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On-line contextual influences during reading normal text: A multiple-regression analysis ☆

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Abstract

On-line contextual influences during reading were examined in a series of multiple-regression analyses conducted on a large-scale corpus of eye-movement data, using Latent Semantic Analysis (LSA) to assess the degree of contextual constraints exerted on a given target word by the immediately prior word and by the prior sentence fragment. A decrease in inspection time was observed as contextual constraints increased. Word-level constraints exerted their influence both forward (on both single-fixation and gaze durations) and backward (on gaze duration only). An independent sentence-level effect was only visible in the forward direction, and only for gaze duration. Gaze duration was also sensitive to the depth of embedding of the target word in the syntactic structure. We conclude that both low-level and high-level contextual constraints can translate in the eye-movement record.
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Keywords: Reading; Eye-movements; Context effects; Predictability; Latent Semantic Analysis

1. Introduction

The context a target word is embedded in is known to affect its reading time. For example, Schuberth and Eimas (1977) compared lexical decision times to target words that were either semantically congruous with respect to a prior sentence fragment, incongruous, or presented in isolation. The presentation of context was found to decrease decision latencies for congruous words and to increase decision latencies for incongruous words. The results for incongruous words can presumably be attributed to post-lexical integration processes (e.g., difficulty integrating an incongruous word into the meaning of the sentence fragment). The facilitation effect obtained for congruous words has generally been taken as evidence that sentential context interacts with word identification processes, for example, by raising the reader's expectations that a particular word is going to be encountered (Stanovich & West, 1981). In this latter case, post-lexical integration processes can be assumed to occur as well. However, their influence would be either masked or overridden by stronger effects, operating at the lexical-access level.

More recently, the debate has moved to normal reading, with eye-movement measurement as the preferred index. Numerous carefully controlled eye-tracking experiments have shown first fixation duration, first-pass gaze duration and skipping probability all to vary as a function of target "predictability" (Altarriba, Kroll, Sholl, & Rayner, 1996; Ashby, Rayner, & Clifton, 2005; Balota, Pollatsek, & Rayner, 1985; Binder & Rayner, 1998; Calvo & Meseguer, 2002; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Ehrlich & Rayner, 1981; Inhoff, 1984; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006; Lavigne, Vitu, & d'Ydewalle, 2000; Rayner & Well, 1996; Rayner, Ashby, Pollatsek, & Reichle, 2004). In most

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of these studies, the "predictability" of a given target word was assessed using a classical Cloze task (Taylor, 1953), which provides an index, over a continuum, of the average probability of guessing a continuation word at a given point in a sentence fragment. In other words, some targets used in the experiments were highly predictable, whereas others were less predictable or not predictable at all. As a consequence, observed effects can theoretically reflect either lexical-access or post-lexical integration processes, or possibly, a combination of both. Moreover, as noted by Frisson, Rayner, and Pickering (2005), there are several sources participants in a Cloze task can rely on in order to complete a sentence fragment. This means that predictability is in fact a composite factor, combining several potential sources of influence, ranging, from global discourse coherence (e.g., involving a representation of the state of affairs denoted by the current and prior sentences) to local inter-word associations.

How much of the high-level integration processes developed during reading are actually reflected in the eye-movement record remains an open question. Early disruption to the course of visual inspection (e.g., first-fixation lengthening) can be obtained by introducing plausibility or selection-restriction violations (Rayner et al., 2004; Traxler, Foss, Seely, Kaup, & Morris, 2000). Occasional disruptions can also be observed with normal coherent text, at clause and sentence boundaries (see Hirotani, Frazier, & Rayner, 2006, for a discussion), or when a specific difficulty is encountered (Frazier & Rayner, 1982). Such phenomena can be interpreted in terms of the need to ensure comprehension. They do not provide any evidence that comprehension processes interact with the mechanisms controlling the pattern of forward fixations on the first pass, however. As Reichle, Pollatsek, Fisher, and Rayner (1998) put it, "...these [syntactic and discourse] processes are usually too slow to be the usual signal to move forward and are better used as an occasional signal to stop lexical-access and sort things out" (p. 150).

In this view, determinants of early predictability effects would thus have to be looked for in lower-level properties. A prime candidate is local inter-word associations. In lexical decision experiments, single words that are preceded by a related prime word have been shown to be processed faster and more accurately than words preceded by an unrelated prime (Meyer & Schvaneveldt, 1971). Since constraining sentence beginnings can be thought of as containing words that are semantically related to the target word, or at least words belonging to the same semantic domain, inter-lexical priming effects can be expected to occur during normal reading as well. Evidence on this question is mixed. For example, Traxler et al. (2000) failed to find effects of word relatedness for schematically related word pairs (e.g., lumberjack-axe) or synonym pairs (e.g., pastor-minister). Such effects seem to only show up in certain circumstances. For example, Morris and Folk (1998) obtained a decrease in gaze duration for schematically related words when the first word of the pair was in linguistic focus. More recently, Camblin, Gordon, and Swaab (2007) obtained a clear word-association effect on first fixation duration, but only when the sentence containing the prime-target pair was presented in isolation. The effect disappeared, or was greatly reduced, when carrying sentences were embedded in multi-sentence congruous contexts. This suggests that inter-word lexical priming effects in continuous reading are subject to the influence of higher-level comprehension processes. Such effects would only occur when the target word cannot rapidly be integrated into discourse-level representations.

New interest has been brought to these questions by McDonald and Shillcock's (2003a, 2003b) finding that contingency statistics (e.g., the likelihood that any two given target words follow each other in the language) can exert an immediate influence on early visual inspection parameters. For example, the verb "accept" is followed more often by the word "defeat" than the word "looses". The transitional probability of "defeat" is thus higher for "accept" than for "looses". In a series of experiments and corpus analyses, transitional probability was found to affect both first-fixation and gaze durations. Importantly, McDonald and Shillcock found a transitional probability effect even when the target and context words were presented in a neutral sentential context, thus suggesting that transitional probability operates independently from the processing operation developed at the sentence-level. However, this position was contested by Frisson et al. (2005) who failed to replicate the results of McDonald and Shillcock in an experiment in which Cloze probability was carefully controlled. They concluded that transitional probability is in fact one of the many components of classical Cloze probability. McDonald and Shillcock also manipulated what they called "backward transitional probability" (e.g., the probability of occurrence of word $n-1$ given the presence of word n to its right). Backward Transitional probability was also found to affect both the first-fixation and the gaze durations on word $n-1$.

Such "parafoveal-on-foveal cross talk" (Kennedy, 2000), occurring as early as on the first fixation on word $n-1$, strongly suggests that low-level inter-word associations do affect the lexical-access stage during normal reading (but see Frisson et al., 2005, for a different outcome and a discussion). Whether backward transitional probability effects (assuming they are real) are immune from any higher-level influences can still be questioned, however. Backward effects[1] have been reported for Cloze probability as well (Kliegl et al., 2006), with shorter gaze durations prior to entering a highly predictable word. However, an

[1] The expression "backward effect" (McDonald and Shllcock, 2003) is used here as a descriptive term, without any connotation of mechanisms. It is thus equivalent to Kliegl et al.'s (2006) "successor-word effect". Backward effects can theoretically originate from low-level "parafoveal-on-foveal cross talk" (Kennedy, 2000), or from higher-level integration processes, e.g., involving expectation generation and "memory retrieval" (Kliegl et al., 2006).

effect in the opposite direction was found for single-fixation durations: single-fixation durations were *inflated* prior to entering a highly predictable word. This quite paradoxical outcome might reflect the time necessary for sentence-level expectations to develop (see Kliegl et al., 2006 for a discussion) and should thus not be considered as a true parafoveal-on-foveal influence. This interpretation is in line with the suggestion by Altarriba, Kambe, Pollatsek, and Rayner (2001) that less parafoveal information may sometimes be obtained from contextually constrained words than from unconstrained words: if a word can be guessed from the prior context, less (possibly no) parafoveal information is necessary for its identification.

A first aim of the present study was to investigate these issues further, using Latent Semantic Analysis or LSA (Landauer, Foltz, & Laham, 1998; Landauer & Dumais, 1997) to assess the degree of semantic constraint exerted on a given target word by the immediately prior word on the one hand, and by the prior sentence fragment as a whole on the other hand. In the LSA framework, word meanings are represented as vectors in a high dimensional space and the distance between two meanings can be expressed as a numerical value. In the present study, the distance between the vector representing the meaning of a given target word and the vector representing the meaning of the prior word (hereafter: word-level LSA or wLSA score) will be interpreted as an index of how much semantic constraint the target word is subjected to from the prior word: the closer the two vectors, the more semantically constrained the target word (and vice versa). Importantly, the meaning of a word sequence, whatever its length, can also be represented as a vector in the same high dimensional space. This means that the meaning of a sentence fragment can be directly compared to the meaning of a single word, the distance between the vector representing the target word and the vector representing the prior sentence fragment providing an estimate of the amount of semantic constraint exerted at the sentence-level. In order to disentangle word-level and sentence-level influences, the word located immediately to the left of a target word was excluded from the measure of sentence-level LSA (or sLSA) scores.

Our conjecture was that LSA-based scores, as defined above, can capture part of low-level and high-level constraints present in sentence contexts, thus permitting an examination of both word-context and sentence-context influences within the same framework. The counterpart to this is that we may be ignoring important components of predictability. For example, syntax plays no part in the computation of LSA scores, as defined above: neither word order, nor morphology are taken into account. But the predictability of a given target word depends on the meaning of the prior sentence fragment, and syntax obviously contributes to sentence meaning. It follows that predictability effects are partly syntactic in nature. Syntax, or some related property associated with individual words, thus should have a role to play. What is more, semantic influences, as assessed by sLSA scores, might be modulated as a function of the position of the target word in the sentence. A second aim of the present study was thus to examine the possible interactions between "semantic relatedness", as assessed by sLSA scores, and a measure of the position of the target word in the syntactic structure, namely the depth of its embedding (see Section 2). As this measure is likely to correlate with the "physical" position of the target word, relative to the sentence beginning, this latter measure was also included in the analysis, as a control.

In order to avoid possible strategies associated with single-sentence presentation (Camblin et al., 2007), the present study was conducted on a large-scale corpus of eye-movement data obtained as participants read long extracts from newspaper articles for comprehension (see details in Section 2). Each word in the corpus was associated with a set of contextual properties (wLSA and sLSA scores, position relative to sentence beginning, depth of embedding in the syntactic structure), whose possible influence on inspection time was examined in a series of multiple-regression analyses. In addition to these contextual properties, each word was also associated with a set of intrinsic properties (e.g., length and frequency), whose impact on visual inspection is already well documented in the literature. A first series of analyses was devoted to examining the respective influence of wLSA and sLSA scores on gaze and single-fixation durations. A second series investigated potential backward context effects. Position in sentence and possible related effects were examined in a final series.

2. Methods

2.1. Materials

The analyses were conducted on the French part (52,173 tokens and 11,321 types) of the Dundee corpus (Kennedy, Hill, & Pynte, 2003) which is based on extended articles taken from the French language newspaper *Le Monde*. Over a number of testing sessions, 10 French-speaking participants read the texts presented at a viewing distance of 500 mm from a display screen, five lines at a time. For selection in the present analyses, a word ("word n" or "target word" hereafter) had to be a content word (noun, verb or adjective), and the saccade entering it to be launched from the immediately prior word. An average of 3341 words per participant met these criteria. Unless specified otherwise, the word immediately to the left of the target word ("prior word" or "word $n-1$") was also a content word. An average of 1822 pairs of adjacent content words per participant remained available for analysis. This number was reduced to 1378 in the analyses of single-fixation durations which excluded words inspected with more than one fixation. LSA scores are of little interest in the case of high-frequency function words such as determiners, prepositions, pronouns, etc., simply because such words can be found in any context. When such words are "predicted", it will almost invariably be on a syntactic rather than a semantic basis.

2.2. Procedure

Each word in the corpus was associated with a set of properties whose influence on inspection time was assessed in a series of regression analyses. Two "semantic" properties (wLSA and sLSA scores) were successively added to a baseline model comprising a set of predictors known to influence gaze duration. The contribution of these semantic properties to the goodness of fit of the resulting models was evaluated. Possible interactions with two "position" properties (rank in sentence and depth of embedding) were subsequently examined. All independent variables were centred. The analyses were conducted in the linear-mixed effects model (*lme*) framework, using the *lme4* package (Bates & Sarkar, 2006) for the *R* system for statistical computing (Development Core Team, 2006). Both readers and words were treated as random factors. LSA, rank and embedding effects were estimated as varying across readers when appropriate, that is, when including the variance estimate of slopes between readers improved the model fit.

2.3. Dependent variables

The analyses were conducted for four dependent variables, namely, single-fixation duration and first-pass gaze duration (the sum of all fixations between the first entry into the word and the first exit from the word) on the target word and the prior word.

2.4. Baseline model

In addition to target- and prior-word length and frequency, the baseline model comprised two predictors whose aim was to account for variations due to landing position and preview benefit. These were the size of the saccade entering the word and its relative landing position (landing position divided by word length, linear and quadratic trends). Saccade size and landing position were measured relative to the word under investigation, that is the target word for the analyses of target word inspection time and the prior word for the analyses of prior word inspection time. To maintain compatibility with previous analyses (Pynte & Kennedy, 2006, 2007), measures of lexical frequency were based on the texts used in the Dundee corpus and were submitted to log transformation.

2.5. LSA scores

A large corpus of novels (14.7 million words) and film dialogues (16.6 million words, see New, Brysbaert, Veronis, & Pallier, 2007) was first used in order to build up a 300-dimension LSA space in which the semantic content of words and sentence fragments could be represented as vectors (see details in Appendix A). The cosines of the angle between the vector associated with a given target word in the eye-movement corpus and the vector associated with the word immediately to its left (wLSA score) and with the prior sentence fragment (sLSA score) were then computed and subsequently log-transformed (the higher the value, the more similar the meanings). All words, at all steps of the procedure, were submitted to lemma transformation. The context taken into account for the measure of sLSA scores consisted of all the words located between the last sentence terminator (e.g., full stop, question mark, etc.) and the target word, minus the word located immediately to the left of the target word. The immediately prior word was excluded from the measure in order to avoid confounds with possible word-level context effects, as measured by wLSA scores. Note that, in contrast to sLSA scores, wLSA scores are symmetrical and provide an index of the degree of constraint exerted on the prior word from the target word as well as the other way around.

2.6. Position variables

The position properties used in this study were based on the original syntactic descriptions of the corpus provided by Abeillé, Clément, and Kinyon (2003). The rank measure was obtained by merely counting the number of words separating the target word from the beginning of the sentence. The depth of embedding of a given target word was assessed by computing the number of syntactic brackets open at that point in the sentence minus the number of closing brackets (ending a constituent) since the beginning of the sentence.

2.7. Correlation between predictors

The correlation matrix is provided as Appendix B. The highest value (+.58) is observed for rank and embedding. This correspond to the fact that depth of embedding usually increases as one moves forward in the sentence. The second highest value is observed between length and frequency, for obvious reasons, and the third highest value (+.34) is observed between wLSA and sLSA scores. LSA scores also correlate with length and frequency: the longer the target word, and the lower its frequency, the higher the LSA scores (+.25 and −.33, respectively, for sLSA; +.23 and −.14 for wLSA). Short high-frequency words can be found in many contexts and are thus less sensitive to LSA, which is based on co-occurrences. wLSA also correlated with prior-word length and frequency (+.19 and −.20, respectively), illustrating the fact that such scores are symmetrical.

3. Results

The results will be dealt with in three sub-sections. The possible influence of word- and sentence-level semantic constraints to single-fixation and gaze durations is examined in Section 3.1; the next section is devoted to the analysis of backward contextual influences; and questions related to the position of the target word in the sentence are finally treated in Section 3.3. Each sub-section starts with a brief description of a baseline regression model, comprising seven well known predictors of inspection time in reading. The corresponding regression equation is subsequently enriched by successively adding new predictors, thus permitting to examine the specific contribution of contextual constraints.

3.1. Semantic influences

Word-level influence on gaze duration is illustrated in Fig. 1a and sentence-level influence in Fig. 1b. Each subfigure was obtained by median split in the distribution of the corresponding independent variable. Mean gaze durations were computed for words with low vs. high wLSA scores (Fig. 1a) and for words with low vs. high sLSA scores (Fig. 1b). Each bar corresponds to the difference between the two means obtained for a given word length. Black bars correspond to the significant part of that difference (i.e., the difference minus two 95% confidence intervals, plotted in white, see Loftus & Masson, 1994). It must be kept in mind that apparent effects in these figures may mask the influence of a number of possible confounds. Only the regression analyses reported below (Table 1) can determine whether each of these factors exerts an independent influence on inspection time.[2]

3.1.1. Baseline model

In the baseline model, the time spent inspecting a given target word is accounted for in terms of its own length and frequency, the length and frequency of the prior word, the

[2] The lme4 package does not provide any p values associated with t-tests. Following Baayen's (2007) suggestion, $-2 > t > 2$ was used here as the threshold for statistical significance.

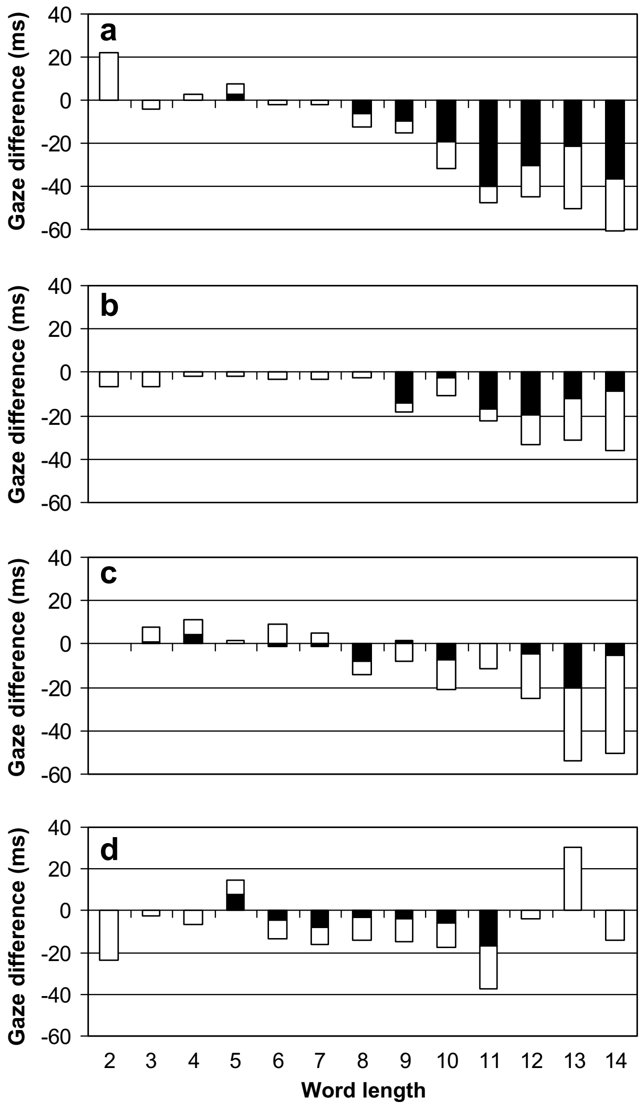

Fig. 1. Contextual effects as a function of word length: difference in gaze duration for target words with low vs. high wLSA scores (a), for target words with low vs. high sLSA scores (b), for prior words located to the left of target words with low vs. high wLSA scores (c) and for target words slightly vs. deeply embedded in the syntactic structure (d).

size of the incoming saccade, the landing position of this saccade (relative to word length) and the square of this latter measure. Unsurprisingly, all of these predictors were found to exert a significant influence. Increasing word length by 1 character led to a 3.6 ms increase in single-fixation duration and a 12.2 ms increase in gaze duration, $t = 11.60$ and 29.94, respectively. Each log frequency unit increment lead to a 5.4 ms and 8.4 ms decrease, $t = -10.32$ and -11.47 for single-fixation and gaze duration, respectively. A spillover effect of prior-word frequency is also present, with a regression coefficient of -3.1 and -4.1, $t = -5.99$ and -5.90, for single-fixation and gaze durations, respectively. A spillover effect of prior-word length was found for single-fixation duration (1.3 ms increase per character, $t = 4.35$) but not for gaze duration ($t < 1$). Both the linear and quadratic trends of

Table 1
Regression coefficients with associated standard errors from the analysis of semantic effects, with single-fixation and gaze durations recorded on the target word as dependent variables

	Single fixation Variance		Gaze duration Variance	
Random effects				
Itm (intercept)	312.15		570.19	
Sub (intercept)	241.25		906.23	
Sub sLSA			21.59	
Residual	4510.34		11313.34	
	Estimate	Std. error	Estimate	Std. error
Fixed effects				
Intercept	207.01	5.89	344.26	10.32
Saccade	0.94	0.15*	0.34	0.21
Landing	87.67	11.15*	−225.97	14.12*
Landingˆ2	−50.92	9.34*	183.46	12.17*
Freq. $n-1$	−3.20	0.51*	−4.37	0.70*
Length $n-1$	1.34	0.29*	0.50	0.39
Frequency	−5.45	0.53*	−8.85	0.73*
Length	3.77	0.31*	12.68	0.41*
wLSA	−2.81	0.69*	−5.56	0.95*
sLSA	−0.85	0.97	−5.67	2.00*
Interactions				
wLSA:sLSA	0.24	0.73	−0.37	1.04
Length:wLSA	0.00	0.28	−0.78	0.37*
Length:sLSA	−0.21	0.35	−0.28	0.47
Freq.:wLSA	−0.41	0.41	−0.23	0.58
Freq.:freq.-1: wLSA	−0.23	0.27	0.13	0.38

Note: Asterisks correspond to significant effects ($t > 2$).

landing position produced significant effects ($t = 7.81$ and -5.42, for single-fixation duration; $t = -16.07$ and 15.11 for gaze duration), thus confirming the role of landing position as a major determinant of visual inspection time. Longer single-fixation durations were also associated with longer incoming saccades, with a 0.9 ms increase for each 1-character increase in saccade size, $t = 6.27$. The effect of saccade size vanished for gaze duration, however ($t = 1.55$, n.s.).

3.1.2. Word-level LSA scores

The wLSA scores associated with target words were added to the regression equation corresponding to the baseline model. The goodness of fit was significantly improved, $\chi^2 = 18.11$, $p < 3\text{e}{-05}$. and $\chi^2 = 41.65$, $p < 2\text{e}{-10}$, for the single-fixation and gaze duration analyses, respectively, suggesting that semantic relatedness is responsible for at least part of the differences apparent in Fig. 1. The regression analysis indicates that each log unit was associated with a 2.9 ms decrease in single-fixation duration and with a 6.1 ms decrease in gaze duration, $t = -4.26$ and -6.47, respectively. A new analysis in which wLSA effects were estimated as varying across participants did not provide any significant improvement in model fit, $\chi^2 = 0.88$ and 0.89, n.s., for single-fixation and gaze durations, respectively.

3.1.3. Sentence-level LSA scores

sLSA scores were added to the resulting "word-level" model (already including wLSA). The goodness of fit was improved for gaze duration, $\chi^2 = 15.45$, $p < 9\text{e}{-05}$, but not for single-fixation duration, $\chi^2 = 0.77$, n.s. The effect visible in Fig. 1b is thus reliable, suggesting a specific contribution of sLSA scores to gaze durations, with a regression coefficient of -5.7 ms, $t = -3.93$. As indicated in the random-effect part of Table 1, the variance estimates of slopes between participants is quite large and the goodness of fit of the model was improved when the impact of sLSA scores on gaze durations was estimated as varying across participants, $\chi^2 = 4.49$, $p < .05$. As a consequence, the t value was reduced to -2.83, but remained significant.

3.1.4. Interactions

The regression coefficients presented in Table 1 are for the model after inclusion of wLSA and sLSA. The values for the seven predictors of the baseline model may thus be slightly different from the description provided in Section 3.1.1. Interaction terms were subsequently added to this resulting model, one at a time. Adding a wLSA-by-sLSA interaction term, did not improve the goodness of fit ($\chi^2 = 0.11$ and 0.13, n.s., for single-fixation duration and gaze duration, respectively), suggesting additive effects. Given the asymmetry visible in Fig. 1, a wLSA-by-length interaction term was included, resulting in a slight improvement in the analysis of gaze duration ($\chi^2 = 4.37$, $p < .05$, and $t = -2.09$ for the interaction term) but not in the analysis of single-fixation durations ($\chi^2 = 0.04$, $t < 1$). Inclusion of a length-by-sLSA interaction term did not result in any improvement ($\chi^2 = 0.37$, n.s.).

3.2. Backward effects

In this section, we deal with single-fixation and gaze durations recorded on the prior word, while the target word was still in the parafovea. Word-level backward influence (obtained by median split in the distribution wLSA scores) is plotted in Fig. 1c. Each bar corresponds to the difference between the two means obtained for a given prior-word length and black bars to the significant part of that difference (difference minus two 95% confidence intervals). Obviously, the observations expressed with regard to the interpretation of Fig. 1a and b apply equally to Fig. 1c. The regression analyses are reported in Table 2.

3.2.1. Baseline model

Although the same predictors were used, the baseline model for the analysis of backward effects differed in a few critical respects. Target length and frequency refer here to properties of an as-yet un-fixated word, whereas "prior-word" length and frequency refer to the word currently being inspected. Saccade size and landing position also refer to word $n-1$, the word currently being inspected. The same factors that were found to affect the time spent inspecting the target word were also found to affect the time spent on word $n-1$. Single-fixation and gaze durations were influenced by length, frequency, the size of the incoming saccade, and by landing position. Importantly, the frequency of the target word (still in the parafovea) did not exert a significant influence on word $n-1$ inspection time ($t = 0.78$ and -1.64 for single-fixation and gaze duration, respectively). This is not necessarily inconsistent with the results of Kennedy and Pynte (2005), obtained from the same corpus of eye-movement data. Although they found parafoveal-on-foveal effects in a combined analysis of English and French data, when separate analyses were conducted for the English and French parts of the corpus, a significant effect was only present for English. In French, parafoveal-on-foveal effects were restricted to the measure of informativeness that was not used in the present study.

Table 2
Regression coefficients with associated standard errors from the analysis of backward effects, with single-fixation and gaze durations recorded on the prior word as dependent variables

	Single fixation		Gaze duration	
	Variance		Variance	
Random effects				
Itm (intercept)	350.69		1232.90	
Sub (intercept)	440.21		1048.70	
Residual	8054.53		18045.30	
	Estimate	Std. error	Estimate	Std. error
Fixed effects				
Intercept	229.60	7.22	329.91	10.84
Saccade	2.71	0.20*	1.74	0.26*
Landing	35.07	9.53*	−181.28	12.10*
Landingˆ2	−25.44	9.46*	146.81	12.33*
Freq. $n-1$	−5.57	0.67*	−8.83	0.96*
Length $n-1$	1.21	0.42*	14.64	0.55*
Frequency	0.46	0.73	−1.74	1.01
Length	−0.53	0.38	−0.03	0.53
wLSA	0.62	0.91	−3.56	1.29*
sLSA	−1.09	1.27	−0.77	1.79
			Estimate	Std. error
Interactions				
wLSA:sLSA			−0.55	1.34
Length:wLSA			−1.50	0.49*
Lgth-1:wLSA			−1.72	0.44*
Length:lgth-1:wLSA			−0.32	0.15*
Freq.: wLSA			1.37	0.77
Freq.-1:wLSA			1.64	0.73*
Freq.:freq.-1:wLSA			−1.20	0.50*

Note: Asterisks correspond to significant effects ($t > 2$).

3.2.2. Word-level LSA scores

The semantic distance between the word being inspected and the target word located to its right exerted little influence on prior-word single-fixation durations ($\chi^2 = 0.32$, $t < 1$). It did influence prior-word gaze durations, however. Adding the wLSA scores associated with target words to the baseline model increased the goodness of fit for the analysis of gaze duration ($\chi^2 = 8.20$, $p < .005$), with a regression coefficient of −3.6, $t = -2.86$. No fit improvement was obtained when slope variance was considered ($\chi^2 = 0.01$, n.s.). These results partly replicate McDonald and Shillcock (2003a, 2003b), who reported backward low-level predictability effects for both first fixation duration and gaze duration.[3]

3.2.3. Sentence-level LSA scores

No significant improvement was obtained when contextual influence was extended to the prior sentence fragment (sLSA scores). The obtained χ^2 values were 0.71 and 0.21, for single-fixation and gaze durations, respectively ($t < 1$ in both cases). These results contrast with those of Kliegl et al. (2006), Kliegl (2007) who reported backward predictability effects for both single-fixation duration and gaze duration (although in opposite directions). However, it should be remembered that function words were explicitly included in those studies. The paradoxical effect observed on single fixations (namely that high predictability of word n was associated with longer single fixations on word $n - 1$) was only obtained if either word n or word $n - 1$ was a function word. Neither of these fixation patterns were selected for the analyses reported in the present study. We come back to this point in Section 4.

3.2.4. Interactions

A backward-wLSA effect was thus obtained for gaze duration. This result must be qualified, however: the effect is only visible for long prior words in Fig. 1c. As already mentioned in Section 2, higher wLSA scores were obtained for longer and lower-frequency prior words. More influence could thus be expected for such words. The corresponding prior-length-by-wLSA and prior-frequency-by-wLSA interaction terms was significant ($t = -3.95$ and 2.25, respectively). Given that wLSA scores are symmetrical, more backward influence could also be expected from long and low-frequency target words. Only the length-by-wLSA interaction term was significant ($t = -3.07$; $t = 1.78$, n.s. for Frequency-by-wLSA). Finally, the three-way interactions, involving wLSA together with both lengths on the one hand and both frequencies on the other hand were significant ($t = -2.07$ and −2.42 for length and frequency, respectively, $p < .05$), suggesting a much stronger backward context effect on prior-word gaze duration when both the prior and target words were long and low-frequency. This is illustrated in Fig. 2 as far as frequency is concerned.

[3] It is important to note that the correlations between wLSA scores and word $n - 2$ properties were quite low, ranging from 0.13 to 0.22 for log-transformed values; and from 0.11 to 0.15 for raw values. This suggests that the observed effect cannot be attributed to forward influence form word $n - 2$.

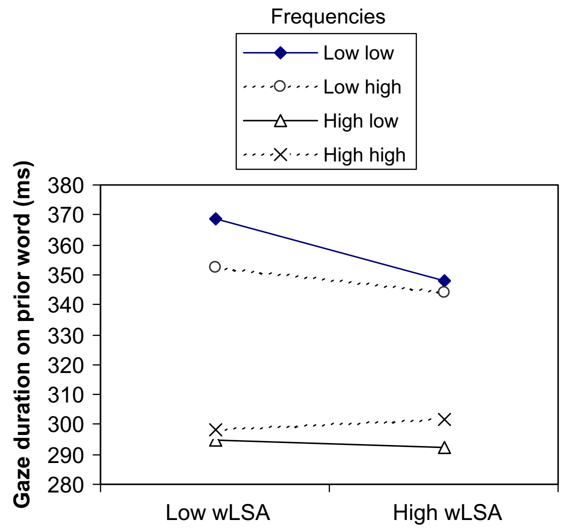

Fig. 2. Backward-wLSA effect for gaze duration, as a function of prior-word and target-word frequency.

3.3. Position in sentence

In this section, we further examine the influence of sentence-level semantic constraints, together with two additional properties of target words, namely, their rank relative to the sentence beginning, and the depth of their embedding in the syntactic structure. Only forward sentence-level effects were examined, thus allowing for some relaxation of the selection criteria (with consequential gains in the statistical power of the analyses). Whereas the prior word had to be a content word in the analyses presented so far, no constraint was put on the prior word in the analyses reported in this section. The dependent variable used was the gaze duration recorded on the target word. Single-fixation duration was not considered any longer, since sentence-level effects did not show up in the analysis of single fixations reported in Section 3.1.2.

The effect of embedding is illustrated in Fig. 1d. Mean gaze durations were computed for words slightly vs. deeply embedded in the syntactic structure. Black bars correspond to the significant part of the effect. The influence of sLSA on gaze duration is illustrated in Fig. 1b. The regression analyses are presented in Table 3.

3.3.1. Baseline model

Note that the numerical values corresponding to the seven predictors of the baseline model in Table 3 are slightly different from those of the baseline model presented in Table 1 above. This is due to the change in selection criteria and the consequential increase in the number of target words included in the analyses.

3.3.2. Position effects

Adding rank in sentence as a predictor of gaze duration did not significantly improve the goodness of fit, relative to the baseline model, $\chi^2 = 0.90$, n.s. Moving one rank for-

Table 3
Regression coefficients with associated standard errors from the analysis of position effects, with gaze duration as the dependent variable

	Variance	
Random effects		
itm (intercept)		685.01
sub (intercept)		867.06
sub sLSA		25.26
Residual		11647.46
	Estimate	**Std. error**
Fixed effects		
Intercept	323.68	9.80
Saccade	0.55	0.16
Landing	−192.01	10.83*
Landing^2	161.81	9.16*
Freq. $n-1$	−2.59	0.44*
Length $n-1$	−0.11	0.35
Frequency	−8.54	0.55*
Length	13.69	0.31*
Rank	0.11	0.07
Embedding	−0.73	0.30*
sLSA	−6.73	1.93*
Interactions		
Rank:embed.	0.02	0.01*
Rank:sLSA	−0.14	0.10
Embed.:sLSA	−0.73	0.45

Note: Asterisks correspond to significant effects ($t > 2$).

ward in the sentence only decreased gaze duration by 0.05 ms, $t = -0.95$, n.s. The next step of the analysis consisted in including the depth of embedding of target words as an additional predictor. This did significantly improve the goodness of fit. Comparison with the prior model, gave a χ^2 value of 6.82, $p < .01$. No improvement was obtained when slope variance was taken into account (χ^2 close to zero). The decrease in gaze duration observed in the raw data (Fig. 1d) is thus reliable. Adding one level of embedding decreased gaze duration by 0.8 ms, $t = -2.61$.

3.3.3. Semantic influences

The resulting model served as a new baseline for examining the specific influence of semantic constraints. sLSA scores improved the goodness of fit of the model, $\chi^2 = 31.32$, $p < 3\text{e}{-08}$, thus replicating the effect reported in Section 3.1.3, obtained with a subset of the data analysed here, and with a different set of covariates. Again, the slope variance was taken into account, with a significant improvement in the goodness of fit of the model, $\chi^2 = 10.57$, $p < .002$. The effect visible in Fig. 1b translated into a significant effect, with a regression coefficient of −6.7 ms, $t = -3.48$.

3.3.4. Interactions

The independence of semantic relatedness, relative to depth of embedding was tested. The corresponding interaction term did not reach significance ($t = -1.63$, n.s.), thus suggesting independent contributions. There was however a marginally significant rank-by-embedding interaction ($t = 2.00$) corresponding to a decreasing influence of embedding as the position of the target word in the sentence increased.

4. General discussion

Inspection times in reading are subject to various sources of influence that can be characterised to differing degrees as intrinsic to a given target word or "contextual". Although the focus of the present study is on context effects, a first group of factors, generally thought to operate at a purely local level, was included as a baseline. Their role, already well documented in the literature, is briefly discussed below.

Word frequency is known to have a powerful effect on first fixation duration, and word length is a significant determinant of refixation probability and gaze duration (Altarriba et al., 1996; Henderson & Ferreira, 1990, 1993; Inhoff & Rayner, 1986; Kennison & Clifton, 1995; McConkie, Kerr, Reddix, & Zola, 1988; Raney & Rayner, 1995; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner, 1977; Rayner, Fischer, & Pollatsek, 1998; Rayner, Sereno, & Raney, 1996). Unsurprisingly, such effects are found in the present study as well. The shorter the target word and the higher its frequency, the less time was spent processing it. Inspection time also varied as function of saccade size and landing position (linear and quadratic trends), reflecting the fact that within-word inspection strategies critically depend on the properties of the saccade entering it: first fixation is longer and refixations are less numerous as the eyes land closer to the middle of the word (O'Regan, Pynte, & Coëffé, 1986; Vitu, McConkie, Kerr, & O'Regan, 2001); and more preview benefit can be obtained when an incoming saccade is short (Radach & Heller, 2000; Vitu et al., 2001; but see McDonald, 2005). Finally, inspection times varied as a function of the frequency of the immediately prior word, in line with a number of prior studies (Ehrlich & Rayner, 1981; Henderson & Ferreira, 1990; Rayner & Duffy, 1986). The interpretation of such spillover effects is still subject to debate (see Kliegl et al., 2006, for a discussion). In serial processing models of reading such as the E–Z reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 2003), they have classically been interpreted in terms of covert-attention switch, so that the parafoveal word would benefit from some preview before being overtly inspected. A low-frequency prior word will take longer to identify, with consequently less time available for parafoveal processing (and less preview benefit obtained on the target word).

The effects discussed above can all be attributed to perceptual and/or processing constraints (i.e., determined by the size of the perceptual span or by the timing of lexical processing). Inspection time has also been shown to depend on target "predictability", a notion which actually covers a variety of potential sources of influence, likely to operate at different processing levels. In the rest of this discussion, we successively examine local semantic constraints, as assessed by wLSA scores (see Section 2), whose influence was assumed to show up at the lexical-access level, and sentence-level semantic and syntactic constraints (sLSA scores, depth of embedding), assumed to tap at a post-lexical integration level.

In line with McDonald and Shillcock (2003a, 2003b), early local contextual influences were observed in the present study. Both single-fixation and gaze durations recorded on the target word significantly decreased as its semantic relatedness to the prior word, as assessed by wLSA scores, increased. Given the nature of the relatedness index used in the present study, the simplest interpretation of the observed effect is in terms of semantic priming. In lexical decision tasks, response time has been shown to decrease when a given target (e.g., the word "nurse") is immediately preceded by a semantically related word (e.g., "doctor"), as compared to a control condition in which the target is preceded by a neutral prime (Meyer & Schvaneveldt, 1971). Such effects have generally been interpreted in terms of spreading activation within a semantic network (Collins & Loftus, 1975). Activation from the prime would lower the amount of perceptual information necessary for the target word to be identified. In this view, the locus of the observed effect would thus have to be looked for in target word recognition processes. It is important to note that an inter-lexical association effect was obtained even though target words were included in quite long and coherent texts. An interpretation in terms of a lack of higher-level coherence (see Camblin et al., 2007) can thus be discarded. Moreover, the observed effect was found to be independent of sentence-level contextual constraints, as assessed by sLSA scores, suggesting that local inter-lexical association could be responsible for part of the early predictability effects reported in the literature.

Word-level semantic relatedness also exerted a backward influence on the time spent inspecting the prior word. In line with McDonald and Shillcock (2003b), we suggest interpreting the obtained facilitative backward effect in terms of parafoveal-on-foveal cross talk (Kennedy, 2000; Kennedy, Pynte, & Ducrot, 2002; Pynte, Kennedy, & Ducrot, 2004). However, since a backward effect was only visible on gaze duration (the regression coefficient for single-fixation duration is close to zero), one can question whether early recognition processes were involved. The effect was apparently driven by refixations, possibly occurring after identification completion. The locus of the effect may thus be looked for at some post-lexical level (relative to word $n-1$). Semantic relatedness is a property of both the prior and target words (the measure provided by wLSA scores is in fact symmetrical), and the fact that an effect was observed on both words points to a common mechanism, initiated at some point during the visual inspection of the prior word, and completed during the visual inspection of the target word.

Our results also indicate that the time spent inspecting a given target word is affected by more remote sources of influence, defined over a sequence of several words, and dependent on the position of the target word, relative to the other words of the sentence. Gaze duration decreased as the sLSA score associated with the target word increased, and this effect cannot be explained in terms of word-to-word parafoveal interactions, since most of the words included in the computation of sLSA scores were no longer in the visual span when the target word was being inspected (it should be kept in mind that the immediately prior word was not taken into account). Whether the observed effect can be assimilated to a classical predictability effect can be questioned, however. An influence of sLSA scores was only visible on gaze duration, suggesting that relatively late integration processes are involved. This outcome contrasts with prior findings, obtained with a measure of contextual constraints based on the classical Cloze task (Kliegl, 2007; Kliegl et al., 2006). Moreover, no sentence-level backward effect was observed here, also in contrast with Kliegl et al.'s results.

The reason for these discrepancies may be found in the nature of the constraints that LSA scores are likely to capture. These may not be strong enough to produce the forward facilitation that Kliegl et al. observed on single-fixation duration, the backward facilitation that they obtained for gaze duration, and the rather paradoxical increase in single-fixation duration that they obtained on the prior word in conditions of high predictability. Another possible reason for the observed discrepancy may stem from the distinction introduced in the present study between word-level and sentence-level contextual constraints (and the fact that the prior word was thus excluded from the computation of sLSA scores). Part of the backward effects found in prior studies might be imputable to the word immediately to the left of the target. Another important difference concerns the class of the target word itself. As indicated in Section 2, LSA scores are of little interest in the case of function words, because they occur in innumerable contexts and their presence is far more powerfully determined by syntactic constraints than by the topic of the sentence. For this reason, the defined target was always a content word in the present study. On the other hand, Kliegl (2007) has recently reported that backward effects of predictability (lengthening of prior-word single fixation) may be stronger when the target word is a function word. Clearly, this may be the source of the discrepancy between the two sets of results. Cloze predictability may be a better predictor than LSA for constellations involving function words.

Finally, the effects that we failed to replicate may be driven in part by syntactic constraints. As already mentioned, LSA is totally syntax-blind, and this may be the main reason why only relatively late sentence-level influences were found in the present study. Syntax did exert an influence, as indicated by the significant decrease in gaze duration observed for deeply embedded target words. Note however that this depth-of-embedding predictor exerted its influence independently from semantic relatedness, which suggests that different kinds of mechanisms may be involved. The tentative explanation that we propose here is in terms of reading strategy. Most of the deeply embedded words were probably in a position of modifier (e.g., member of a preposition phrase, adjectival phrase, relative clause, etc.) and were thus less central to the main topic of the sentence than less deeply embedded words. For this reason, they may have received less attention, with less time devoted to high-level integration processes.

To summarise, word-level semantic constraints were found to exert both forward and backward influences (only for gaze duration in the backward case), whereas only forward sentence-level effects were visible, and only for gaze duration. Gaze duration was also found to be sensitive to the depth of embedding of the target word in the syntactic structure. Although local inter-word associations seem to be responsible for most of the early effects (e.g., affecting the lexical-access level), higher-level processes can apparently exert an influence of their own, at a post-lexical integration level. Both sentence-level semantic relatedness and depth of embedding were found to exert an immediate and independent influence on gaze duration, suggesting that the eye-movement control system may be sensitive to both semantic-integration and syntactic-parsing processes. Together with wrap-up effects occurring at clause and sentence boundaries and other occasional disruptions, the effects described in the present study contribute to drawing an integrated picture of high-level influences in reading, with both on-line and occasionally delayed effects.

Appendix A. LSA scores

Building up the semantic space. "Latent Semantic Analysis (LSA) is a corpus-based statistical method for inducing and representing aspects of the meaning of words and passages reflected in their usage" (Landauer, 2002). A representative sample of French text (a set of novels representing 14.7 million words and a set of film dialogues representing 16.6 million words, see New et al., in press) was collected and divided in 100-word passages. All words were submitted to lemma transformation. This corpus was then converted to a word-by-passage occurrence matrix, with each cell containing the log of the frequency of a given word in a given passage. The matrix was subsequently submitted to singular value decomposition (Berry, 1992), a method close to eigenvector decomposition, and the number of its dimensions was reduced to 300. According to Landauer (2002), it is this dimension-reduction step that extracts semantic similarities between words, via "a method of global constraint satisfaction" (i.e., from mutual constraints among words and contexts).

Computing LSA scores. Once the semantic space has been built up in this way, any word, whether present in the original corpus or not, can be represented as a 300-dimensional vector, and it is straightforward to compute the similarity between vectors by means of the cosine function. This was done for each pair of adjacent words in the Dundee corpus, thus providing a semantic distance between each target word and the word immediately to its left (wLSA scores). Similarly, any sentence fragment, whether present in the original corpus or not, can be represented as a vector in the same semantic space: LSA's representation of a sentence fragment is just the average of the vectors of the words it contains independent of their order. The distance between each word in the Dundee corpus and the sentence fragment located to its left (minus the immediately prior word) was thus computed, again using the cosine function (sLSA scores). sLSA scores, like wLSA scores were computed after lemma transformation of all the words in the Dundee corpus and were subsequently submitted to log transformation. It may be important to note that a high wLSA score can be obtained, even though the two words do not co-occur in the original corpus, if they statistically co-occur with similar words. In the same way, a high sLSA scores can be obtained if the target word and the words contained in the prior sentence fragment statistically co-occur with similar words.

Selecting data. LSA scores computed for function words are of little interest here, simply because such words can be found in any context. For this reason, only content words (either nouns, verbs or adjectives) were selected as target words and submitted to regression analysis. Moreover, for all analyses involving wLSA scores, only those cases where the prior word was itself a content words were considered, the data set being thus reduced to pairs of adjacent content words.

Appendix B. Correlation between predictors

	Freq.	sLSA	wLSA	Lgth-1	Freq.-1	Embed.	Rank
Length	−0.42	0.25	0.23	0.12	−0.10	0.20	0.07
Freq.		−0.33	−0.14	0.04	0.02	−0.06	−0.02
sLSA			0.34	−0.02	0.02	0.22	0.25
wLSA				0.19	−0.20	0.12	0.03
Lgth-1					−0.47	0.06	0.00
Freq.-1						−0.08	−0.02
Embed.							0.58

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