 3 provides a visualization of twelve main effects for single-fixation durations on word *n*. The first three rows represent the influence of frequency (row 1), predictability (row 2), and length (row 3) for word *n*-1 (column 1), word *n* (column 2), and word *n*+1 (column 3). Row-4 panels display the effects of the "incoming" saccade amplitude (left), the relative fixation position in word *n* (middle), and the amplitude of the "outgoing" saccade (right). Symbols represent observed mean fixation durations over suitably binned category means. There were at least 2000 fixations per bin. Error bars are within-subject 99%-confidence intervals (Loftus & Masson, 1994).

The results of the rmMRA of single fixations are shown in Table 3. We list 14 unstandardized regression coefficients. These coefficients are the means from the MRAs estimated separately for each individual (Lorch & Myers, 1990; method 3, individual regression equations). An analysis of medians yielded the same pattern of results. For each regression coefficient, we also provide the associated standard deviation and the decrease in R^2 for its removal from the complete model, that is, its unique variance. This decrease was statistically reliable for all significant coefficients; test statistics were based on Lorch and Myers (1990, method 3, single-equation procedure). Finally, the stability of the sign of regression coefficients was very high across the nine independent subsamples (see right column of Table 3; see Table 1 for a description of subsamples).

In the following, we interpret results with reference to significant regression coefficients; first-order correlations in parentheses are provided as supplementary information.

Lexical immediacy effects. The middle column of panels in Figure 3 shows that, as expected, fixation duration decreased significantly with frequency (*r*=-.07) and predictability (*r*=-.07) of the currently fixated word. Word length (i.e., 1/wl) was only weakly correlated with fixation duration (*r*=-.02) but highly correlated with frequency (*r*=.58), predictability (*r*=.37), and relative fixation position (linear: *r*=.17; quadratic: *r*=.35) .[2] Moreover, the regression coefficient of word length had a sign opposite to its correlation with fixation duration. Therefore, the reliable effect of word length in the regression equation reflects a suppressor effect; its source is that long words are read faster than expected from the additive effects of the other predictors. We will provide an explanation of this effect in terms of a multiplicative interaction between frequency and word length of current word (see below).

Oculomotor immediacy effects. The bottom panel of the middle column of Figure 3 shows the expected inverted optimal viewing position effect on fixation duration: Fixations at the edges of words were shorter than those in the word center; note the strong contribution of the quadratic trend (*r*=-.07) in Table 3. Thus, oculomotor immediacy effects are in agreement with previous research, including effects of word frequency, word predictability, and relative position within word.

Lag effects. The left column of panels in Figure 3 reveals reliable and systematic influences of frequency (*r*=-.15), predictability (-.08), and word length (-.12) of word *n-1* on the fixation duration on word *n.* Note that the frequency of the left word correlates stronger with fixation duration than the frequency of the fixated word itself (-.07). The strongest effect is due to incoming saccade amplitude (.16). Most importantly, this effect is consistent with the assumption that reduced parafoveal preview contributes to longer subsequent fixations. In addition, strong effects of last word frequency and predictability suggest effects due to delayed lexical processing (i.e., "spillover"). Note that these effects are reliable under simultaneous statistical control of next, present and last word length, immediacy effects, and relative fixation-position effects.

Successor effects. The right column of panels in Figure 3 illustrates the influence of properties of the upcoming word on the fixation duration prior to the outgoing saccade. Table 3 reveals highly reliable effects of word frequency in the usual direction (i.e., a decrease in duration of fixation *n* with an increase in frequency of word *n*+1) but also a reliable effect of predictability in the opposite direction: The more predictable the upcoming word *n*+1, the longer the current duration of fixation *n*–as if unpredictable words to the right of fixation "attract" the eye. The signs of first-order correlations with fixation duration are also consistent with this pattern (1/word length: *r*=-.02, log frequency: *r*=-.02, logit predictability: *r*=+.05). Thus, there is reliable evidence for opposite influences of frequency and predictability of word *n*+1 on the fixation time on word *n* despite a positive correlation between these two variables (*r*=.38). The opposite influence of frequency and predictability on fixation duration is reliable for the nine samples of readers (see right column of Table 3). Finally, we had also included the amplitude of the outgoing saccade as a predictor because fixation duration *n* may be indicative of saccade programming time: Fixation durations increase significantly with the length of the outgoing saccade (.05).

Goodness of fit and unique amount of variance. The rmMRA model accounts for 25% of the variance in single-fixation durations; variance between 222 subjects accounts for 18% and the thirteen predictors account for 7% of variance. At first glance this appears to be a poor fit. Note, however, that we model “raw” fixation durations. The correlation between observed category means displayed in Figure 3 and the corresponding means predicted from the regression equation was .93. The redundancy of the predictors can be assessed by removing each predictor in turn from the complete model and assessing the associated drop in explained variance (see "-ΔR^2" column in Table 3). Amplitude of last saccade, frequency of last word, frequency of current word, predictability of current word, and length of current word (via its suppressor quality) are the best five predictors. Thus, apparently there is a fair balance between lexical, visual, and oculomotor contributions to single fixation durations. These influences derive not only from the currently fixated word but also from the properties of the words immediately to the left and to the right of the fixated word.[3]

Binocular reliability

There is one important limitation on the interpretation of lag and successor effects so far: They could be due fixations in the data base that were allocated erroneously to a neighboring word because of inaccuracies in the calibration. Given enough statistical power, such misallocated fixations could cause the observed lag and successor word effects. As we had measured both eyes, we are able to check whether lag and successor effects are stable if we restrict the analyses to fixations that were allocated to the same word for both eyes. 67,260 (77%) first-pass single fixations met this criterion. The results are not different from those of the complete set with one exception: Means (standard deviations) for within-word letter positions are 2.5 (1.6) for the right eye and 3.2 (1.6) for the left eye; 58% of fixations are assigned to the same letter, for 26% the left eye fixated 1 letter to the right of the right eye, and for 15% the left eye fixated 1 letter to the left of the right eye. The difference between linear trends of relative fixation positions for the two eyes is significant (right eye: b=-7.4, SE=1.6; left eye: b=-1.4, SE=1.7; see Table 4 for all coefficients of right-eye and left-eye rmMRAs). No other coefficients were different between the two eyes; note also the similarity between these values and those for all single fixations (i.e., compare with the left part of Table 3).

The important result for the theoretical questions addressed here is that there were very high correlations between right-eye and left-eye fixation durations (r=0.98) as well as incoming (r =0.99) and outgoing saccade amplitudes (r =0.99); in contrast, for relative fixation positions, the correlation between eyes was only 0.69. Similarly, with the exception of correlations for linear (r =0.50) and quadratic (r =0.42) trends for relative position within words, regression coefficients for left and right eye correlated between 0.95 and 0.98 (M=0.96) across 222 readers. Thus, it seems unlikely that inaccuracies of measurement are the cause of the influence of word n-1 and word n+1 on fixation durations on word n.

Tests of foveal load and parafoveal-on-foveal effects

The tests of the main effects of the twelve independent variables on single fixation durations in first-pass reading were followed by tests of interactions among some of these variables, focusing on theoretically predicted interactions. To this end, we used only first-pass fixations that were assigned to the same word in both eyes (n=67,260). Due to the high similarity of estimates for the two eyes, we describe only results for single fixations measured in the right eye in the text; test-statistics for right and left eye are reported in Table 4.

Relative current-word frequency effect. In the main-effects analysis, we identified a suppressor constellation relating to length and frequency of the fixated word n. This suppressor constellation disappeared when we included a multiplicative interaction term of log frequency and (1/word length). The interaction coefficient is highly significant; b=25, t=7.9. As shown in Figure 4a, a 2 x 2 breakdown of word length (fewer than seven letters vs. seven letters and more) and frequency (median split) reveals a stronger frequency effect for long words (220 ms - 206 ms = 14 ms) than for short words (211 ms - 205 ms = 7 ms).[4] With this relative-frequency effect in the regression equation, effects of reciprocal word length (b=-60, t=-3.9) and frequency (b=-12.1, t=-12.2) are significant in the expected direction (i.e., long fixation durations for long and low-frequent words; see Table 4). The direction of effect associated with this interaction holds for all nine samples of readers.

Foveal load hypothesis: lag effect. In the introduction, we derived two predictions for interactions on the assumption that the difficulty of the fixated words restricts the perceptual span (Henderson & Ferreira, 1990). If a low-frequency word *n*-1 restricts the perceptual span, then word *n* is less processed during the preceding fixation *n*-1. So when word *n* is fixated subsequently, duration of fixation *n* should be longer and the effect of frequency of word *n* should be larger. The interaction of word-*n*-1 frequency with word-*n* frequency is significant, *b*=1.0, *t*=5.4. As shown in Figure 4b and as predicted by the foveal-load hypothesis, the word-*n* frequency effect is stronger if word *n* follows a low-frequency word *n*-1 (228 vs. 210 ms) than if it follows a high-frequency word *n*-1 (204 ms vs. 199 ms).

Foveal load: successor effect. The second hypothesis, based on the assumption that foveal load dynamically restricts the perceptual span (Henderson & Ferreira, 1990), predicts a smaller frequency effect of word *n*+1 for low-frequency foveal words *n,* because word *n*+1 is likely to fall outside the perceptual span in this case (see bottom panels of Figure 1). This interaction of frequency of word *n* and frequency of word *n*+1, however, is not significant; the regression coefficient (*b*=-0.2) is within twice the standard error (.02; *t*=-1.2).

Parafoveal word frequency effect. Given an average fixation location in the word center, the eyes are closer to the parafoveal word if word *n* is a short rather than a long word (see top panels of Figure 1). So word *n*+1 is more likely to fall within the perceptual span if it follows a short word *n.* As expected, frequency of word *n*+1 expresses itself more strongly in fixation durations on short rather than on long words *n*; *b*=14, *t*=4.3, for the interaction of reciprocal length of word *n* and frequency of word *n*+1. The frequency of word *n*+1 affected fixation durations only for short fixated words (212 vs. 204 ms); the mean fixation durations on long words are 217 ms and 216 ms for low-frequency and high-frequency words *n*+1, respectively (see Figure 4c). Note also that this interaction qualifies the main effect of frequency of word *n*+1 reported above: The parafoveal frequency effect is only reliable after short words, replicating Kennedy and Pynte (2005) for natural reading. The direction of effect associated with this interaction holds for 8 out of 9 samples.

Parafoveal word predictability effect. In addition to a main effect of frequency of word *n*+1, we also obtained a main effect of predictability of word *n*+1 which was opposite to its usual direction, that is, low predictability of word *n*+1 was associated with shorter fixation durations on word *n.* It turns out that word *n*+1 has a larger effect when word *n* is long, so that word *n*+1 is partly outside the perceptual span (see the lower panel of Figure 1)*;* b=-8, t=-2.1. As shown in Figure 4d, the parafoveal predictability effect is stronger when the target fixation is on a long word *n* (212 ms vs. 221 ms) rather than when it is on a short word *n* (206 ms vs. 209 ms). The qualitative direction of this effect holds for 8 out of 9 samples of readers. Thus, it appears that a highly predictable word *n*+1 is in part processed while fixating word *n*; the eyes only move on quickly if the mind cannot guess the next word from the currently available context of the sentence. Note also the modulating role of the length of word *n* for parafoveal frequency and predictability effects of word *n*+1: If word *n* is short, fixation duration *n* depends on the frequency of word *n*+1 (see Figure 4c); if word *n* is long, fixation duration *n* depends on the predictability of word *n*+1 (see Figure 4d).

Gaze durations

In this section, we determine how single-fixation results compare to those for gaze durations. Gaze duration is defined as the sum of fixation durations on a word during first-pass reading, also including single-fixation cases. We submitted 98,211 first-pass right-eye gaze durations based on fixations that were assigned to the same word in both eyes to the same 18-coefficient regression model used for single-fixation durations. Note that the single fixations analyzed above are a true subset of fixations contributing to this analysis of gaze durations; they represent roughly 2/3 of these gaze durations. Relative fixation position of gaze was computed as the average position of contributing fixations; incoming saccade amplitude was referenced to the first fixation on the word and outgoing saccade amplitude to the last fixation. The statistics of regression coefficients are summarized in the right part of Table 4, next to those estimated for binocularly defined single fixations. Main effects are visualized in Figure 5.

Despite the large overlap between the data sets, there are striking differences between the two analyses. Foveal word length and word frequency exert a much stronger effect on gaze than single-fixation durations (i.e., coefficients for gaze were larger than those for single fixations by factors of 7.5 and 2.8, respectively; this is also very noticeable in the unique variance column). The much stronger frequency x length interaction underlines this trend (compare Figure 4a and Figure 6a). Also, the IOVP effect is much more pronounced for gaze than for single fixations (compare Figures 3 and 5). Finally, the influence of predictability is similar in both measures.

As far as lag and successor effects are concerned, the effects are very different. Most importantly, the influence of frequency of word *n*-1 is greatly reduced by a factor of 4.5 in coefficients; the interaction of frequencies of word *n*-1 and word *n* is strongly reduced (compare Figures 4b and 6b). The main effect of predictability of word *n*+1 is opposite in direction to its effect on single-fixation duration. For gaze durations, we observe reliably stronger effects of parafoveal frequency and predictability for long than for short fixated words *n* (compare Figure 4c and 4d with Figures 6c and 6d). Consequently, in comparison with single-fixation durations, we “lost” the different direction of effects associated with parafoveal frequency and parafoveal predictability for short and long fixated words *n*. Thus, for gaze durations we do not replicate the different patterns of interactions we observed for single-fixation durations.

Two-fixation gaze durations

From a dynamical perspective, multiple-fixation patterns are a heterogeneous set because averaging across them ignores the sequence of fixations within words (see also Blanchard, 1985).[5] The following analyses establish different distributed processing effects for simple right-directed and left-directed intraword refixations. The statistics in Table 2 already indicate that these patterns differ from other single fixations and from each other. Compared to single fixations, the forward pattern occurs on long words (mean length 8.2 vs. 5.6 letters), low-frequent words (mean log frequency 1.3 vs. 2.1), and low-predictable words (mean logit predictability -2.0 vs. -1.6). In contrast, the regressive pattern occurs after long saccades (mean saccade length 9.1 vs. 7.3 letters) and is characterized by very short first fixations (mean duration 152 ms vs. 206 ms). Obviously, the forward pattern tends to occur on difficult words. In contrast, the regressive pattern seems to reflect primarily situations of saccadic overshoot, which triggers an immediate adjustment of the fixation position within the word, possibly irrespective of the lexical status of the fixated word (O'Regan, 1990, 1992).

We again used rmMRA to analyze the gaze durations from two-fixation patterns. We needed at least 24 observations per person to obtain stable parameter estimates for the model without interaction terms (see Table 3). This criterion left us with 8,846 right-directed patterns from 148 readers and with 3,297 left-directed patterns from 81 readers. In Table 5, we assembled the coefficients for frequency and predictability of current, left, and right words from this analysis; for ease of comparison, the table also includes the corresponding effects for single-fixation durations (taken from Table 3). First, note that irrespective of the direction of the intraword saccade, frequency of word *n* is a much stronger predictor of two-fixation gaze duration than of single-fixation duration; the effects of predictability of word *n* are similar in the three analyses. Overall, this is in line with results reported above. There is only one qualification:

In an additional rmMRA of individual fixations the frequency effect in the regressive pattern was solely due to the variance in the second fixation (*b*=-7.5, *SE*=1.7; statistics for first fixation: *b*=-1.2, *SE*=1.5). This observation supports the interpretation offered above that the first fixation in a regressive pattern is ended quickly by an oculomotor correction, independent of the word's lexical status.

Second, gaze durations associated with forward patterns are influenced by the predictability of word *n*-1; in rmMRAs of individual fixations, the effect was reliable for the first fixation (*b*=-3.6, *SE*=1.0) and the second fixation (*b*=-2.5, *SE*=1.0). In contrast, the influence of the frequency of word *n*-1 was not reliable. Recall that single-fixation durations showed the reverse pattern (see Table 4). We propose that both results are compatible with catch-up processing. They may simply reflect differences in the time lines for lexical access and semantic coherence; last-word frequency may show its influence earlier than last-word predictability.

Third, gaze durations associated with regressive patterns are strongly predicted by the frequency of word *n*+1. Analyses of first and second fixation durations of this pattern indicated that the effect originates primarily in the second and longer fixation which is actually further away from word *n*+1 than the first fixation. This is again compatible with the assumption that the first fixation in regressive patterns reflects only the time needed for an immediate oculomotor correction. Fixation durations in regressive patterns were not reliably predicted by properties of word *n*-1.

The pattern of results associated with gaze durations suggests that they reflect occasions of attention focusing, in good agreement with the foveal-load hypothesis (see bottom panels of Figure 1). Word frequency is a much better predictor for gaze duration than for single-fixation durations. This is good news for psycholinguistic research which uses gaze durations as a primary dependent variable to assess the processing difficulty of the fixated word. There were also distinct and different lag and successor effects for right-directed and left-directed two-fixation patterns. The former appear to reflect primarily catch-up processing; the latter primarily adjustments of fixation position.

DISCUSSION

A Principled Account of Eye-Movement Control in Reading

Properties of the fixated word, (i.e., its frequency, predictability, and length) are reflected in the fixation duration. Beyond this agreed-upon fact, there are, however, three major empirical issues associated with eye movements in natural reading (Starr & Rayner, 2001). Two of them are concerned with whether fixation durations, in addition to the difficulty of the fixated word, also reflect the difficulty of previous and upcoming words. The third issue concerns the relative importance of lexical, perceptual, and oculomotor processes. We argue that the empirical evidence presented here forces one to acknowledge that distributed processing is the default rather than an exception during first-pass reading. We propose that the relation between word recognition and eye movements in reading is mediated by five principles, one of them relating to a key mechanism underrated in current research, *cued memory retrieval*.

First, word recognition depends on the perceptual span which limits the influence of parafoveal visual, sublexical and lexical cues. Thus, parafoveal-on-foveal effects depend first and foremost on the length of word *n* (e.g., Inhoff et al., 2000b; Kennedy et al., 2002; Schroyens et al., 1999; Vitu et al., 2004). With short foveal words even lexical properties of the next parafoveal word–in our data, its frequency–can be shown to affect fixation duration (see also Kennedy & Pynte, 2005).

Second, word recognition continues to influence fixation durations after the eyes have moved on, setting up a cognitive lag. On the basis of the strong and pervasive lag effects in our data, we propose that this is the default for reading rather than an exception restricted to spillover of processing of very difficult words or the resolution of long-distance syntactic dependencies. This principle is compatible with timelines of word recognition established with event-related potentials (see discussion below).

Third, memory retrieval of a parafoveal word, driven by prior sentence context, can cause an extended fixation duration on the foveal word. The strongest evidence for this principle is related to the paradoxical effect of parafoveal word predictability on fixation durations. If prior sentence context retrieves an upcoming word *n*+1 (i.e., if its recognition is anticipated), the eyes stay on word *n* longer or move with a delay, as if they were already processing this word during the fixation on word *n*.

Fourth, fixation durations also reflect the need to synchronize the *where* and *when* of saccade generation, at least occasionally. The effect of inverted optimal viewing position (i.e., shorter fixation durations at the edges of words) is probably due to quick restarts of saccade programs after mislocated fixations (Nuthmann et al., 2005). In addition, first fixations in intraword regressive two-fixation cases appear to subserve such corrective functions.

Fifth, cognitive load dynamically modulates the extent of the perceptual span, implying a distinction between the actual and the potential perceptual span (e.g., Henderson & Ferreira, 1990; Rayner & Pollatsek, 1987). The frequency effect of word *n* on the associated fixation duration *n* is much stronger after a low-frequency than after a high-frequency word *n-1*. (However, the critical companion effect of a parafoveal influence of the frequency of word *n*+1 on the fixation duration *n* given a high-frequency foveal word *n* was not significant.)

Certainly some of these principles are not new (see, e.g., Engbert et al., 2002; Inhoff et al., 2000a; Kennedy et al., 2002; Kolers, 1976; Rayner, 1978). Indeed, they combine into a model that could be tabulated under the heading of "mixed models" by Rayner (1978, Table 2), who noted that most researchers acknowledge the possibility of joint influences of cognitive, perceptual, and oculomotor influences. Rayner left the “mixed model” line in his table without an entry because nobody had attempted an integrated assessment of these effects.

Implications for Dynamics of Processing during Reading

Synopsis

We claim some originality (1) for establishing pervasive lag-of-processing effects in single-fixation durations, (2) for documenting influences of the upcoming, not yet fixated word in natural reading, and (3) for uncovering different processes in regressive and forward refixation cases. We replicated controversial parafoveal-on-foveal effects from experimental research and provide empirical support for several theoretically predicted interactions, all within the confines of a single data base. Therefore, these results reconcile earlier differences between results based on reading of experimentally manipulated target words and results based on natural reading. In the following, we review immediacy, lag, and successor effects, highlighting the implications of distributed processing in reading fixations for an understanding of the dynamics of related cognitive processes. Note that the effects were obtained under simultaneous statistical control of all other effects in repeated-measures multiple regression analyses (rmMRA). We consider this remarkable given the high correlations among some of the predictors (e.g., between word length and frequency).

Immediacy effects

Frequency, predictability, and word length. We replicated well established frequency and predictability effects on single fixations of the fixated word. The effect of word length, a somewhat tenuous result in previous research (e.g., Rayner et al., 1996, vs. Hyönä & Olson, 1995), is reliable in the present study but much larger for low-frequency words as indicated in the interaction of frequency and length of word *n*. Both word-length and word-frequency effects are much enhanced for measures of gaze with a stronger contribution by word length. The notion of gaze had been subject to controversy some time ago (e.g., Just & Carpenter, 1980; Kliegl, Olson, Davidson, 1982) but is an established measure in psycholinguistic research. The present results support its validity for assessing effects of lexical frequency. Note, however, that gaze durations exhibited a greatly attenuated influence of lag and successor effects compared to single-fixation durations; attention appears to be summoned to the fixated word (e.g., Henderson & Ferreira, 1990). Thus, if experimental manipulations increase the number of fixations on target words, they possibly do so at the cost of interrupting the natural reading process which appears to be distributed by default.

Fixation position within word. The position of the fixation in the word also exerted an independent strong effect on its duration, replicating the *inverted optimal viewing position effect (IOVP)* with longer fixations in the center of the word than at its edges (Vitu et al., 2001). The IOVP effect can be construed as a simple consequence of the two assumptions that mislocated fixations are likely to be found at the edges of words and that these fixations quickly trigger saccade programs to correct the position error (Nuthmann et al., 2005). Here we show that the IOVP effect is obtained even with simultaneous statistical control for a large number of other well-known influences on fixation durations.

Lag effects

We have presented pervasive evidence that fixation durations on word *n* depend very much on the amount of preprocessing this word has been subjected to. Thus, there is undeniable evidence for lagged distributed processing. The amount of preprocessing, that is the strength of the lag effect, depends on how close fixation *n*-1 was to fixation *n* and it depends on the frequency, predictability, and length of word *n*-1.

Perceptual span and parafoveal preview. Saccade programs in first-pass reading specify targets to the right of the current fixation (McConkie & Rayner, 1975; Rayner, 1975). This requires some extraction of information from the parafovea. Indeed, normally distributed within-word fixation locations, irrespective of word length, are clear evidence for such parafoveal preprocessing (McConkie, Kerr, Reddix, & Zola, 1988; Nuthmann et al., 2005). Another uncontroversial effect is the parafoveal preview benefit (e.g., Balota et al. 1985; Rayner & Bertera, 1979). Here the assumption is that a short distance between the current fixation position and the next word affords preprocessing of information from the next word. This implies that long saccades lead the eye into a region that was less preprocessed, compared to short saccades. Indeed the amplitude of the incoming saccade was the strongest predictor of single fixation durations in our regression equations: As predicted, the longer the incoming saccade, the longer the fixation duration on word *n*.

Word properties. Our results also revealed strong influences of frequency, predictability, and length of word *n*-1 on fixation duration on word *n.* In the main effects analyses (Table 3), the regression coefficient for the frequency of word *n*-1 was similar in size to the one for the frequency of word *n*. The unique amount of variance associated with the linear lag-frequency effect was actually larger than the one for linear current-word frequency. The opposite was observed with respect to predictability: The linear current-word predictability coefficient and its associated unique amount of variance were larger than the respective values for linear lag-word predictability. The direction of these effects was observed qualitatively (i.e., same signs of regression coefficients) for all nine samples of readers. These lag effects are compatible with explanations in terms of spillover (i.e., incomplete processing) and in terms of dynamic modulation of the perceptual span by foveal load (i.e., foveal load on word *n*-1 contracts the perceptual span and thereby reduces preview benefit for word *n*).

Evidence from gaze durations. In the analysis of gaze durations, lag effects were greatly attenuated compared to the analysis of single fixations. Analyses of two-fixation patterns revealed evidence for a very distinct lag effect related to the low predictability of word *n*-1 in intraword forward but not in intraword regressive patterns; the effect was reliable for both fixations of this pattern. The undifferentiated use of gaze duration would have missed this effect. This lag-predictability effect is noteworthy, because single-fixation durations were more strongly affected by frequency than by predictability of word *n*-1. This effect may reflect different time scales for lexical access and for establishing semantic coherence (i.e., an earlier influence of last-word frequency than last-word predictability, see also next paragraph).

Lag effects and event-related potentials

Our findings of pervasive lag effects on fixation durations are compatible with the time course of lexical and semantic processing as revealed by event-related potentials (ERPs). ERPs measured during word-by-word reading of the Potsdam Sentence Corpus revealed that current-word frequency is effective at least 200 ms after word onset (Dambacher, Kliegl, Hofmann, Jacobs, & Engbert, 2005; see also Sereno, Brewer, & O'Donell, 2003; Sereno & Rayner, 2003; Sereno, Rayner, & Posner, 1998). Given an average fixation duration of 200 ms, it is indeed plausible to expect frequency effects during the fixation on the next word, that is after the eye has already moved on.

The predictability of the previous word in two-fixation forward patterns is also in good agreement with ERP effects on semantic incoherence, occurring around 400 ms after word onset (e.g., the N400 component, Kutas & Hillyard, 1980). Obviously, given an average fixation duration of 200 ms, semantic incoherence often occurs during the subsequent fixation. In Dambacher et al.’s (2005) study, predictability related very consistently to the N400. These results provide independent neurophysiological evidence for the plausibility of the lagged frequency and predictability effects. Thus, distributed processing in reading fixations can be related to the high temporal-resolution patterns delivered by ERPs.

Successor effects

Evidence for distributed processing was not only observed for past processing. There were also reliable, albeit weaker, effects associated with the properties of the upcoming word.

Lexical effects in parafoveal preview. There is a controversy about the type of processing during parafoveal preview. Rayner et al. (2003) argued that there is no solid evidence for preprocessing at the lexical level. We argue that, given a fixation on a short word *n,* there should be enough room for processing word *n*+1 within the perceptual span. Indeed, the effect of frequency of word *n*+1 was reliable only if the fixation was on a short word, in agreement with other recent research (e.g., Kennedy & Pynte, 2005). In principle, such effects could be due to eye-tracker error or due to oculomotor error. Our binocular measurements rule out the first, but not the second explanation. Of course, accepting lexical processing of parafoveal words from a mislocated fixation is tantamount to accepting parafoveal lexical processing.

Foveal load. Assuming a broader perceptual span during a fixation on high-frequency word, we predicted a parafoveal frequency effect in this condition. This prediction was not supported. Thus, a strong test of the foveal-load hypothesis failed. However, the companion interaction between the frequency of the previous word and the frequency of the fixated word revealed a stronger current-word frequency effect for words following low-frequency than high-frequency words. This result is compatible with focusing of attention in response to foveal load, as postulated by Henderson and Ferreira (1990). The attenuation of lag and successor effects in gaze duration relative to single-fixation duration is also compatible with this hypothesis. Clearly, more research is needed to determine the conditions in which foveal load modulates the extent of the perceptual span natural reading (see also White et al., 2005).

The Predictability Effect of Word *n*+1: Cued Memory Retrieval?

The observation that high-predictable words *n*+1 are preceded by longer fixation durations in the nine samples of readers reported in this article runs counter to default expectations about the relation of fixation duration and its predictors: Typically, an increase in word difficulty increases fixation duration. Our explanation of this paradoxical result implies a stronger role for memory retrieval during reading than explicitly recognized in most research. Recall that the predictability norm of word *n*+1 was actually generated in an incremental cloze task, that is *in the absence* of word *n*+1; participants in the norming study tried to retrieve word *n*+1 given the prior words of the sentence as retrieval cues. We propose that such predictions are also generated implicitly during natural reading. In addition, a high-predictability context allows readers not only to retrieve word *n*+1 from memory, it also allows them to stay at word *n* for its processing. It is in a low-predictability context that readers move their eyes to word *n*+1 comparatively quickly.

There is an additional constellation of results in our eye-movement corpus that supports the above interpretation of the parafoveal predictability effect as linked to memory rather than to perception. As was shown in Table 1, two of the nine samples of readers forming the present data base were young adults (20 to 30 years; samples 1 and 2) and two were older adults (65 to 80 years; samples 8 and 9) who read a bit slower than young adults; an additional sample of young adults (i.e., sample 5) read the material with monitor-contrast reduced to a level so that overall reading speed was similar to that of the old adults (Kliegl, Nuthmann, Laubrock, & Engbert, 2005). The main results of between-group comparisons related to the role of frequency and predictability. With respect to frequency, low reading speed, either due to age or due to contrast reduction, increased the effect of current-word frequency and reduced the effect of next-word frequency, as expected from reduction of the visual quality of parafoveal input and a focus on processing of foveal material. Note that larger frequency effects for old adults (e.g., Balota & Ferraro, 1993; Balota et al., 2004) and larger effects of frequency due to visual degradation (e.g., Norris, 1984; Plourde & Besner, 1997) have also been reported in single-word recognition experiments. Possibly, slower processing of visual input (i.e., by age or reduced contrast) gives word frequency a better chance to express itself. With respect to predictability, in contrast, there was a remarkable stability of the influence of predictabilities of word *n*-1 and of word *n*+1 across the three groups, that is, effects of predictability were not linked to the visual quality of the input. The invariance of the successor-effect of predictability of word *n* corroborates our interpretation that this variable indicates the effect of memory retrieval rather than visual parafoveal preprocessing of word *n*+1.

The memory-retrieval proposition has important implications for how we should go about disentangling controversial results surrounding the effects of visual, sublexical, and lexical properties of parafoveal words in natural reading. Ratcliff and McKoon's (1988) compound-cue account of priming in memory or Bodner and Masson's (2001, Bodner, Masson, & Richard, in press) memory-recruitment account may serve as guides for further theoretical specification. For natural reading, the prediction is that the joint effect of prior-sentence context and parafoveal information serves as a retrieval cue for the parafoveal word: The higher the net predictability of the parafoveal word, the more likely the eyes will stay at the foveal word. The relevance of anticipations in discourse has recently been demonstrated by Van Berkum, Brown, Zwitserlood, Kooijman, and Hagoort (2005) with ERPs and reading times. We propose to go even a step further. Perhaps the time has come to recognize the "motor chauvinist's point of view [that] the entire purpose of the human brain is to produce movement" (e.g., Wolpert, Ghahramani, & Flanagan, 2001, p. 487). Even reading may very much depend on the mind generating predictions about the sensory consequences of eye movements.

Implications for Computational Models

There are three fully implemented computational models of saccade generation in reading which simulate a set of benchmark data such as the dependencies of single and gaze durations or skipping and refixation probabilities as a function of word frequency and word length (E-Z Reader: Pollatsek et al., in press; Reichle et al., 2003, 1998; SWIFT: Engbert et al., 2005, 2002; SERIF: McDonald et al., 2005). These models also account for landing positions within words as a function of word length and amplitude of the incoming saccade. The pattern of lag and successor effects reported here as well as the interactions, which were explicitly derived from principles of distributed processing, provide a new set of benchmark data for all of them.

The loose coupling of lexical processing, visual acuity, and oculomotor constraints advanced in this article is in agreement with core assumptions of our SWIFT model as embodied in its acronym (i.e., autonomous *S*accade generation *W*ith *I*nhibition by *F*oveal *T*argets; Engbert et al., 2002, 2005). For example, we assume that words within the perceptual span are processed in parallel at rates decreasing with distance from the fixation location. Indeed, the model reproduces the opposite main effects of next-word frequency and next-word predictability from spatial selection in the perceptual span. Moreover, the lexical difficulty of the foveal word postpones the start of an autonomously triggered saccade program by an inhibition signal and generates a word-frequency effect for the fixated word. A delay line of this inhibition signal is needed to induce the word-frequency lag-effect. Finally, we also integrated the account of the IOVP effect in terms of mislocated fixations and accelerated restart of saccade programs. There are also limitations. For example, SWIFT underestimates the effects of word frequency relative to those of word length; it also does not dynamically adjust processing rate according to foveal load. Therefore, it cannot reproduce the attenuation of lag and successor effect in multiple-fixation cases nor the interaction between frequencies of words *n* and *n*-1. An implementation of such a dynamical modulation of the perceptual span could be pursued in future simulations.

The demonstration of parafoveal-on-foveal effects is also critical for the E-Z Reader Model (Pollatsek et al., in press; Reichle, et al., 1998, 2003) and other sequential attention shift models (e.g., Engbert & Kliegl, 2001). These models account for spillover effects and the interaction of frequencies of previous and current word as indirect costs of reduced parafoveal preview. However, in these models, attention is sequentially allocated to words in the order of their appearance in the text. These serial attention shifts to the next word are conditional on complete lexical access of the current word. Consequently, the current fixation duration cannot be influenced directly by parafoveal lexical word properties. The new version of the E-Z Reader model explains parafoveal on-foveal effects by allowing for mislocated fixations due to saccadic undershoot. In this case, word *n*+1 influences a fixation duration on word *n.* The model cannot account, however, for the predictability effect of word *n*+1 that goes in the *opposite* direction from the predictability effect of word *n*, as reported here.

For other phenomena, the nonlinear dynamical characteristics of these models often prevent deductions of predictions without simulations. In the end, computational models will be measured by their success in recovering reliable behavioral regularities. At present, they serve as a testbed for testing the limits of core theoretical assumptions such as the assumption of sequential attention shifts or graded parallel processing within the perceptual span. The present data will contribute to the further development and refinement of these models.

Methodological Issues

Selection effects

We focused on first-pass single fixations and two-fixation cases. They comprised 76% of within-sentence fixations and appear to be quite representative of the full set (see Table 2). Thus, our lag and successor effects clearly concern the majority of reading fixations. There are three methodological concerns which we addressed in additional control analyses.

First, we recorded movements of both eyes to guard against the objection that lag and successor effects could be due to erroneous assignment of fixations to neighboring words as a consequence of limited spatial resolution, calibration errors, or drift of the eye tracker. The analysis of fixations for which both right and left eye were fixating the same word did not reveal any attenuation of lag, successor, lexical or oculomotor processing effects. Thus, it is highly unlikely that distributed processing of words during reading is an artifact of measurement error. We also established the generalizability of results across nine independent samples of readers.[6]

Second, in an additional analysis, lag and successor effects were observed also for the select set of single fixations where the last and the next fixation were on neighboring words. Thus, lag and successor effects did not depend on the skipping of prior or successive words. Coefficients are listed in the middle column of the Appendix table.

Third, one might also worry about using the same word up to three times in the same regression analysis, that is, for example, as predictor for the fixation on the word itself, as the lag-word for a single fixation on the next word, and as the successor-word for a single fixation on the previous word. (Of course, fixation durations were used only once!) We checked this concern with a resampling analysis of fixations in which we randomly selected fixations with the constraint that there are no fixations on neighboring words. We found no reliable differences to the analyses reported above; details are presented in the right column of the Appendix table.

Repeated-measures multiple regression analyses and experimental design

Preview benefit, spillover, and foveal load effects are typically associated with sophisticated experimental designs that orthogonally manipulate one or a couple of target words per sentence or that provide readers with upcoming information contingent on one eye crossing a virtual border. These effects are substantial and solidly established. Interestingly, so far they have not been reported for analyses of natural reading data. There are several reasons for this lack of evidence. Previous studies did not collect a sufficiently large data set of fixations; also they usually did not employ the correct statistical procedure for estimating the effects (e.g., Just & Carpenter, 1980; Kliegl, et al., 1982). Moreover, studies of this kind concentrated on documenting an expanding number of current-word properties which, in line with the immediacy-of-processing hypothesis, influence fixation duration; indeed, we are not aware of any study which included properties of word *n,* word *n*-1, and word *n*+1 in a regression model. The agreement of the present results for natural reading with those from experimental designs manipulating a few target words per sentence should reinforce the productive exchange between experimental and statistical control techniques (Kennedy at al., 2005; Kliegl, Olson, & Davidson, 1983, Kliegl et al., 2004).

The unique contribution of eye-movement analyses of natural reading is the possibility to examine simultaneously a large number of variables (and their potential redundancy) as well as interactions among them (given sufficient statistical power). Indeed, it is hardly conceivable that twelve variables could be manipulated simultaneously within a single experimental design. There is also a serious drawback to the multiple-regression approach. Since we are always assessing effects conservatively in the presence of correlated alternative predictors, we are in a much weaker position to argue the null hypotheses in this case than in experimental-design research, especially with respect to interactions (McClelland & Judd, 1993).

Limitations

Reading is visual word recognition in context. There are more than 50 word properties that could account for variance in fixation durations; examples are lexical neighborhood frequency, initial bigram and trigram frequency, orthographic-phonological consistency.[7] Recently, Juhasz and Rayner (2003) reported effects of frequency, length, subjective familiarity, concreteness, and age of word acquisition using rmMRA. Similarly, there are a number of variables at the sentence level (subject-initial or object-initial constructions, main or subordinate clause, passive or active, the gradual build-up of a semantic representation, etc.) that relate to eye-movement control. Most of these variables are or will be coded for the Potsdam Sentence Corpus and their impact on fixation durations can be checked. In principle, the agenda is similar to the large-scale analyses of visual word recognition of single-syllable words (Balota et al., 2004). Here we confined our analyses to the “big three” influences on fixations: frequency, predictability, and length of words. Inclusion of additional variables for current, previous, and future words requires that we collect additional eye movements to secure stable and replicable estimates for regression coefficients.

Finally, there are several other well-defined domains of eye-movement research in reading that can be addressed with the eye-movement corpus. Specifically, we offer no explanations for fixation probabilities and locations (but see Engbert et al., 2005; Kliegl & Engbert, 2005; Kliegl et al., 2004; Nuthmann et al., 2005). So far, we also did not analyze second-pass readings (including regressions back to previous words) which will be needed, for example, to link eye-movement control to theories of sentence parsing (e.g., Lewis & Vasishth, in press).

Conclusion and Outlook

We presented evidence for the distributed nature of lexical, visual, and oculomotor processing in eye fixations during reading. For single fixations, lexical processing of the previous word is reflected almost as strongly as that of the present word in the current fixation duration. Moreover, there is solid evidence for effects of parafoveal preprocessing on the duration of the current fixation and for the dependence of its duration on the fixation position within words. Our results are compatible with a loose set of principles, nevertheless constrained enough to be subjected to experimental tests. We propose (1) that the perceptual span defines the region of access largely independent of word boundaries, (2) that lexical access may cognitively lag behind the eyes–as a default setting rather than as an exception, (3) that memory retrieval cued by prior sentence context may delay saccades, (4) that perceptual and lexical processing and oculomotor control synchronize only occasionally to prevent loss of comprehension or to correct oculomotor error, and (5) that foveal load dynamically attenuates processing within the perceptual span. Taken together, these principles imply that during reading the mind is ahead of the eyes "scouting" the next saccade target, doing some parafoveal preprocessing, and generating predictions about the upcoming word using the available sentence context as retrieval cue; at the same time, the mind is with and behind the eyes finishing up word recognition, syntactic analyses, and establishing semantic coherence. Therefore, in reference to the eye-voice span of oral reading, we propose an *eye-mind span* for silent reading, because–within (sentence) limits–the mind can be simultaneously ahead of the eyes, at the fixation location, and lagging behind cognitively. And, finally, introspection tells us that occasionally the mind lets the eyes move on their own, while it wanders off, thinking about other things...

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Appendix

Regression Coefficients Estimated for Triplet-Constrained Single Fixations

The "first-pass" constraint eliminates all fixations that arise from a regression back to a word. However, single fixations in first-pass readings may be preceded or followed by word-skipping saccades. Thus, an important control question is whether lag- and successor-word effects on fixation durations on foveal words are due to the cases when the respective words are skipped. Therefore, we analyzed a true subset of these first-pass single fixations, that is, single-fixation triplets. A single-fixation triplet was defined by a single fixation on word n preceded by a saccade from word n-1 to word n and followed by a saccade from word n to n+1. In other words, we replicated the analyses of single fixations for first-pass reading patterns where three successive fixations occurred on three successive words. If distributed processing can be established for these patterns, the influences are obviously not due to lack of fixation on the respective neighbors.

Frequency and predictability effects were obtained for triplet-constrained single fixations (see middle columns of Table A1). The frequency effect was stronger for unconstrained single fixations (-12 vs. -4, *SE*=0.4, for the difference between regression coefficients, $p<.01$); length and predictability effects were of similar magnitude. There was one difference in the direction of effect between unconstrained and triplet-constrained single fixations: Length of word n-1 affected fixation duration in the expected direction when this word had been fixated (coefficient: -29, $p<.01$) but in the opposite direction for all single fixations (coefficient: 15; $p<.01$). The reason for this reversal lies in skipped words prior to the fixation. The length of skipped words n-1 was unrelated but the length of fixated words n-1 was strongly related to fixation duration (-.02 vs. -.19). Therefore, like the length of the fixated word, the length of skipped words contributed positively as a suppressor, boosting especially the unique variance accounted for by last saccade amplitude. Finally, oculomotor immediacy effects were very similar for the subset of triplet-constrained single fixations; the effects of predictability and the IOVP effect were even reliably stronger for this subset of fixations (p <.01, for the difference between regression coefficients between the two samples of fixations).

Regression Coefficients Estimated via Random Resampling of Fixations from Non-Overlapping Word Triplets

One concern about the rmMRA used in this article may be that words (not fixations!) could contribute one to three times to the estimates of a reader, that is, (a) as the fixated word, (b) as the lag-word, and (c) as the successor word. Selection effects may generate unwanted contingencies. As a control of this potential confound, we estimated the 18 coefficients of the model listed in Table 4 with the following constraints: From the fixations of each sentence, we randomly selected a subset of fixations such that fixations on words before or following the word with the sampled target fixation were not included in the data base. Thus, for a randomly sampled fixation on word *n*, the two neighboring words could not serve as the carrier of a target fixation in the same run. Table B1 lists unstandardized regression coefficients and associated standard errors based on 200 resampled runs for binocularly defined right-eye first-pass single fixations in the left columns. The standard error is the standard deviation of the resampled coefficient means; see Efron & Tibshirani, 1993). We also include the corresponding estimates from Table 4 for ease of comparison. The agreement is remarkable. One exception was the interaction between word length of word *n* and predictability of word *n*+1 which was not reliable in the resampling estimate. The estimated coefficient, however, was quite similar in magnitude.

Table A1. Regression coefficients with associated standard errors for two control analyses; values from estimates for all single fixations from Table 4 are included for comparison.

	single fix (right eye)		triplet-constrained (right eye)		resampled (200 runs)	
Coefficient	*M*	*SE*	*M*	*SE*	*M*	*SE*
constant	**211**	2	**203**	2	**211**	1
Present word						
frequency	**-12.1**	0.9	**-4.8**	0.5	**-12.1**	2.3
predictability	**-5.0**	0.4	**-6.5**	0.7	**-4.6**	0.5
1/length	**-60**	16	**44**	11	**-77**	25
Past word						
frequency	**-7.2**	0.4	**-4.0**	0.5	**-6.7**	0.9
predictability	**-2.1**	0.3	**-2.2**	0.5	**-2.0**	0.8
1/length	**23**	4	**-29**	8	**23**	11
Future word						
frequency	**-5.3**	0.6	**-2.1**	0.4	**-5.7**	1.3
predictability	**4.1**	0.8	**1.8**	0.4	**4.0**	1.6
l/length	-2	3	**18**	6	-1	3
Viewing position						
last sacc. ampl.	**4.7**	0.2	**4.7**	0.2	**4.8**	0.1
l-trend in word	**-7.2**	1.6	**-5.2**	2.4	**-6.9**	2.8
q-trend in word	**-40**	4.3	**-48**	6	**-41**	8.9
next sacc. ampl	**0.9**	0.3	**1.6**	0.3	**0.8**	0.1

Table A1 (continued)

	single fix		triplet-constrained		resampled (200 runs)	
Coefficient	*M*	*SE*	*M*	*SE*	*M*	*SE*
Interactions						
(freq *n)*/(lgth *n)*	**25**	3	**-**	-	**28**	8
(freq *n)**(freq *n*-1)	**1.0**	0.2	**-**	-	**1.1**	0.4
(freq *n)**(freq *n*+1)	-0.2	0.2	-	-	-0.4	0.4
(freq *n*+1)/(lgth *n)*	**14**	3	**-**	-	**19**	9
(pred *n*+1)/(lgth *n*)	**-8**	4	**-**	-	-6	10
mean/median R	0.45/0.45		0.47, 0.45		0.51/0.49	
mean/median words	442/441		217/202		203/210	

Note. All data are based on right eye. Left column: Coefficients for reference single fixations; these values are identical to those in Table 4. Middle column: Regression coefficients with associated standard errors for triplet-constrained single fixations. Right column: Regression coefficients with associated standard errors from 200 rmMRAs based on resampling non-overlapping word-triplets for the estimate of a specific target fixation. Resampled coefficient means (*M*) and standard errors (*SEs;* i.e., standard deviations of resampled means) are based on 200 runs for 222 readers; l-trend, q-trend: linear and quadratic trend for relative fixation position (rfp) within words; significant coefficients are printed in bold (*p*<.01).

Author Note

Data and programs generating the results of this article can be retrieved from the project web page. We plan to add to this data base as the research unfolds. The lag effects were presented first at the 12th European Conference on Eye Movements, Dundee, Scotland, August 2003. We thank Petra Grüttner for research assistance and Michael Dambacher, Robin Hoernig, Asher Koriat, Klaus Oberauer, Ralph Radach, Eike Richter, and Françoise Vitu for helpful comments. This research was supported by grants KL 955/3 and KL 955/6 from Deutsche Forschungsgemeinschaft. Address for correspondence: Reinhold Kliegl, Department of Psychology, University of Potsdam, PO Box 60 15 53,14451 Potsdam, Germany, email: Kliegl@rz.uni-potsdam.de

Footnotes

1. The results did not depend on this particular choice of transformations of predictors. Rather they represent what we perceive as a coherent conceptual perspective for research on eye movements in reading that tries to integrate current knowledge about oculomotor and cognitive processing in a single analysis (see also General Discussion). The rmMRA procedure is completely analogous to a repeated-measures ANOVA. Thus, a significant regression coefficient of any of the predictors corresponds to a significant main effect in the ANOVA; a significant regression coefficient for a term derived from the multiplication of predictors corresponds to a significant ANOVA interaction between these effects. The difference between rmANOVA and rmMRA is that the rmMRA handles continuous independent variables and that a much larger number of observations is needed to overcome statistical power problems due to non-uniformly distributed variables and due to the correlations between the predictors. These problems especially concern statistical tests of interactions (McClelland & Judd, 1993).

2. We give correlations for the inverse of word length (i.e., 1/wl), log frequency, and logit predictability because this was the coding used for the regression analyses. Consequently, in this metric, length, frequency, and predictability correlate positively with each other and (usually) negatively with fixation duration. For visualization of word-length effects we reverted to the conventional metric number of letters for ease of comprehension and compatibility with saccade amplitudes.

3. There are two arguments in anticipation of the criticism that we do not account for much variance of single fixations. First, there is much variance associated with aggregated measures; the fits in Figure 2 increase this statistic to about 80%. Second, we appeal to the authority of Duncan (1975, pp. 65) who wrote: "Indeed the 'problem' of partitioning R^2 bears no essential relationship to estimating or testing a model, and it really does not add anything to our

understanding of how a model works. The simplest recommendation–one which saves both work and worry–is to eschew altogether the task of dividing up R^2 into unique causal components. In a strict sense, it just cannot be done, even though many sociologists, psychologists, and other quixotic persons cannot be persuaded to forego the attempt." He recommends to focus the interpretation on unstandardized regression coefficients.

4. The 2x2 plots of Figures 4 and 6 each visualize only one of potentially many sources of variance related to the significant multiplicative interaction terms. The patterns illustrate whether the data are consistent with theoretical expectations at the highest level of aggregation.

5. Our focus is on the impact of distributed processing of frequency, predictability, and length of fixated and neighboring words on durations in two-fixation cases, not with causes of fixation positions within words (e.g., Radach & McConkie, 1998; Vitu, in press, for reviews).

6. The effects were also obtained in a recently completed experiment in which we had participants read with a bite bar. We are currently collecting eye movements during reading of the English sentences of the Schilling, Rayner and Chumbley (1998) corpus. In the data we have collected to date, lag and successor effects are significant in a sample of students with German as first language.

7. Research on word recognition is fundamentally a quasi-experimental field because it is hardly possible to come up with experimental manipulations of word material that are not confounded with one or the other of these word properties (see Graf, Nagler, & Jacobs, 2004, for a factor analysis of 57 word properties leading to six orthogonal factors; also Balota et al., 2004).

Table 1. Information about samples of readers yielding eye movements (1–9) and predictability norms (10–12)

Sample	*N*	Age (years)			Temporal resolution (Hz)
		M	*SD*	range	
1	33	22	2.2	19 – 28	250
2	27	22	2.7	19 – 31	500
3	19	20	2.1	19 – 27	500
4	24	18	0.6	16 – 18	500
5	22	44	6.3	30 – 56	500
6(a)	29	22	2.9	18 – 30	250
7(b)	18	71	3.5	65 – 79	250
8	18	66	5.1	61 – 80	500
9	32	71	4.0	65 – 84	250
10	116	17	0.5	17 – 19	-
11	76	23	2.6	19 – 38	-
12	80	71	3.9	66 – 80	-

Notes. a: sample 6 read the sentences with 12% decrement between luminance of background and letters (i.e., 19.5 cd/m^2 and 17.1 cd/m^2; normal contrast levels were 53.2 cd/m^2 and 3.2 cd/m^2). b: participants of sample 7 had read a random 25% of the sentences six months earlier in the context of collecting predictability norms; eye tracker: 250 Hz = EyeLink I; 500 Hz = EyeLink II.

Table 2. Means (*M*) and standard deviations (*SD*) for fixation durations and word properties for all fixations as well as all first-pass single-fixation, two-fixation (2 types), and multiple (>2) fixation cases

Variable		valid	single fixation	right-dir. refixation		left-dir. refixation		gaze >=3 fixations
N of fixations		159,883	87,004	9,791*2		4,714*2		9,014
[# binoc. fix. = 238,158]		(100%)	(54%)	(12%)		(6%)		(5.6%)
Fixation number				1	2	1	2	n=2723
Fixation dur. [ms]	*M*	196	206	201	165	190	152	634
	SD	73	69	70	69	65	74	244
Rel. fix. pos.[0-1]	*M*	0.5	0.5	0.2	0.7	0.7	0.3	0.5
	SD	0.3	0.3	0.2	0.2	0.2	0.2	0.1
Amplitude [letters]								
last saccade	*M*	6.8	7.3	6.6		9.1		6.5
	SD	3.5	3.0	2.9		3.7		3.4
next saccade	*M*	7.1	7.5	4.2		10.0		7.8
	SD	3.6	2.8	1.9		3.6		3.2
Length [# of letters]								
word *n*	*M*	6.2	5.6	8.2		5.9		10.3
	SD	3.0	2.3	3.0		2.7		3.8
word *n*-1	*M*	5.1	5.3	5.0		5.5		4.3
	SD	2.6	2.6	2.7		2.8		2.4
word *n*+1	*M*	5.5	5.4	5.6		5.5		5.8
[corpus: *M*=5, *SD*=3]	*SD*	2.6	2.6	2.6		2.5		2.4
Frequency [log/mio]								
word *n*	*M*	1.9	2.1	1.3		1.9		0.9
	SD	1.3	1.2	1.1		1.3		1.0
word *n*-1	*M*	2.4	2.3	2.6		2.2		3.0
	SD	1.4	1.4	1.4		1.4		1.3
word *n*+1	*M*	2.2	2.3	2.2		2.1		1.9
[corpus: *M*=2.2, *SD*=1.3]	*SD*	1.3	1.3	1.3		1.3		1.3
Predictability [logit]								
word *n*	*M*	-1.7	-1.6	-2.0		-1.7		-2.3
	SD	1.0	1.0	0.8		1.0		0.6
word *n*-1	*M*	-1.6	-1.6	-1.5		-1.7		-1.5
	SD	1.0	1.0	1.0		1.0		0.9
word *n*+1	*M*	-1.3	-1.2	-1.2		-1.3		-1.7
[corpus: *M*=-1.5, *SD*=1.1]	*SD*	1.2	1.2	1.2		1.2		1.1

Note. Fixations in "valid" column exclude (a) first and last fixations in sentences (2*28,106), (b) fixations on first or last words of sentences (first word: 36,860, last word: 27,416), (c) fixations shorter than 30 ms (n=7,209) or longer than 1000 ms (n=27), and (d) fixations preceded or followed by a microsaccade (n=2*5275). The difference between total N and valid fixations was mostly due to "first" and "last" fixations; only 3.4% of fixations were too short, too long, or bordered by a microsaccade. Single-fixations, two-fixation, and gaze>=3-fixation cases were preceded and followed by an interword forward saccade in first-pass reading. Data are from right eye.

Table 3. Regression coefficients from rmMRAs of all first-pass, single fixation durations (fd)

Fixation type	first-pass single fd			9 samples
Coefficient	*M*	*SE*	$-\Delta R^2$	123456789
*constant	**208**	2		+++++++++
Present word				
frequency	**-4.6**	0.3	.0036	−−−−−−−−−
*predictability	**-5.0**	0.3	.0039	−−−−−−−−−
1/length	**55**	5	.0035	+++++++++
Past word				
*frequency	**-5.1**	0.3	.0050	−−−−−−−−−
predictability	**-1.6**	0.3	.0004	−−+−−−−−−
*1/length	**15**	4	.0002	++−++++−+
Future word				
frequency	**-2.5**	0.3	.0016	−−−−−−−−−
predictability	**1.9**	0.3	.0009	+++++++++
*l/length	-1.2	3	.0000	+−+−+−−−+
Viewing position				
last sacc. ampl.	**4.7**	0.2	.0256	+++++++++
l-trend rfp	**-7.7**	1.2	.0011	−−−−−−+−−
*q-trend rfp	**-37**	4	.0021	−−−−−−−−−
*next sacc. ampl	**1.5**	0.2	.0027	+++++++++
mean, median R	0.41, 0.40			
R^2(predictors)	0.06			
R^2(subjects)	0.18			
R^2(model)	0.25			

Note. Coefficient means (M) and standard errors (SE) are based on 222 readers from nine experimental or adult age-comparative groups; ΔR^2=decrement for removal of effect; l-trend, q-trend: linear and quadratic trend for relative fixation position (rfp) within words; significant coefficients are printed in bold (p<.01). Readers contributed an average of 392 words (median: 406). *Samples:* Signs of coefficients in single-fixation rmMRA for nine samples are shown in the right column (see Table 1 for sample descriptions).

Table 4. Regression coefficients with associated standard errors and unique variances from rmMRAs of binocularly defined first-pass single fixations (left and right eye) and gaze durations (right eye), including also five multiplicative interaction terms.

	single fix (left eye)			single fix (right eye)			gaze (right eye)		
Coefficient	*M*	*SE*	-ΔR^2	*M*	*SE*	-ΔR^2	*M*	*SE*	-ΔR^2
constant	**212**	2		**211**	2		**227**	3	
Present word									
frequency	**-12.1**	0.9	.0025	**-12.1**	0.9	.0025	**-33**	1.7	.0095
predictability	**-5.1**	0.4	.0038	**-5.0**	0.4	.0037	**-5.9**	0.4	.0024
1/length	**-60**	15	.0002	**-60**	16	.0003	**-450**	25	.0094
Past word									
frequency	**-7.1**	0.4	.0041	**-7.2**	0.4	.0042	**-1.6**	0.6	.0002
predictability	**-2.2**	0.3	.0006	**-2.1**	0.3	.0006	**-1.9**	0.4	.0002
1/length	**21**	4	.0005	**23**	4	.0006	**37**	5.2	.0006
Future word									
frequency	**-5.6**	0.7	.0012	**-5.3**	0.6	.0012	**-6.9**	0.8	.0009
predictability	**3.7**	0.7	.0007	**4.1**	0.8	.0009	**-3.9**	0.8	.0002
l/length	-1	3	0	-2	3	0	**-12**	4	.0001
Viewing position									
last sacc. ampl.	**4.6**	0.2	.0242	**4.7**	0.2	.0243	**4.0**	0.2	.0079
*l-trend in word	-1.5	1.7	0	**-7.2**	1.6	.0007	2.1	2.0	0
q-trend in word	**-38**	3.9	.0021	**-40**	4.3	.0020	**-140**	6.2	.0104
next sacc. ampl	**1.2**	0.3	.0019	**0.9**	0.3	.0013	.05	0.3	.0006

Table 4 (continued)

	single fix (left eye)			single fix (right eye)			gaze (right eye)		
Coefficient	*M*	*SE*	-ΔR^2	*M*	*SE*	-ΔR^2	*M*	*SE*	-ΔR^2
Interactions									
(freq *n)*/(lgth *n)*	**25**	3	.0012	**25**	3	.0012	**140**	7	.0191
(freq *n)**(freq *n*-1)	**1.0**	0.2	.0005	**1.0**	0.2	.0005	**-1.2**	0.2	.0002
(freq *n)**(freq *n*+1)	-0.3	0.2	0	-0.2	0.2	0	-0.5	0.2	0
(freq *n*+1)/(lgth *n)*	**15**	3	.0003	**14**	3	.0003	**25**	3	.0004
(pred *n*+1)/(lgth *n*)	**-8**	4	.0002	**-8**	4	.0002	**24**	4	.0004
mean/median R	0.45/0.46			0.45/0.45			0.44/0.43		
R^2(predictors)	0.06			0.06			.09		
R^2(subjects)	0.19			0.19			.12		
R^2(model)	0.26			0.26			.22		
N of fixations	67,260						98,211		
mean/median words	303/309						442/441		

Note. Coefficient means (*M*) and standard errors (*SE*) are based on 222 readers from nine experimental or adult age-comparative groups; ΔR^2=decrement for removal of effect; l-trend, q-trend: linear and quadratic trend for relative fixation position (rfp) within words; significant coefficients are printed in bold (*p*<.01). * = different between right and left eye (*p*<.01).

Table 5. Frequency and predictability effects on single fixation durations and gaze durations for two-fixation patterns

	Single fixations (N=87004)	Gaze for right-directed refixation (N=8846)	Gaze for left-directed refixation (N=3297)
Current word			
frequency	**-4.6** (0.3)	**-8.3** (1.2)	**- 8.6** (2.4)
predictability	**-5.0** (0.3)	**-5.7** (1.9)	**-3.8** (2.4)
Last word			
frequency	**-5.1** (0.3)	-1.7 (1.5)	-1.8 (2.7)
predictability	**-1.6** (0.3)	**-6.2** (1.7)	3.0 (2.9)
Next word			
frequency	**-2.5** (0.3)	**-2.9** (1.3)	**-7.3** (2.5)
predictability	**+1.9** (0.3)	1.2 (1.2)	-0.8 (2.0)

Note. Table entries are unstandardized regression coefficients extracted from rmMRA without interaction terms (i.e., analogous to the one reported in Table 3; coefficient for single fixations are reproduced from Table 3); significant coefficients printed in bold, standard errors in parentheses.

Figure Legends

Figure 1. Processing rate over foveal eccentricity; peak indicates fixation location. Two hypotheses about parafoveal-on-foveal effects. Perceptual span (top panels): Frequency of word *n*+1 affects only fixation durations on short words *n,* because in this case word *n*+1 falls (largely) inside the perceptual span. Foveal load hypothesis (bottom panels): Frequency of word *n*+1 affects only fixation durations on high-frequency words *n*, because there is a restriction of the perceptual span for low-frequency words *n*.

Figure 2. Example sentence with traces for right and left (dashed) eye superimposed. The down-and-right movement signaled the end of reading; numbering indicates fixation sequence, fixations durations are listed in parentheses.

Figure 3. Twelve main effects for *single fixation durations* on word *n* (open symbols). Predictors are frequency, predictability, and length of words *n*-1, *n*, and *n*+1 (first three rows), the amplitude of the incoming saccade, the relative fixation position (rfp) in the word (linear + quadratic trend), and the amplitude of the outgoing saccade (last row). For each predictor, fixations were binned into categories with a minimum of 2000 fixations. Error bars are within-subject 99% confidence intervals. Data are from right eye.

Figure 4. Modulation of single-fixation duration on word *n* due to four interactions: (a) length of word *n* x frequency of word *n,* (b) length of word *n* x frequency of word *n*+1, (c) length of word *n* x predictability of word *n*+1, and (d) frequency of word *n*-1 and frequency of word *n*. Dependent variable is always single fixation duration on word *n*. Short words are 6 or fewer letters long; CELEX frequency were split on medians; low predictability words were predicted by at most 2 of 83 persons (2.5 %). Error bars are within-subject 99% confidence intervals. Data are from right eye.

Figure 5. Twelve main effects for *gaze durations* on word *n* (open symbols). Predictors are frequency, predictability, and length of words *n*-1, *n*, and *n*+1 (first three rows), the amplitude of the incoming saccade to the first fixation, the mean of relative fixation positions (rfp) in the word (linear + quadratic trend), and the amplitude of the outgoing saccade from the last fixation (last row). For each predictor, fixations were binned into categories with a minimum of 2000 fixations. Error bars are within-subject 99% confidence intervals. Data are from right eye.

Figure 6. Modulation of gaze duration on word *n* due to four interactions: (a) length of word *n* x frequency of word *n,* (b) length of word *n* x frequency of word *n*+1, (c) length of word *n* x predictability of word *n*+1, and (d) frequency of word *n*-1 and frequency of word *n*. Short words are 6 or fewer letters long; CELEX frequency were split on medians; low predictability words were predicted by at most 2 of 83 persons (2.5 %). Data are from right eye. Error bars are within-subject 99% confidence intervals. Data are from right eye.

Figure 1

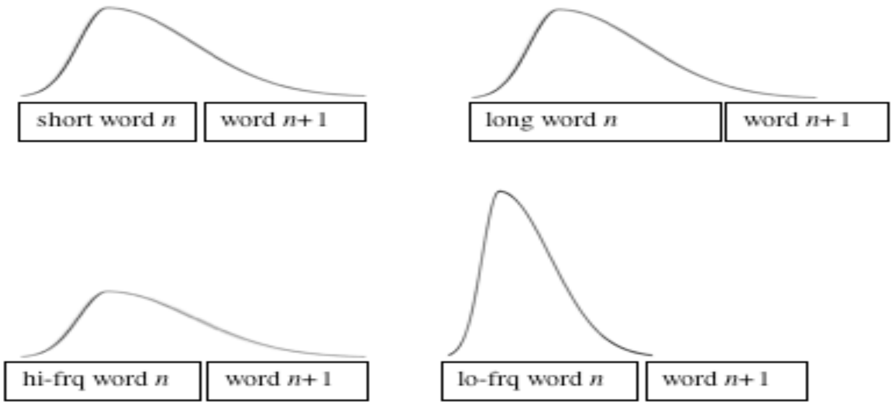

short word *n*
word *n*+1
long word *n*
word *n*+1
hi-frq word *n*
word *n*+1
lo-frq word *n*
word *n*+1

Figure 2

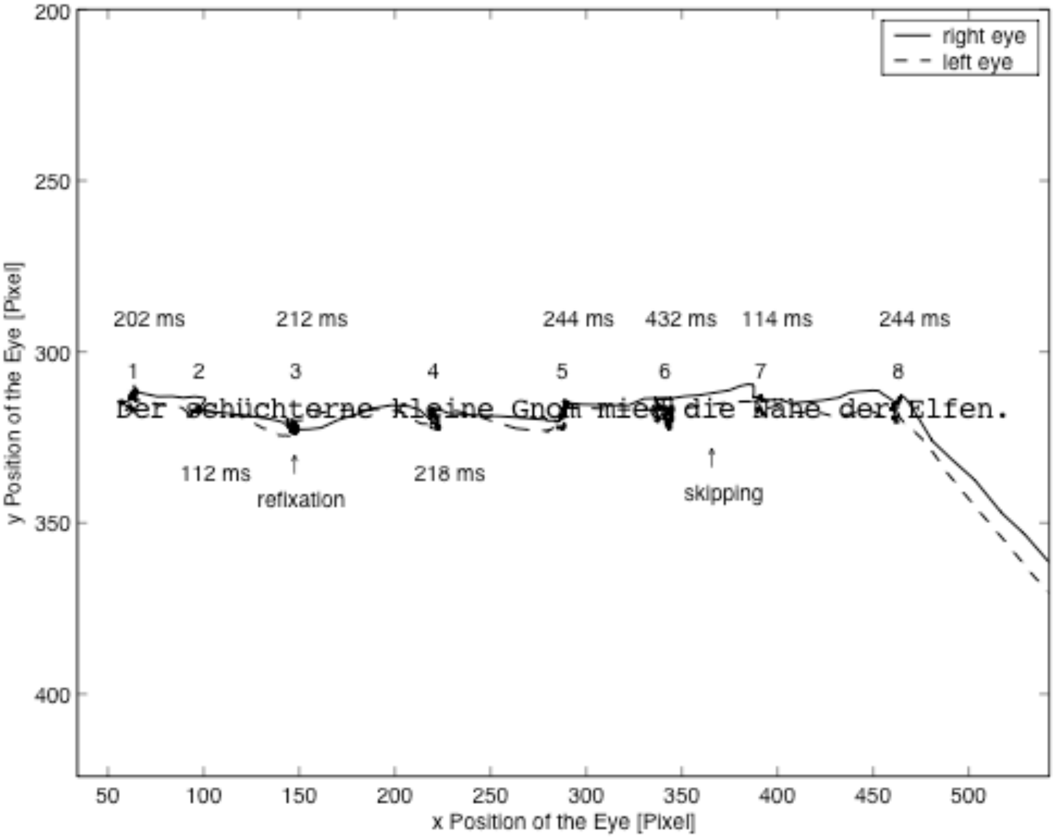

right eye
left eye
202 ms
212 ms
244 ms
432 ms
114 ms
244 ms
1
2
3
4
5
6
7
8
Der schüchterne kleine Gnom mied die Nähe der Elfen.
112 ms
218 ms
refixation
skipping
y Position of the Eye [Pixel]
x Position of the Eye [Pixel]
200
250
300
350
400
50
100
150
200
250
300
350
400
450
500

Figure 3

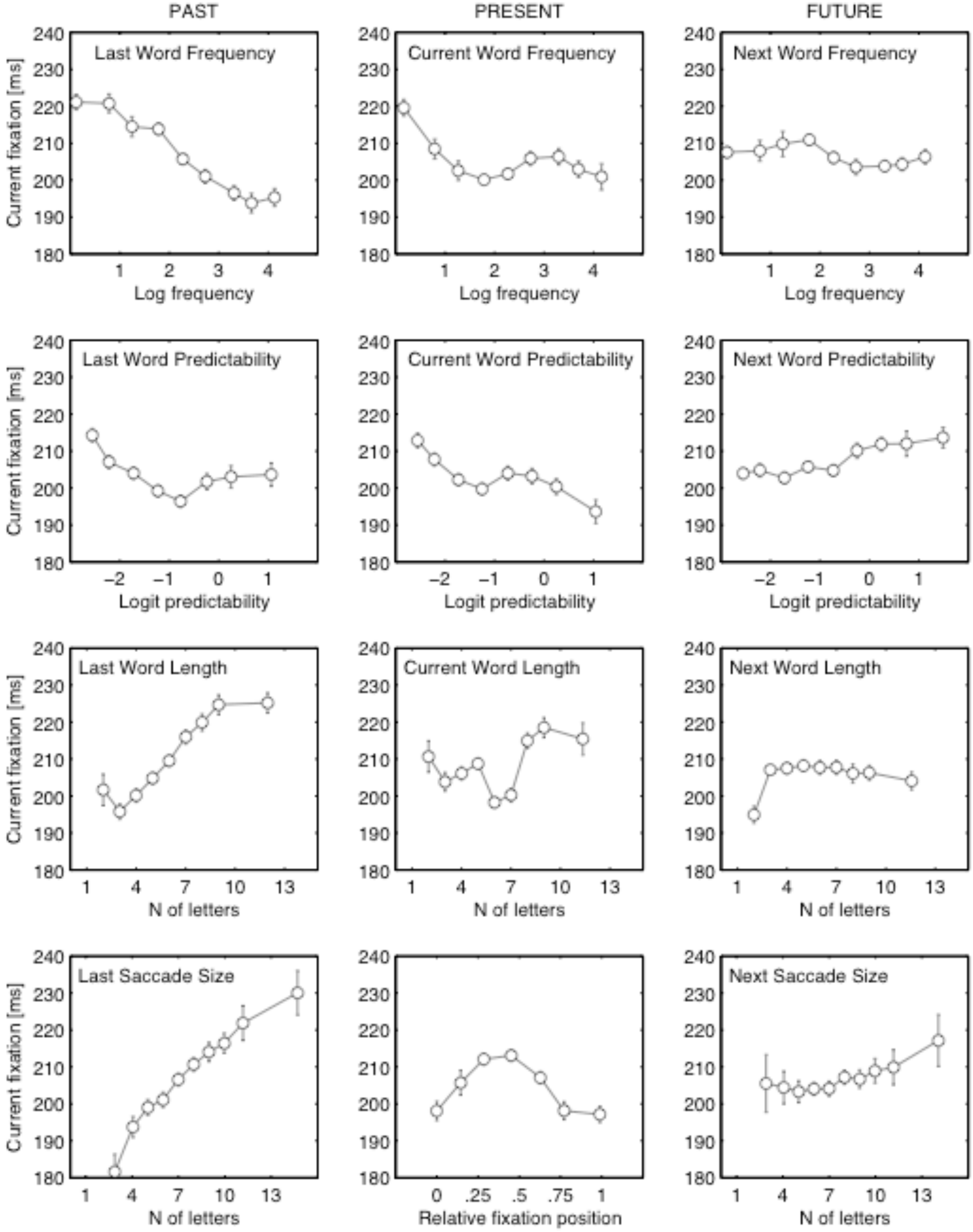

PAST
PRESENT
FUTURE
Last Word Frequency
Current Word Frequency
Next Word Frequency
Last Word Predictability
Current Word Predictability
Next Word Predictability
Last Word Length
Current Word Length
Next Word Length
Last Saccade Size
Next Saccade Size
Current fixation [ms]
180
190
200
210
220
230
240
Log frequency
1
2
3
4
Logit predictability
−2
−1
0
1
N of letters
1
4
7
10
13
Relative fixation position
0
.25
.5
.75
1

Figure 4

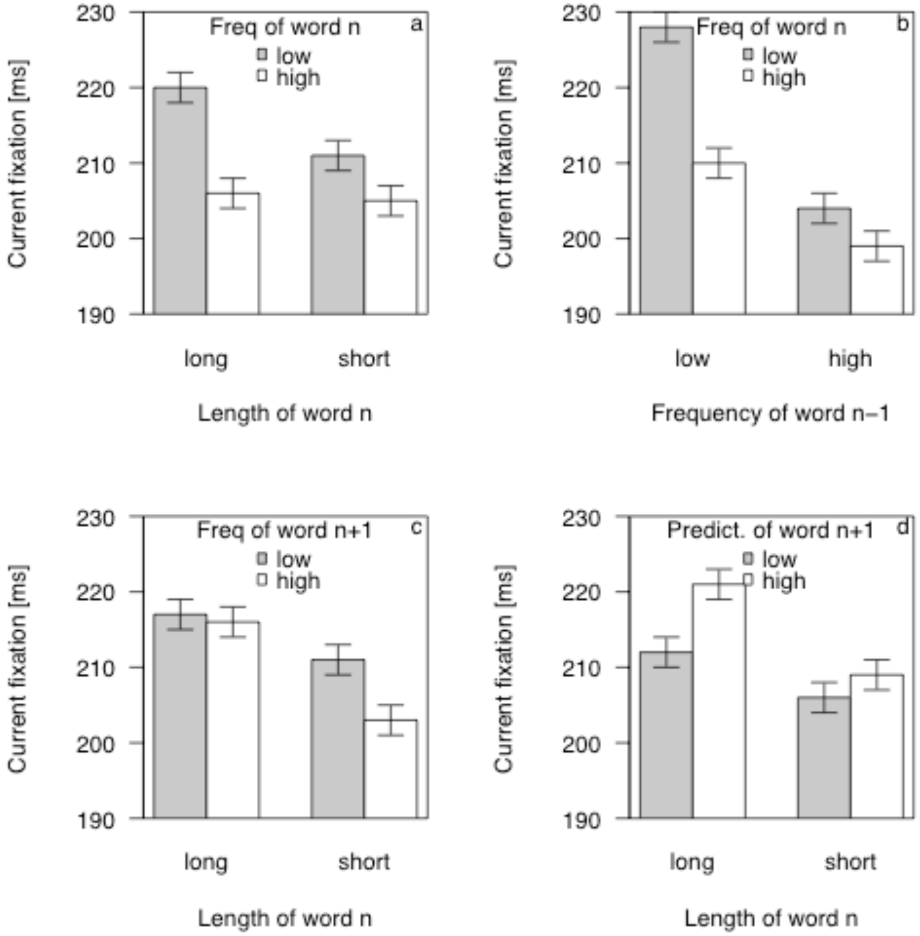

a
Freq of word n
low
high
Current fixation [ms]
230
220
210
200
190
long
short
Length of word n
b
Freq of word n
low
high
Current fixation [ms]
low
high
Frequency of word n−1
c
Freq of word n+1
low
high
Current fixation [ms]
long
short
Length of word n
d
Predict. of word n+1
low
high
Current fixation [ms]
long
short
Length of word n

Figure 5

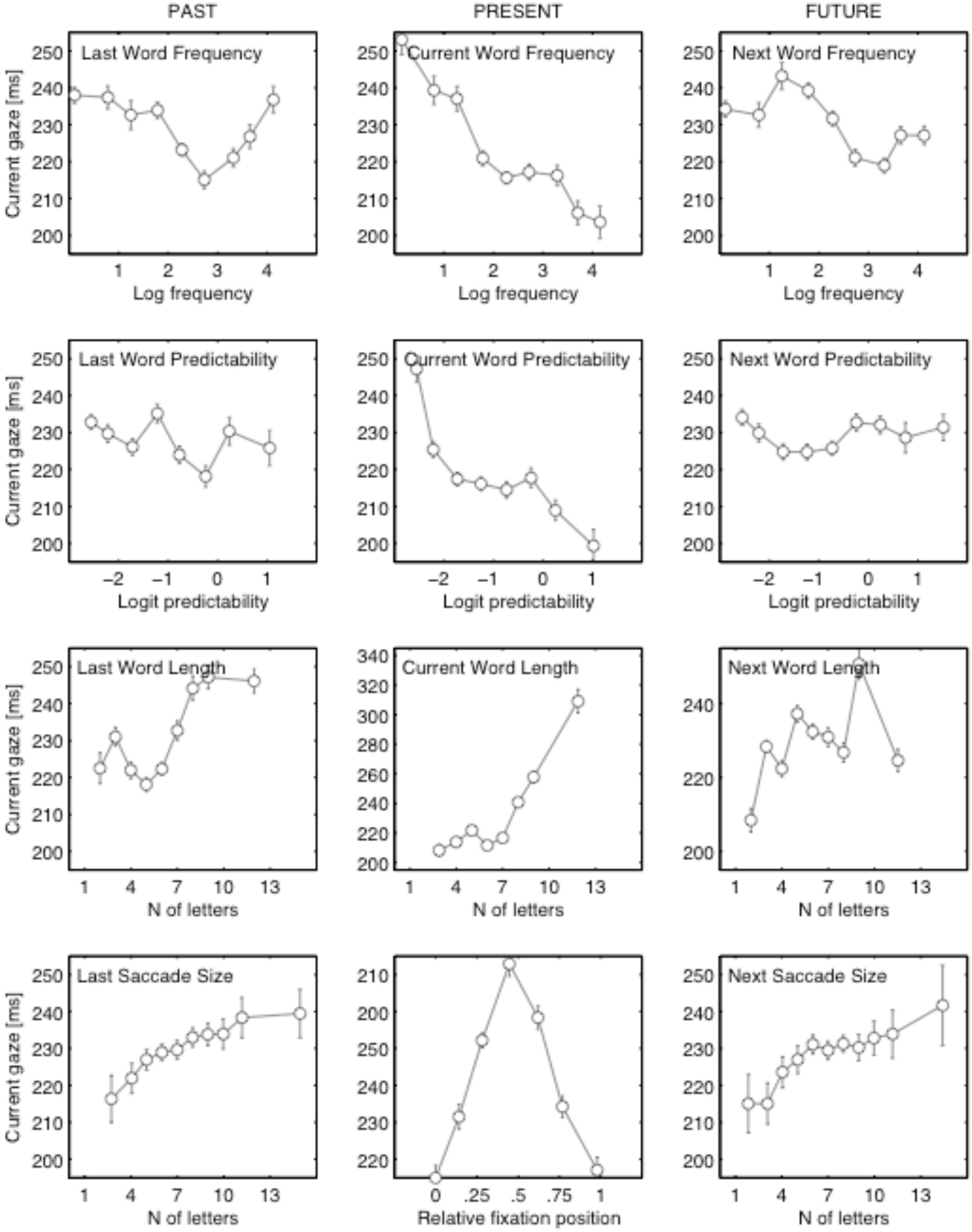
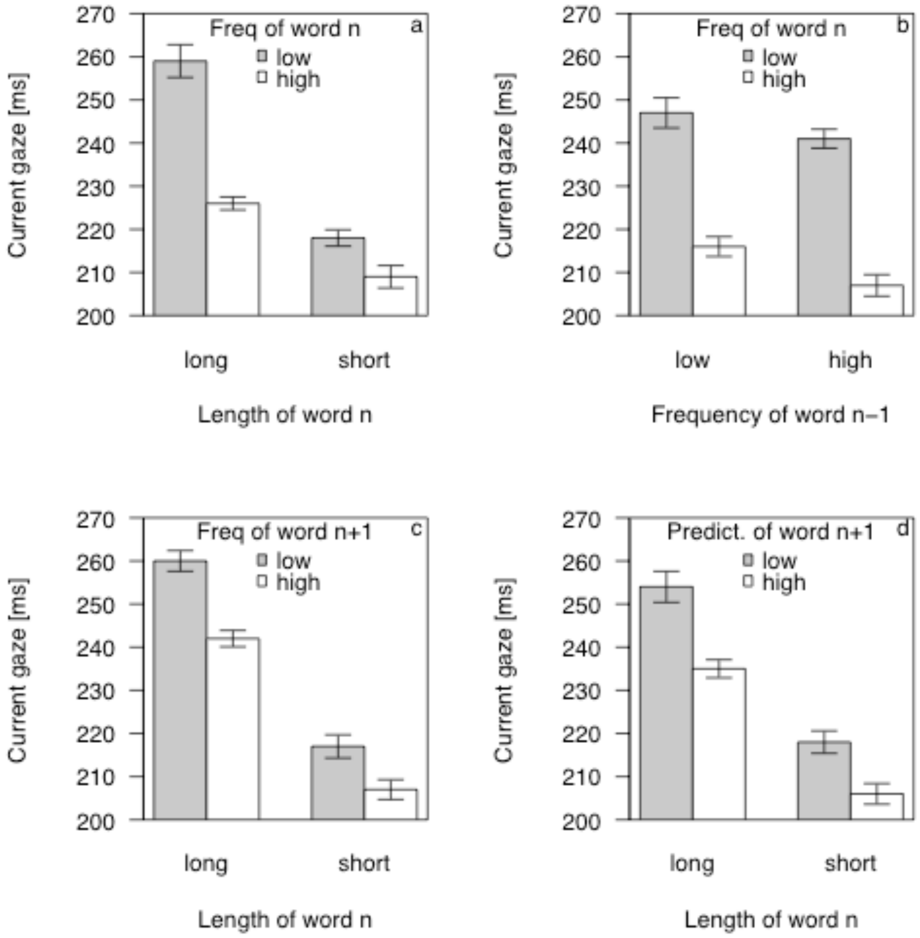

PAST
PRESENT
FUTURE
Last Word Frequency
Current Word Frequency
Next Word Frequency
Last Word Predictability
Current Word Predictability
Next Word Predictability
Last Word Length
Current Word Length
Next Word Length
Last Saccade Size
Next Saccade Size
Current gaze [ms]
250
240
230
220
210
200
340
320
300
280
260
Log frequency
1
2
3
4
Logit predictability
−2
−1
0
1
N of letters
1
4
7
10
13
Relative fixation position
0
.25
.5
.75
1

Figure 6


Current gaze [ms]
200
210
220
230
240
250
260
270
Freq of word n
a
▨ low
☐ high
long
short
Length of word n
Freq of word n
b
▨ low
☐ high
low
high
Frequency of word n−1
Freq of word n+1
c
▨ low
☐ high
long
short
Length of word n
Predict. of word n+1
d
▨ low
☐ high
long
short
Length of word n