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Contextual constraint and N + 2 preview effects in reading

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Extracting linguistic information from locations beyond the currently fixated word is a core component of skilled reading. Recent debate on this topic is focused on the question of whether useful linguistic information can be extracted from more than one (parafoveally visible) word to the right of a fixated word (N). The current study examined this issue through the use parafoveal previews with a short and high-frequency next (N + 1) word, as this should increase the opportunity for the extraction of useful information from the subsequent (N + 2) word. Pairs of N + 2 words were selected so that contextual constraint was either high or low. Using saccade contingent display manipulations, preview of a N + 2 target word during word N viewing consisted of either a visually dissimilar nonword or a word. The results revealed a substantial drop in fixation probability for word N + 1 when the N + 2 preview was masked with a nonword. Furthermore, the masking of word N + 2 influenced its viewing duration even when word N + 1 was fixated prior to word N + 2 viewing. These results provide compelling evidence for the view that the linguistic processing can encompass more than one word at a time.

Keywords: Eye movements; Reading; Parafoveal processing; Contextual constraint; Parafoveal-on-foveal effects.

The last three decades have seen a dramatic increase in the use of eye movement research to study skilled reading (e.g., Kennedy, Radach, Heller, & Pynte, 2000; Radach & Kennedy, 2004, 2013; Rayner, 1998, 2009). Much of this work is based on the fact that spatial and temporal eye movement measures provide detailed information about perceptual and cognitive processes during reading. Looking at the spatial aspect of oculomotor control, it appears that eye movements (saccades) are generally directed to the centre of one of the next words in the current line of text. With respect to the temporal aspect of oculomotor control, it has become clear that the duration of individual fixation and of the time spent viewing a word is influenced by the ease of its perceptual and linguistic processing. These findings imply that skilled readers' moment-to-moment eye movement programming is effectively coordinated with the ongoing linguistic processing.

Although most saccades move the eyes forward in the text, not all progress from one word to the

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next. Instead, some words are fixated more than once, others are skipped over. Short, high-frequency words are rarely refixated and are frequently skipped, with skipping rates of over 50% for three-letter, high-frequency words (Brysbaert, Drieghe, & Vitu, 2005). These high skipping rates indicate that the processing of a word need not coincide with its fixation, and there is converging evidence according to which readers routinely obtain useful visual and linguistic information from the fixated word (N) and also from the next (parafoveally visible) word N + 1. Parafoveally obtained word N + 1 information is used for the coordination of word recognition and saccade programming, so that it influences the likelihood with which word N + 1 is skipped and its viewing duration when it is fixated (see Rayner, 1998, 2009, for detailed reviews).

Theoretical accounts regarding the relationship between parafoveal information extraction and eye movement programming differ primarily along two dimensions: the extent to which eye movement programming is subject to cognitive rather than visuomotor control, and the extent to which word processing during reading fixations is either strictly serial or, to a limited extent, parallel (see Kliegl, Nuthmann, & Engbert, 2006; Radach, Reilly, & Inhoff, 2007; Reichle, Rayner, & Pollatsek, 2003, for detailed discussions).

Serial attention shift (SAS) models, in particular the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998), assume that the linguistic processing of words requires the allocation of visual attention. Following Posner (1978; Posner, Snyder, & Davidson, 1980), attention is considered a spotlight that confines lexical processing to one word at a time during reading, where successful recognition of one word further results in the shifting of the spotlight to the next word in the text. In the E-Z Reader model, saccade programming and attention shifting are dissociated, though both are controlled by the strictly serial recognition of individually attended words. Specifically, the model assumes that saccadic eye movement programming from word N to N + 1 is triggered at the end of an initial (L1) stage of word N processing, often referred to as a familiarity check, and that a corresponding shift of attention is assumed to occur after a final stage of N processing, L2, has been completed. Because saccade programming typically requires more time than completion of L2, the spotlight of attention will be shifted to the next word (N + 1) before the corresponding saccade is executed (saccade programming involves a modifiable/labile and committed/nonlabile stage in the model). Whenever attention reaches N + 1 before a corresponding saccade is executed, lexical processing of word N + 1 will begin before it is fixated, and an N + 1 preview benefit will be obtained when the word is subsequently fixated.

Oculomotor responding can be different when the processing of word N and of parafoveal word N + 1 is particularly effective. When the L2 processing of fixated word N takes relatively little time—that is, when a shift of attention to N + 1 can occur relatively quickly after the onset of saccade programming—and when parafoveal L1 processing of word N + 1 can be completed before the programming of a saccade to N + 1 reaches its nonlabile stage, then the saccade to N + 1 will be cancelled. A new saccade is programmed that skips N + 1 and directs the eyes to the following word (N + 2) instead.

Based on the idea of a spatially variable gradient of processing resources (LaBerge & Brown, 1989), processing gradient (PG) models offer a theoretical alternative, as these models assume that the fixated word and spatially adjacent words can be attended and processed simultaneously (e.g., Engbert, Longtin, & Kliegl, 2002; Reilly & Radach, 2006). The degree to which the processing of neighbouring words is assumed to overlap in time and space can vary, creating a space of solutions ranging from massive to very limited parallel processing (Engbert, Nuthmann, Richter, & Kliegl, 2005). The basic idea can be demonstrated using one PG implementation, the Glenmore model, proposed by Reilly and Radach (2003). These authors suggest that letter-level information is acquired in parallel from words within the perceptual span and can thus encompass one or more than one word at any point in time, at a rate determined by eccentricity. Letter-perception-based activation will increase until a lexical match is found, which will occur, for instance, earlier for high-frequency than for low-frequency words. The dynamics of activation are transmitted to a saliency map, where word locations are represented as potential saccade targets. The global level of activation is also transferred to a fixate centre, where the time of triggering the next saccade is determined, with saccades always moving to the word location with highest level of activation. This will, in most cases, be either the next (N + 1) word or the following (N + 2) word in the text (see Reilly & Radach, 2006, for details).

A widely used means to study visual–spatial and linguistic aspects of parafoveal information acquisition use is the boundary technique (Rayner, 1975). In most studies utilizing this technique, the parafoveal preview of a word N + 1 provides different types of useful N + 1 information until word N is fixated, and the intact N + 1 word is shown when the eyes move from N to N + 1. The time spent viewing the intact word N + 1 can then be examined as a function of previously available preview types, and a typical finding is that N + 1 viewing durations are shorter and that N + 1 skipping is more common when the preview revealed useful spatial and linguistic information, findings that are accommodated with equal success by the strictly serial spotlight assumption of SAS models such as the E-Z Reader and by the parallel word processing assumption of PG models. The two assumptions make different predictions, however, regarding the effect of N + 2 previews during word N and N + 1 viewing.

Rayner, Juhasz, and Brown (2007) were the first to examine whether a parafoveal preview benefit can be obtained from a preview of word N + 2, arguing that in sequential attention shift models like the E-Z Reader model, "lexical processing is generally restricted to the currently fixated word and the word to the right of fixation (p. 230)". Acquisition of linguistic information from N + 2 —before the eyes move out of word N—would require the completion of the L2 processing of word N, the completion of L1 and L2 processing of word N + 1, and some L1 processing of word N + 2. For this to occur, the L2 processing of word N and the full recognition of N + 1 would have to be exceedingly efficient. In PG models, by contrast, N + 2 processing should be common if linguistic processing was often distributed over more than two words. Consistent with the serial attention shift models, Rayner et al. (2007) reported virtually no benefit of N + 2 previews on subsequent N + 2 viewing when N and N + 2 words could be relatively long, as occurred in Experiment 1, and when they were short, as occurred in Experiment 2. Similarly, Angele, Slattery, Yang, Kliegl, and Rayner (2008) did not find any evidence for N + 2 preview effects when N + 1 were four-letter words or longer. Moreover, Angele and Rayner (2011) did not obtain lexical N + 2 preview effects, even when N + 1 consisted of the word "the", a short functor word with the highest word frequency count in the English language. With Chinese text, Yang, Rayner, Li, and Wang (2012) showed that a N + 2 word preview did not yield a benefit when the intervening N + 1 single-character word had a low frequency of occurrence.

Other work revealed, however, effects of N + 2 previews, on either subsequent word N + 1 or N + 2 viewing, when the N + 1 word was short and common. Using three-letter N + 1 words, Kliegl, Risse, and Laubrock (2007) obtained effects of N + 2 previews on N + 1 viewing with German materials. Glover, Vorstius, and Radach (in press), reported N + 2 preview benefits when N + 1 words were high-frequency three-letter adjectives, and N + 2 words were high-frequency nouns. Furthermore, Yang, Wang, Xu, and Rayner (2009) obtained benefits from N + 2 Chinese character previews when the N + 1 character was a high-frequency function word. Although these results are problematic for serial attention shift models, Rayner et al. (2007) noted that N + 2 preview benefits are possible when N + 1 words are short. Under favourable linguistic processing conditions—for example, when words are short and common, and when contextual constraints are high, the time line of L1 and L2 processing can approximate zero in serial attention shift models, and processing conditions can be established within which N + 2 preview effects can be accommodated (see Balota, Pollatsek, & Rayner, 1985, for a demonstration of effects of contextual constraint on parafoveal word processing). Furthermore, following Rayner, White, Kambe, Miller, and Liversedge (2003), it could be argued that the effect of N + 2 previews on N + 1 viewing durations in Kliegl et al.'s (2007) study might have been due to mislocated fixations—that is, the eyes were directed at N + 2 but landed on N + 1 instead.

If the spotlight of attention encompassed one word a time, as suggested by SAS models, then the likelihood with which useful linguistic information can be obtained from N + 2 must decrease rapidly with increases in the recognition duration of word N + 1. That is, when the recognition of N + 1 is relatively short so that it can be skipped, attention may reach N + 2 prior to the skipping saccade, and useful information may be obtained from a N + 2 preview (see Angele & Rayner, 2011, for a recent discussion). However, no information should be obtained from N + 2 when N + 1 recognition is too slow for N + 1 skipping. Furthermore, in a strictly serial word processing scheme, processing of N + 2 previews cannot act forward and influence the viewing of word N + 1. Precisely these effects were obtained in the current study.

Method

Participants

Thirty-six students of the Florida State University participated in a 45-min session in exchange for experimental credits in their Introduction to Psychology course. They were all native English speakers and had normal or corrected-to-normal vision via glasses or soft contact lenses. Participants were naïve as to the purpose of the experiment. Their mean age was 20.2 years, with 56% of the sample being female.

Apparatus

The sentences were displayed, one at a time, in black on a light-grey background using a 21″ IIyama CRT monitor with a display resolution of 1,024 × 768 pixels, running at 150-Hz refresh rate. Regular Courier-type font 12 was used, and the viewing distance between each reader's eyes and the monitor was set to approximately 60 cm. At this distance, each letter subtended 0.33° of visual angle laterally. Viewing was binocular but eye movements were recorded from the right eye only using an EyeLink 1000 eye tracking system (SR Research, Mississauga, Ontario, Canada) sampling at a rate of 1000 Hz. Heads were positioned on a chin rest to minimize head movements. Relative accuracy of measurement was in the order of 0.02°; absolute accuracy was maintained at less than one character width via calibration and validation routines (McConkie, 1981).

Procedure and materials

Participants were asked to read the sentences for comprehension while their eye movements were monitored. Before trials began, the accuracy of the eye tracker was checked and recalibrated, if necessary. After each sentence, the participants were instructed to press a button to continue or to respond to questions. Prior to the experimental session, participants were administered a standard vision test routine (Stereo Optical Model 5000 Vision Tester), and following the experimental session a standardized test of reading ability was administered (e.g., Woodcock Reading Mastery Test) to gain information on their level of reading ability. This information ensured that the participants did not have visual acuity limitations or general reading difficulties.

The materials consisted of 6 practice and 96 experimental sentences. In addition there were a total of 18 multiple-choice questions randomly distributed over the set of experimental sentences. These questions ensured that reading for comprehension took place. The criterion for inclusion was the correct answering of at least 14 of the 18 (fairly easy) comprehension questions. Two N + 2 variables were manipulated, predictability and preview, with two and three levels, respectively, and six lists were used to counterbalance these conditions across the experimental sentences (see Table 1 for a sentence frame example that was used in the experiment). For each sentence frame, two N + 2 words with identical length and grammatical role were selected, one that was highly predictable given prior context and one whose

Table 1. *Examples of sentence materials using one sentence frame in all six conditions*

High predictable, no mask:				
Ashley quickly	**vacuumed**	|	**the carpet**	before her friends arrived for the party.
	N		N + 1 N + 2	
High predictable, N + 2 *word mask:*				
Ashley quickly	**vacuumed**	|	**the stairs**	before her friends arrived for the party.
	N		N + 1 N + 2	
High predictable, N + 2 *nonword mask:*				
Ashley quickly	**vacuumed**	|	**the cwoyok**	before her friends arrived for the party.
	N		N + 1 N + 2	
Low predictable, no mask:				
Ashley quickly	**vacuumed**	|	**the stairs**	before her friends arrived for the party.
	N		N + 1 N + 2	
Low predictable, word mask:				
Ashley quickly	**vacuumed**	|	**the carpet**	before her friends arrived for the party.
	N		N + 1 N + 2	
Low predictable N + 2 *nonword mask:*				
Ashley quickly	**vacuumed**	|	**the skwbom**	before her friends arrived for the party.
	N		N + 1 N + 2	

Note: Boundary location was kept constant, as denoted by "|" in the examples, and immediately followed word N. Note that word notation is relative to critical fixation so that the primary target word is referred to as word N + 2.

predictability was low. All target words contained five or six letters, and their frequency of occurrence was relatively high according to the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). Furthermore, the two preceding words and posttarget word were controlled for in length as well; see Table 2 for means and ranges of word lengths and mean frequencies of the words of interest: word N, word N + 1, and word N + 2.

During fixation of word N, preview of N + 2 consisted of either the N + 2 target word itself (no mask) or the alternative member of the high–low-predictable word pair (word mask). For instance, the high-predictable member of the N + 2 word pair was used to mask the visually dissimilar, subsequently shown (and fixated) low-predictable target. In a nonword masking condition, preview of a high- or low-predictable N + 2 target consisted of a sequence of letters, where the first letter and the overall word shape were kept identical, while the rest of the letters were dissimilar to the target. Care was taken to match the properties of these words in term of orthographic regularity (e.g., Radach, Inhoff, & Heller, 2004). The beginning token bigram frequencies of nonword masks for high- and low-frequency target words were 3,934 and 3,547 per million, while their mean token bigram frequencies amounted to 1,809 and 1,661, respectively. The initial token trigram frequencies were 138 and 192 per million. None of these measures were

Table 2. *Word lengths and word frequencies of words N, N+1, and N+2 as used in the present study*

		Word length (letters)		*Word frequency (per million)*	
Word	*Predictability*	*Mean*	*Range*	*Mean*	SD
N		6.36	4–8	314.86	1,263.44
N+1		3	3	60,974.04	0.00
N+2	High	5.29	5–6	56.24	70.93
	Low	5.41	5–6	49.26	78.96

statistically different, which was also true for the corresponding type based bigram and trigram parameters (see White, 2008, for a discussion).

Sentence contextual constraint was determined by means of cloze scores in an independent norming study with 30 participants, confirming the experimenter's intuitions as to how predictable a word was within a given sentence frame. Participants were given the beginning portions of the experimental sentences and were asked to provide a word that they felt would fit as the next word in the sentence. In line with Frisson, Rayner, and Pickering (2005), words with probabilities of .70 to .90 were designated as high-constraint words, and words with probabilities of less than .10 as low-constraint words. The mean probabilities for high- and low-predictable words were .86 and 0, respectively.

Analysis

A word was considered fixated when a fixation fell on one of its letters or the blank space preceding it. Fixations with durations less than 70 ms and more than 800 ms were removed from analyses. In analyses of the remaining data, deviations of fixation durations more than 3 standard deviations of the cell means were eliminated as well. Trials where the first fixation on the target word was not preceded by a progressive saccade with a length of 20 characters or less were also excluded. Together with blinks or track losses, these restrictions resulted in the elimination of about 3.7% of all observations. Five oculomotor measures were analysed: the fixation probability of words (the inverse of skipping rate), the landing position of fixated words with the space preceding a word assuming a value of zero, and three viewing duration measures. Gaze duration, often used as a primary viewing duration index (Inhoff & Radach, 1998; Rayner, 1998), constituted the time spent viewing the target word during first-pass reading. It included the time spent refixating a word but excluded saccade durations. The duration of the first fixation on a word, irrespective of the number of fixation, constituted the second measure, and single fixation duration, computed for words that received a single fixation, constituted the third measure.

All data were analysed using linear mixed models (LMM), as implemented in the lme4 package of the R system for statistical computing (Baayen, 2011; Bates, Maechler, & Dai, 2008, R-version 2.12.1; R-Development-Core-Team, 2010). Trial-based data were entered, which make computation relatively immune to inequalities in the number of available data. This was common, for instance in the analyses of viewing duration data, because skipping rates differed across words and across conditions. Furthermore, more than one random factor can be entered simultaneously into the model, and individual differences can be considered. The data were analysed using two fixed factors, N + 2 preview (no mask, dissimilar word mask, dissimilar nonword mask) and N + 2 predictability (high vs. low). Effects of preview were examined with two orthogonal Helmert contrasts, one that compared the no mask condition with the mean of the word and nonword condition to determine the effect of N + 2 masking. The second compared the word with the nonword mask condition to determine whether specific linguistic properties of the N + 2 influenced oculomotor activity. The first comparison is referred to as *preview-mask contrast* and the second as *mask-type contrast*. When possible, two crossed random factors, subjects and items, were entered into the model (since N + 1 was constant, no item factor was used for its analysis), and random intercepts and random slopes were used with a maximal random effect structure.

A binomial link function was used for the analysis of the fixation probabilities, and an identity link function was applied to landing positions and to log-transformed viewing durations (the untransformed viewing duration data were positively skewed). The LMM analyses yielded intercepts, regression coefficients (b), standard errors (SE), and z-values for the binomial fixation probability data and t-values for the continuous measures. The significance level of t-values was determined through Markov Chain Monte Carlo (MCMC) simulations with the pvals program of the languageR package (1,000 samplings). T-values

Table 3. *Means and number of cases for fixation probability, initial first-fixation duration, single-fixation duration, and gaze duration as a function of predictability and preview conditions for word N*

	Low predictability			*High predictability*		
Oculomotor measure	*No mask*	*Letter mask*	*Word mask*	*No mask*	*Letter mask*	*Word mask*
Fixation probability	.89	.89	.90	.89	.88	.91
	(.31)	(.31)	(.30)	(.32)	(.32)	(.29)
	547	*550*	*537*	*548*	*552*	*548*
Initial landing position	2.98	3.20	3.14	3.05	3.15	3.01
	(1.85)	(1.87)	(1.88)	(1.85)	(1.87)	(1.88)
	488	*492*	*483*	*485*	*486*	*496*
First-fixation duration	222	224	223	222	225	225
	(72)	(77)	(77)	(72)	(77)	(77)
	488	*492*	*483*	*485*	*486*	*496*
Gaze duration	255	257	252	254	255	251
	(103)	(108)	(104)	(103)	(108)	(104)
	488	*492*	*483*	*485*	*486*	*496*
Single-fixation duration	224	228	227	226	227	229
	(73)	(77)	(75)	(73)	(77)	(75)
	398	*409*	*402*	*399*	*400*	*422*

Note: Standard deviations in parentheses. Number of cases in italics. Initial landing position: letters. Initial first-fixation duration, gaze duration, and single-fixation duration in ms.

>2 were reliable in all simulations, and LMM statistics are reported for reliable ($p < .05$) and marginally reliable effects ($p < .1$); summary p-levels are reported for the remaining effects.

There was considerable overlap across the three viewing duration measures. All three measures are, for instance, identical when a word receives exactly one fixation. All data are shown in tables, but—to reduce redundancy—we report the statistics of the gaze data (see Rayner, 1998, for a detailed discussion) unless the other viewing duration measures show a different effect pattern.

Results

Word N

Table 3 shows the full-set oculomotor data for word N as a function of N + 2 preview and N + 2 predictability.[1]

The approach of the eyes to word N was not expected to be influenced by the two manipulated N + 2 factors. Consistent with this, fixation probability differed by less than 2% across all comparisons, and landing positions for fixated words differed by less than 0.1 letter spaces, all $p > .1$. Moreover, manipulation of N + 2 had no effect on word N viewing durations. All differences were relatively small (less than 5 ms), and none of the effects approached significance, all $p > .2$.

Word N + 1

N + 1 fixation probabilities are shown as a function of the parafoveal preview and predictability of N + 2 during word N viewing in Figure 1. The remaining oculomotor indexes are shown in Table 4.

The analysis of fixation probabilities did not reveal a main effect of N + 2 predictability ($p > .4$), but it yielded robust N + 2 preview effects (Table 5 shows

[1] The lmer function used to predict oculomotor measures included two fixed factors, N + 2 preview and predictability; the random effect structure included random intercepts (1|subjects) and (1|items) plus random intercepts for subjects (1|subjects:preview:predictability) and items (1|items:preview).

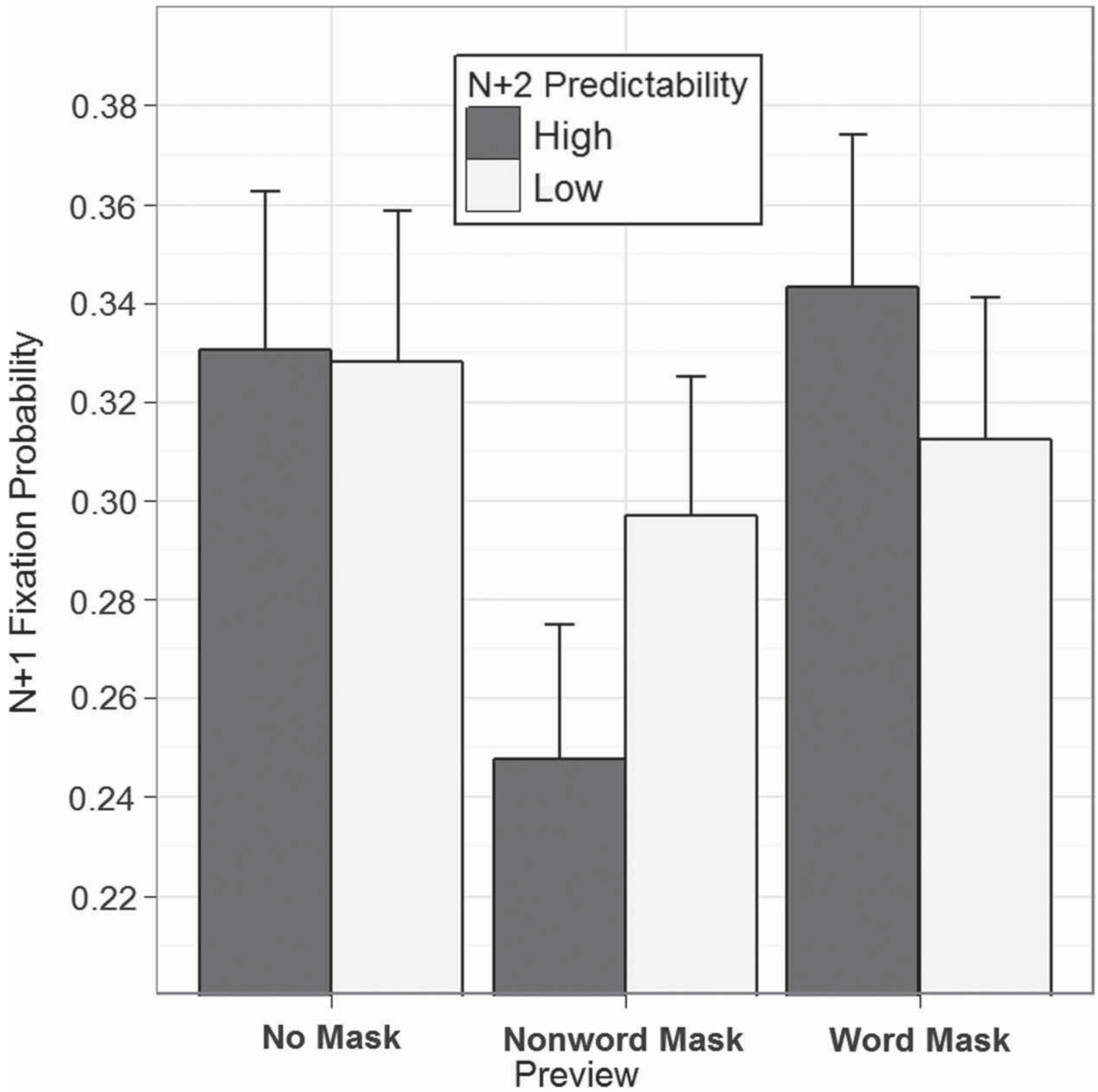

Figure 1. *Word N + 1 fixation probabilities as a function of N + 2 predictability and preview. Standard errors were computed across subjects.*

a detailed LMM output). Fixation of N + 1 was more likely in the no mask condition than in the two masking conditions ($b = 0.06$, $SE = 0.03$, $t = 2.11$), and N + 1 fixation was also more likely when the N + 2 preview was masked with a word than when it was masked with a nonword ($b = 0.14$, $SE = 0.05$, $t = 2.84$). Moreover, the mask-type effect was modulated by the predictability of the N + 2 preview, with the lowest N + 1 fixation rate when high-predictable N + 2 words were masked with nonwords during N viewing ($b = 0.23$, $SE = 0.10$, $t = 2.32$). The corresponding interaction was negligible for the preview-mask contrast, $p > .7$. Together these results suggest that saccades were attracted to a parafoveally visible nonword, in particular when it occupied the position of a high-predictable N + 2 word. The remaining analyses did not yield any reliable effect (all $p > .1$), as N + 2

Table 4. *Means and number of cases for initial first-fixation duration, single-fixation duration, and gaze duration as a function of predictability and preview conditions for word N+1*

	Low predictability			*High predictability*		
Oculomotor measure	*No mask*	*Letter mask*	*Word mask*	*No mask*	*Letter mask*	*Word mask*
Initial landing position	1.88	1.80	1.78	1.80	1.72	1.77
	(1.16)	(1.15)	(1.14)	(1.16)	(1.16)	(1.18)
	166	*148*	*154*	*170*	*120*	*173*
First-fixation duration	204	196	192	190	192	201
	(83)	(60)	(59)	(64)	(64)	(68)
	166	*148*	*154*	*170*	*120*	*173*
Gaze duration	210	202	204	194	197	212
	(86)	(68)	(78)	(67)	(77)	(81)
	166	*148*	*154*	*170*	*120*	*173*
Single-fixation duration	210	202	204	194	197	212
	(86)	(68)	(78)	(67)	(77)	(81)
	166	*148*	*154*	*170*	*120*	*173*

Note: Standard deviations in parentheses. Number of cases in italics. Initial landing position: letters. Initial first-fixation duration, gaze duration, and single-fixation duration in ms.

Table 5. *LMM fixed effect pattern for the fixation probability of word N+1*

Fixed effects	*Estimate (b)*	SE	*Z-value*	*Pr(>|z|)*	
(Intercept)	−0.86037	0.10826	−7.947	1.91E−15	***
Preview-type	0.14462	0.05089	2.842	.00448	**
Preview-mask	0.06032	0.02861	2.108	.035	*
Predictability	0.05808	0.08199	0.708	.47869	
Preview-type by predictability	−0.23656	0.10177	−2.324	.02011	*
Preview-mask by predictability	−0.01873	0.05719	−0.328	.74324	

Note: LMM = linear mixed models.
*$p < .05$; **$p < .005$; ***$p < .0005$.

preview and predictability during N viewing influenced neither N + 1 landing positions nor ensuing fixation durations.

Word N + 2

Table 6 shows oculomotor activity for word N + 2 as a function of its predictability and its preview during word N viewing.

There was almost no skipping of word N + 2, and no statistical analyses were applied due to lack of variability. The examination of another oculomotor measure, N + 2 fixation locations, revealed negligible differences, all $p > .2$.

The predictability and preview manipulation of word N + 2 during word N viewing influenced, however, all three viewing duration measures. Viewing durations were longer when the predictability of N + 2 was low ($b = 0.07$, $SE = 0.013$, $t = 6.71$, for gaze duration), and, importantly, it also determined the viewing duration of N + 2. All three viewing durations were shorter in the no mask condition than in the two masking conditions ($b = -0.18$, $SE = 0.004$, $t = -3.89$, for gaze duration). The preview-mask contrast was modulated by predictability ($b = 0.019$, $SE = 0.008$, $t = 2.22$), with larger masking effects when predictability of N + 2 was high than when it was low.

Table 6. *Means for initial landing position, first-fixation duration, single-fixation duration, and gaze duration as a function of predictability and preview conditions for word N+2*

	Low predictability			*High predictability*		
Oculomotor measure	*No mask*	*Letter mask*	*Word mask*	*No mask*	*Letter mask*	*Word mask*
Initial landing position	2.34	2.30	2.33	2.37	2.25	2.40
	(1.58)	(1.52)	(1.63)	(1.57)	(1.57)	(1.57)
	477	*492*	*484*	*480*	*504*	*486*
First-fixation duration	231	229	238	213	224	225
	(78)	(68)	(88)	(66)	(66)	(74)
	477	*492*	*484*	*480*	*504*	*486*
Gaze duration	258	260	272	229	249	248
	(97)	(96)	(120)	(77)	(91)	(95)
	477	*492*	*484*	*480*	*504*	*486*
Single-fixation duration	256	255	249	252	254	251
	(105)	(109)	(102)	(102)	(99)	(93)
	409	*410*	*403*	*410*	*405*	*432*

Note: Standard deviations in parentheses. Number of cases in italics. Initial landing position: letters. First-fixation duration, gaze duration, and single-fixation duration in ms.

The corresponding interaction was marginally reliable for gaze duration ($b = 0.017$, $SE = 0.009$, $t = 1.89$, $p < .07$) and first-fixation duration ($b = 0.013$, $SE = 0.008$, $t = 1.76$, $p < .09$). Contrasts involving preview type were not reliable, all $p > .2$. Together, the viewing duration data suggest that readers sought graphemic information from N + 2 during word N viewing and that denial of this information was particularly deleterious for the recognition of contextually constrained words.

Supplementary analyses

Most N + 1 words were skipped, and useful information could have been obtained from N + 2 either because the window of effective processing during word N viewing encompassed more than one word to the right of fixation or because recognition of N + 1 during N viewing took relatively little time and because a subsequent shift of the attention spotlight to N + 2 could be completed before the skipping saccade reached N + 2. To determine whether N + 2 review and predictability influenced N + 2 viewing even when N + 1 was fixated, we analysed the subset of N + 2 fixations that was preceded by N + 1 viewing ($n = 665$). The resulting gaze durations are shown as a function of N + 2 preview and predictability in Figure 2. The first- and single-fixation effects are reported in Table 7.

In addition to the two fixed factors preview and predictability and their interaction, N + 1 gaze duration was included in the statistical model to control for N + 1 recognition duration. The N + 1 viewing duration effect was not reliable, $p > .3$, but the main effect of predictability was again highly reliable ($b = 0.12$, $SE = 0.03$, $t = 4.02$, for gaze duration). The gaze data also revealed a significant preview-mask contrast ($b = -0.022$, $SE = 0.01$, $t = -2.09$), which was also obtained for the full set of N + 2 data, with shorter durations in the no mask condition than the two masking conditions, but the corresponding contrast was not reliable for the two remaining measures ($p > .2$). Notably, this subset of data also revealed a mask-type contrast for all three viewing duration measures ($b = 0.04$, $SE = 0.02$, $t = 2.19$, for gaze duration), with longer viewing durations for word than for nonword masks, and this main effect was modulated by predictability ($b = 0.09$, $SE = 0.037$, $t = 2.44$). Specifically, N + 2 viewing durations were longer when a low-predictable N + 2

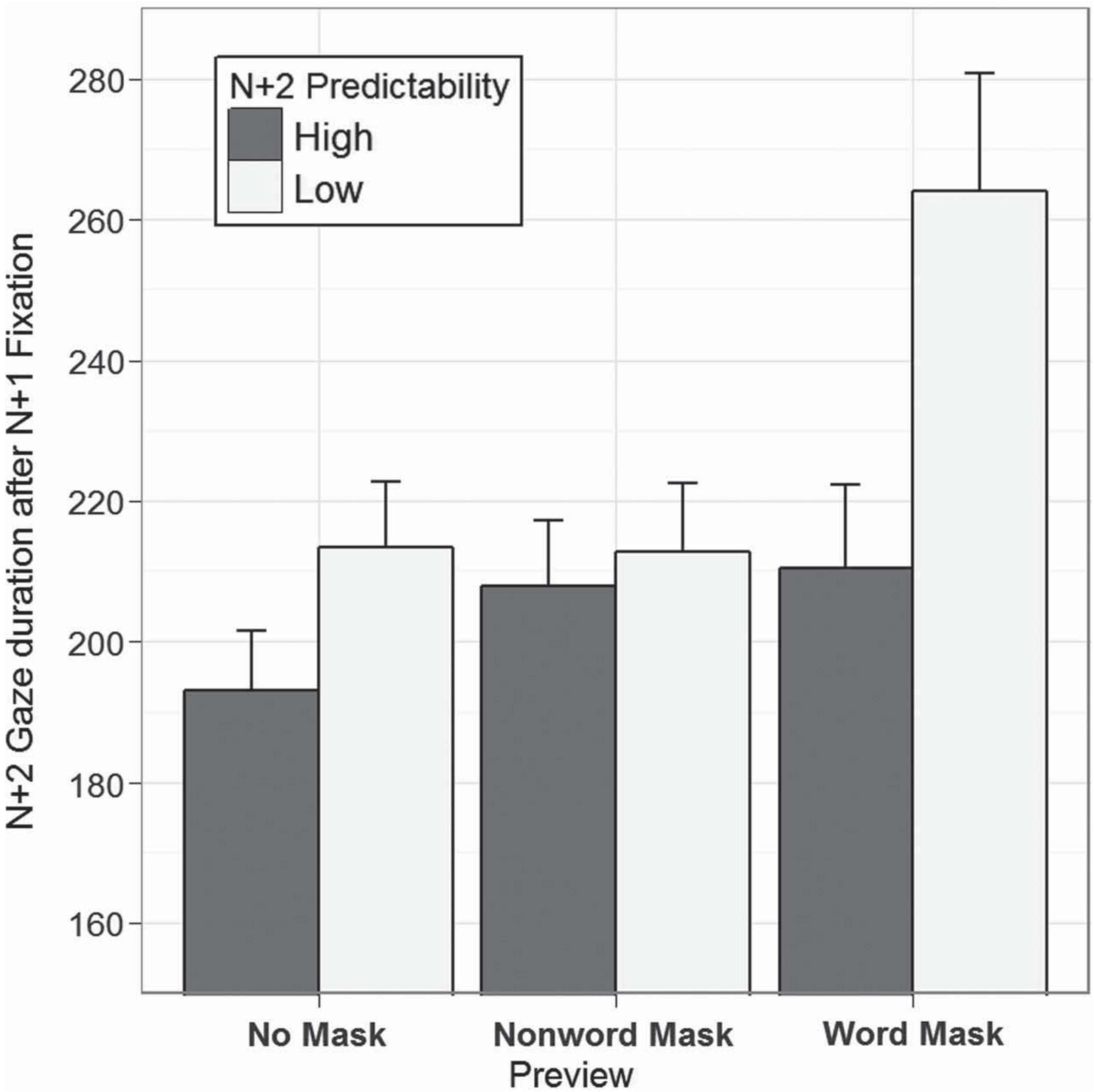

Figure 2. *N + 2 gaze duration when word N + 1 was fixated as a function of N + 2 predictability and preview. Standard errors were computed across subjects.*

target had been masked with a (high-predictable) word during N viewing. These effects indicate that readers discerned lexical properties of parafoveally visible N + 2 words when they were highly predictable.

A second supplementary analysis examined preview and predictability spillover effects during word N + 3 viewing, irrespective of the fixation of word N + 1. The results showed 21 ms shorter gaze duration when N + 2 predictability was high than when it was low predictability ($b = -0.074$, $SE = 0.017$, $t = 4.23$), and a marginally shorter gaze duration when N + 2 had been visible during word N viewing than when it had been masked, 256 ms and 266 ms, respectively ($b = 0.01$, $SE = 0.005$, $t = 1.89$, $p < .06$).

Table 7. *Means for first-fixation duration and single-fixation duration as a function of predictability and preview conditions for word N+2 after fixation of word N+1*

	Low predictability			*High predictability*		
Duration	*No mask*	*Letter mask*	*Word mask*	*No mask*	*Letter mask*	*Word mask*
First-fixation duration	211	197	231	181	198	194
	(81)	(63)	(83)	(51)	(66)	(62)
	111	*109*	*111*	*114*	*95*	*125*
Single-fixation duration	210	192	229	182	199	192
	(83)	(55)	(99)	(51)	(66)	(62)
	105	*100*	*98*	*109*	*90*	*116*

Note: Standard deviations in parentheses. Number of cases in italics. First-fixation duration and single-fixation duration in ms.

Discussion

The current study sought to examine the usefulness of word N + 2 previews during word N viewing under optimal N + 2 processing conditions: when N + 1 was relatively short, when its frequency of occurrence was high, and when N + 2 could be highly predictable. These conditions yielded the most comprehensive pattern of N + 2 preview effects reported in the literature to date: Preview of N + 2 during word N viewing influenced the fixation probability of word N + 1, it influenced the time spent viewing word N + 2, even when N + 1 was fixated, and it influenced even the viewing of subsequent word N + 3. Together, these results have clear and compelling implications for the understanding of the time line of parafoveal information usage during reading fixations and for models of eye movement control.

A key manipulation in the current study was the use of the high-frequency functor "*the*" as N + 1 word during the reading of alphabetic (English) text. The processing of this word was expected to be highly effective, and prior work showed that it is frequently skipped (e.g., O'Regan, 1979). Yet, irrespective of the effectiveness of its processing, the word needs to be attended before the spotlight of attention can move to N + 2 according to strictly serial word processing models. In Reichle et al.'s (2003) comprehensive comparison of the E-Z Reader model with other models of eye guidance during reading, it is the word "the" that is used to illustrate the E-Z Reader model's focus of attention (linguistic processing) at one word at a time. Even when the full linguistic (L1 and L2) processing of the word "the" can be completed within a very short interval, the programming of a saccade and the subsequent shifting of the attention spotlight to it are assumed to be obligatory. This must occur because the N to N + 1 saccade is programmed after the initial stage of word N processing is completed, and the programming of the saccade must continue throughout this word's L2 processing. Once attended, N + 1 processing could be very short—close to zero when it is highly predictable (see, Pollatsek, Reichle, & Rayner, 2006). This can generate two oculomotor movement patterns from word N toward word N + 1 in the E-Z Reader model.

When the programming of the N to N + 1 saccade has not yet entered the nonlabile stage, then the saccade to N + 1 can be cancelled and directed to N + 2. Furthermore, attention may be shifted from N + 1 to N + 2 before the ensuing N + 1 skipping saccade reaches N + 2. In these cases, preview of N + 2 can influence subsequent N + 2 viewing duration.

When, however, recognition of N + 1 is too slow for programming of a skipping saccade, N + 1 will be fixated, and the effect pattern should change. Attention should not be shifted serially from N to N + 2—or such double shifts during the fixation of word N should be exceedingly rare—and linguistic properties of the N + 2 preview should not be noted. Robust N + 2 preview-mask and mask-type effects on N + 2 viewing duration, and the interaction of the mask-type contrast with N + 2 predictability, thus disagree with the serial attention shift assumption of SAS models.

The E-Z Reader model and other serial attention shift models also make a specific prediction regarding N + 1 skipping. Preview of N + 2 during word N viewing cannot influence oculomotor activity associated with the processing of an earlier word, and the masking of N + 2 as well as the type of masking should not have influenced N + 1 skipping. The effects of N + 2 masking on N + 1 skipping cannot be accounted for by mislocated fixations—that is, by fixations that were directed at word N + 1 but landed on word N + 2—as oculomotor targeting of N + 1 and extraction of useful information from N + 2 are incompatible with the spotlight assumption.

In principle, PG models such as Glenmore and SWIFT are in harmony with effects of N + 2 previews on N + 1 skipping rate and N + 2 viewing durations when word N + 1 was fixated, as attention (visual and linguistic processing resources) can be spread across words N + 1 and N + 2 while word N is fixated. However, it needs to be considered whether specific mechanisms of processing suggested in such models can accommodate our detailed pattern of results. As one straightforward example, the relatively low fixation probability of N + 1 when the N + 2 target location was occupied by a nonword mask suggests that difficulties with the initial processing of the N + 2 target word were effective during N viewing; to account for this, PG models need to assume that this attracted attention and modified saccade targeting. Indeed, within the framework of Glenmore, the nonword mask would be treated as an extremely low-frequency word, quickly raising its activation value within the saliency map and making it a more attractive saccade target relative to competitors within the current perceptual span.

A second interesting case is our finding of relatively long N + 2 gaze durations after fixation of N + 1 when the position of a low-predictable target had been masked with a high-predictable companion word. First, it appears that the fixation of N + 1 has provided additional time for the preview to have an effect in the ensuing cascade of processing. In the case of a highly predictable N + 2 preview, this processing may have progressed relatively far, perhaps approaching the selection of the previewed word, and this might have interfered with the subsequent recognition of the low-predictable target. In contrast, the processing of a low-predictable parafoveal preview should have progressed slower, so that its replacement with a different word had far less dramatic consequences. This interaction, should, in principle, be amenable to an interactive activation account of word processing as suggested in Glenmore (see Balota et al., 1985, for a discussion). However, current PG models appear underspecified regarding this issue, as in Glenmore no specific mechanism for word predictability is implemented, and the time line of to-down contextual modulation is unresolved. It remains to be seen how future implementations of PG models will attempt to accommodate such mask–target interactions.

In processing gradient-based models, effective acquisition of useful linguistic information from N + 2 may not only influence the size of outgoing word N saccades and the ensuing N + 2 viewing durations, but can also influence word N viewing duration. This parafoveal-on-foveal effect was absent in the current data. To accommodate this finding, we propose that the attentional viewing during N viewing does not encompass word N + 2 at the very onset of word N viewing (see Inhoff, Eiter, & Radach, 2005, for empirical support). By the time the attentional window encompassed word N to N + 2, readers may still have been able change spatial parameters of the saccade out of word N, and this influenced N + 1 skipping rate, but it may have been too late to change temporal saccade parameters. We suspect that temporal properties of the outgoing saccade can be modified when N processing is particularly effective, and we plan to examine this possibility in the future.

Taken together, the results of this study provide further evidence for the view that, depending on the current visual configuration and the demands of ongoing linguistic processing, the extent of parafoveal processing during reading is quite flexible. Within the constraints of the current perceptual span, information from all letters can potentially be acquired concurrently, at a rate that decreases rather sharply from the centre of the current fixation. Further downstream this will lead to the processing of words with more or less temporal and spatial overlap (Inhoff, Radach, & Eiter, 2006). This includes the possibility of completely sequential word processing as one special case, while in most cases a moderate extent of parallel processing may be typical. We believe that the best environment to accommodate this conception of flexible parallel processing is currently provided with PG models such as Glenmore and SWIFT.

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