

Word skipping:
Implications for theories of eye movement control in reading¹

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Abstract

When proficient readers are reading English texts, about one third of the words are skipped. In this chapter, we review the different explanations that have been proposed. We also have an in-depth look at the variables that influence word skipping. These are: errors in the programming and execution of a saccade, the length of the upcoming word $n+1$ in parafoveal vision, the distance from word $n+1$ relative to the current fixation location (also known as the launch site), and the difficulty of word $n+1$ within the sentence. We provide evidence that the effects of word length and distance cannot be explained by assuming that word $n+1$ is skipped only when it has been identified in parafoveal vision. Rather, readers often seem to make an educated guess about where to send the next forward saccade on the basis of incomplete information. If this guess turns out to be incorrect (and a difficult word has been skipped inappropriately), an immediate correction follows. This is either a regression to the skipped word or a longer fixation duration. In that way, eye movements remain closely coupled to the ongoing language processing.

Word skipping

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Introduction

Eye movements in reading are characterized by short periods of steadiness (fixations) followed by fast movements (saccades). Saccades vary from 1 to 18 letter positions and are needed to bring new information into the centre of the visual field where acuity is highest. Fixations take some 150-300 ms and are required to identify the words. Assuming that the fixated word is recognised by the end of the fixation, it is tempting to think of eye movements in reading as a sequence of word-to-word movements, with the eyes starting from the first word of a line, going to the second word, the third, . . . , and so on until the end of the line is reached, at which point a return sweep is made to the first word of the next line and the whole cycle starts over again. Unfortunately, such a simple sequence of movements is rarely observed in empirical data. Many words are fixated more than once, are initially not fixated but immediately afterwards regressed to, or are not fixated at all. Ever since the first measurements of eye movements in reading, researchers have been puzzled by this complicated pattern of activity and suggested various explanations. In this chapter, we will focus on one aspect, namely the fact that when proficient readers are reading an English text, their eyes are never directed at about one-third of the words.

Before we discuss the different explanations of word skipping and the available empirical evidence, it may be good to state explicitly that in eye movement control there are two decisions to be made: When to initiate an eye movement, and where to send the eyes to? There is substantial evidence indicating that these “when” and “where” decisions are largely independent of one another (e.g., Rayner & Sereno, 1994; Rayner & Pollatsek, 1989). The decision of **where** to fixate next is partly determined by the length of the words to the right of fixation and partly by the ongoing language processing. If word or text comprehension are experiencing difficulties, a decision is made either to refixate the currently fixated word or to regress to a previous part of the text (some 14% of the eye movements in text reading are regressions). If text comprehension is running smoothly, the eyes are sent to one of the words to the right of fixation, either to the first word or to a word further down the line (in which case one or more words will be skipped). When a forward saccade is made, it is generally assumed that the eyes are programmed so that they will land between the beginning and the middle of the target word. The actual landing position depends on a number of factors such as the launch site, the features of the first letters of the word, and the position of the word within a line of text. The landing position is closer to the word beginning when the eyes were launched from a long distance (see below), when the first three letters of a word form a rare combination (as in *awkward*; Underwood, 2003, White & Liversedge, 2004), and when the word is situated towards the end of a line of text (Vitu & McConkie, 2003).

There are two different views about what drives the decision of **when** to move the eyes. The dominant view is that this depends entirely on the ongoing word processing: The decision to move the eyes is taken only when the processing of the currently fixated word has reached a certain level (Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2003). The alternative view is that a significant proportion of saccades are triggered autonomously

after a certain time delay and that the influence of the ongoing text processing is limited to an inhibition of the automatic signal or to determining the place where the eyes are sent to (Engbert, Longtin, & Kliegl, 2002; Yang & McConkie, 2001).

Needless to say, the issue of word skipping deals with the where decision, and in particular with the where decision related to first-pass, forward, interword eye movements. These are saccades directed to words to the right of the current fixation location, that have not been read yet (i.e., that are not part of a line of text which is reread after a regression). Although this decision is an important component of eye movement control in reading, it is obvious that any explanation of it should be integrated within a larger, comprehensive model of eye movement control in reading. We will start our discussion with a short overview of the various ideas that have been proposed to explain why so many words are skipped in text reading.

Word skipping in different models

The loose relation between eye movements and text lay-out made many of the first researchers believe that eye movements were controlled by an autonomous oculomotor control centre (e.g., Buswell, 1920; Erdman & Dodge, 1898; Huey, 1908). According to this view, saccade sizes were more or less constant and only changed as a function of the global difficulty of the materials being read. Variations in saccade size resulted from noise in the oculomotor system and adjustments to the difficulty of the text. As for word skipping, this implied that the probability of skipping a word depended on the overall easiness of the text but not on the easiness of the word itself.

The autonomous oculomotor control model remained the dominant model until the middle of the 1970s, although some refinements were added. For instance, Bouma and de Voogd (1974; see also Shebilske, 1975) attributed changes in saccade size to the limited capacity of an input buffer which could contain but a few activated word units. When the buffer became overloaded, saccade sizes decreased. Gradually, however, the possibility of word-based influences on the probability of word skipping began to be taken into account. In his cognitive and peripheral search guidance theory, Hochberg (1975) still maintained that eye movements were primarily determined by pre-established scanning routines independent of the linguistic information extracted at each fixation, but these routines depended on both the readers' knowledge of the language constraints and on the task they set for themselves when reading. If the task required paying attention to the letters and the spelling of the words without paying attention to the meaning (proofreading), readers were assumed to adopt a letter-by-letter or word-by-word scanning routine. If, however, the reading purpose was to extract meaning from the text, then larger saccades were made in order to reduce the number of samples per line. In that case, the size of the saccades was controlled by peripheral search guidance mechanisms. At each fixation, readers anticipated what they would find next on the basis of the meaning and the grammatical status of the words read so far and on the basis of global visual information extracted from parafoveal vision (such as the next word's length). Readers directed their eyes to those parts of the text that seemed to be the most informative to test their predictions. So, according to Hochberg, the size of a saccade depended on the text difficulty and redundancy (which affected a word's predictability and the size of the perceptual span), and on the reader's ability to extrapolate upcoming information and to process parafoveal information.

A similar reasoning can be found in Shebilske (1975). Saccade sizes were mainly determined by the capacities of the input buffer (see above), but on some instances the on-going text processing could intervene. If both the overall meaning of the words read on previous fixations and the visual information extracted from the parafovea (such as the next word's length) made the next word highly predictable, then the automatic oculomotor program could be interrupted and the word skipped. This could occur independently of the state of the internal buffer. So, discourse based word skipping was possible when the word was highly predictable from prior context and when the parafoveal visual information was compatible with the prediction.

In the late 1970s, the idea that word skipping did not happen at random but was determined by the probability of the parafoveal word being identified on the previous fixation was promoted in a series of highly influential papers. Rayner (1978) and McConkie (1979) hypothesized that saccade lengths were determined by the size of the perceptual span. The perceptual span is a 16-letter region around the fixation location in which the letters are visible enough so that words can be identified. At each fixation, the upcoming saccade was directed to the word in the text that was not clearly visible from the current fixation location. The position of this word depended on visual acuity constraints, but also on the difficulty of the words involved (i.e., their predictability on the basis of the preceding text and their frequency of occurrence).

The word-identification account of word skipping was further developed in a series of papers by researchers from the University of Massachusetts (UMass), who put forth a sequential, attention-based model of eye movement control in reading (Henderson and Ferreira, 1990; Morrison, 1984; Pollatsek & Rayner, 1990; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle et al., 2003). In the original version of this sequential attention-based model (Morrison, 1984) it was assumed that at the beginning of the first fixation attention was focused on the word in foveal vision (called word n). As soon as this word was identified, the attention beam shifted towards the next word $n+1$ and that word started to become processed. The shift of attention triggered the programming of a saccade to word $n+1$, which could only be executed after a programming time of some 150 ms. If during this time, processing of the word $n+1$ was completed fast enough, the program of the original saccade to word $n+1$ could be cancelled and replaced by a saccade to word $n+2$, to which the attention beam had shifted meanwhile. If processing of word $n+1$ was not finished rapidly enough, then the saccade to word $n+1$ was executed and no word skipping took place. Because in this view word skipping depended on the speed with which word $n+1$ could be processed, the model predicted that more word skipping would be observed for easy words than for difficult words. Easy words are high-frequency words and/or words that are highly predictable from the preceding context. Difficult words are low-frequency words and/or words that are not expected on the basis of the text read thus far. Evidence in favour of this prediction was reported by Ehrlich and Rayner (1981) and Balota, Pollatsek, and Rayner (1985).

Morrison's (1984) sequential attention-based model was subsequently implemented in a computer model of eye movement control in reading, the so-called E-Z Reader model (Reichle et al., 1998, 2003). A major change introduced at this stage was that the programming of an eye movement started not when the fixated word n was fully identified

(and the attention beam shifted to word $n+1$) but some 100 ms earlier when a familiarity check indicated that the fixated word was likely to be recognised shortly. This change was needed to finish the various processes within a normal fixation duration. The fact that the saccade programming and the shift of the attention beam were to some extent decoupled, also allowed the authors to account for the spill-over effect. This effect refers to the fact that the first fixation duration on word $n+1$ tends to be longer after a difficult word n than after an easy word n (presumably because there is less time between the shift of attention and the eye movement for a difficult word n than for an easy word n).

The various versions of the UMass model have dominated eye movement research over the last two decades, but in recent years other language-related models of eye movement control have gained impetus (Engbert et al. 2002; Reilly & Radach, 2003). The origin of these contenders lay in some unease with the strong sequential assumption of the UMass model. In the UMass model, words are selected and identified one at a time by the attention beam. However, there is evidence that such early, attention-based selection may not be possible. When in a visual word recognition experiment a foveally presented target word is accompanied by a parafoveal flanker word, there are indications that the parafoveal word is processed even though the attention beam never is directed towards it. Fuentes and Tudela (1992), for instance, in a lexical decision task showed that the processing of a foveally presented word is faster when it is semantically related to a parafoveally presented word on the previous trial. This suggests that a parafoveal word may be processed in parallel with the foveal word, but with some time delay because of the lower visual acuity in the parafovea and the slower projection pathways from the parafoveal retina to the language centres in the brain. According to the new, parallel-processing view, three or four words become activated in parallel and compete as the target for the next saccade. Their strength of attraction increases up to a certain threshold level, and then decreases again (because the word is almost identified). The speed with which the attraction strength increases, and the threshold level it has to reach depend on the frequency of the word and its predictability from the context. Thus, high-frequency words and/or words that are highly expected on the basis of the preceding part of text, will exceed their threshold value and start to decrease in attraction strength sooner than words that are less easy to recognise. As a result, high-frequency words and/or highly-predicted words may have less pulling power to be the target than the word next to them by the time the next saccade is programmed and, thus, will be skipped. Engbert et al. (2002) wrote a computer model on the basis of these principles (called the SWIFT model) and showed that it accounts for human eye movement data in reading as well as the E-Z Reader model does.

Although language-related views of word skipping are dominant nowadays, the idea that word skipping may be controlled by non-linguistic strategies has not completely vanished. For instance, Just and Carpenter (1980, 1987) argued that saccade sizes were independent of the ongoing discourse processing and were programmed so that the eyes fixated every word and landed between the beginning and the middle of these words. The hypothesis was that the information that could be extracted from the parafovea was not detailed enough to identify an upcoming word and simply served to locate the target for the next saccade. The only exception occurred when the eyes were located at the very end of a word and the upcoming word was a short, high-frequency word (e.g., a function word). In that case, the parafoveal word could be skipped because it had been recognised. So, according to Just and Carpenter, word skipping was largely independent of the easiness of the parafoveal word, and the variability in saccade sizes mainly resulted from visual and

oculomotor factors. Just and Carpenter's view on landing sites is surprising, if one considers how high-level the rest of their theory of eye movement control in reading was. This is a particularly clear example of how strongly the ideas about the when and the where decisions can differ within a theory.

Another prime example of a non-linguistic view of word skipping can be found in O'Regan's (1990, 1992) strategy-tactics theory. According to this view, forward interword saccades are always aimed at the centre of one of the upcoming parafoveal words. Which word is selected, depends on the length of the words and their distance from the current fixation position. The most detailed proposal of this selection process has been made by Reilly and O'Regan (1998). They tried to simulate McConkie, Kerr, Reddix, and Zola's (1998) empirical findings of the landing site positions (see Figure 1 below) with four different computer models. The first computer model simulated a word-by-word reading strategy, in which the target word always was the first word to the right of the fixation location. The second computer model was based on a strategy in which the target word was the longest word in the 20-letter window to the right of the fixation location. The strategy of the third computer program consisted of skipping words as a function of their frequency. Finally, the fourth computer program was based on an implementation of Morrison's (1984) sequential attention model. Reilly and O'Regan (1998) observed that the second computer program yielded the best fit: The empirical data were best predicted by a strategy that consisted of simply choosing the longest word in the parafovea, without any further identification of the words involved. The computer program based on a word-by-word strategy performed poorly, because it predicted many more short saccades than were observed in the human data. The sequential attention model underestimated the skipping rates because there was not enough time to complete all the stages needed for word skipping.

Brybaert and Vitu (1998) also pointed to the time constraints that seriously limit the possibility of language-related influences on word skipping. It is well-accepted that visual signals at the centre of the visual field require at least 50 ms before they can start to activate word representations in the brain (e.g., Pynte, Kennedy, & Murray, 1991). In addition, saccade programming time is assumed to require some 100-150 ms, although there is evidence that a programmed saccade can be cancelled up to 70 ms before the initiation of the movement (Deubel, O'Regan, & Radach, 2000). Given a fixation duration of 250 ms, this leaves a time interval between 50 and 100 ms (250-50-100/150) for a foveally presented word to determine the target of the upcoming saccade, and a time interval of some 130 ms (250-50-70) to cancel an upcoming saccade. These are the time constraints for foveally presented words. However, there is evidence that words presented in the parafovea require more time to activate word representations in the brain, partly because there are less receptors in parafoveal vision and partly because projection times from the retina to the brain are slower. One estimate of the extra time needed before parafoveal input can activate word representations in the brain is 90 ms per degree of eccentricity (Rayner & Morrison, 1981). This means that a parafoveally presented word at a distance of 7 letter positions (2 degrees of eccentricity) from the fixation location requires an extra 180 ms before it can be identified. This is more than the maximum time interval that is available within a fixation to influence the target of the upcoming saccade. Reichle et al.'s E-Z Reader model (1998, 2003) addressed this criticism by introducing the notion of a familiarity check in order to speed up the saccade programming, but even this model has been criticised because the information from a parafoveal word cannot reach the brain

in time to cancel the saccade to word $n+1$ and replace it by a saccade to word $n+2$ (see the comments by Findlay & White, Radach et al., and Sereno et al. to the Reichle et al. (2003) target article in BBS). The E-Z Reader model requires fixations that are on average 60 ms longer when word $n+1$ is skipped than when it is not skipped.

Because parafoveal word information requires a long time before it can influence the target of the next saccade, Brysbaert and Vitu (1998) proposed that within the first 100 ms of a fixation, an educated guess is made about the chances of recognising the parafoveal word $n+1$ based on the length of the word and its distance from the fixation location (rather than on a familiarity check). This initial estimate is used to select the target of the next saccade. When a word (e.g., a three-letter word starting at a distance of three letters from the fixation location) on average has 70% chances of being identified by the end of the current fixation, it will be skipped with a probability of 70%. As in the E-Z Reader model, the programming of the initial saccade can be cancelled up to 70 ms before execution, if the ongoing language processing indicates that the initial estimate was wrong.

Finally, it should be noted that McConkie in more recent publications (McConkie, Kerr, & Dyre, 1994; Yang & McConkie, 2001) also returned to the idea of independent oculomotor strategies during reading. Having found that the probability of word skipping can be predicted rather well by equations that only involve word length and launch site (see below), he started to question the viability of linguistic control theories. Or to put it in his own words (McConkie et al., 1994, p. 325): "..., we have briefly outlined the approach we are taking in our attempt to produce a mathematical model of the eye movements of normal, skilled readers. Our greatest surprise thus far has been to observe how much of the variance in the data can be accounted for with a relatively few parameters, and these often reflecting such low-level variables as word length, eye position in word and launch site."

In summary, there are two different views on word skipping. In the first view, which we will call the autonomous oculomotor scanning strategy, the decision where to move the eyes is based on the visual lay-out of the word blobs in a line of text. A word is skipped, because it is short and/or close to the current fixation location. In the second view, which we will call the language control view, a word is skipped because it has been identified on the previous fixation. Historically, the first view was dominant up to the late 1970s, whereas the second view has received more attention in the last two decades.

Empirical data

In this section we will look carefully at the empirical evidence on which the above models are based. We will deal successively with (1) the existence of oculomotor error in the execution of eye movements, (2) the effects of word length and launch site, and (3) the contribution of language factors such as word frequency and the extent to which a word is predicted by the sentence context. In the last part of this section, we will try to find out the relative importance of visual and linguistic variables, in order to decide which should come first in an acceptable model of interword eye movement control.

Errors in the programming and execution of eye movements

A first factor that influences word skipping is the fact that the eyes do not always land exactly on the intended position. As is true for all biological processes, the programming and execution of eye movements is subject to a certain degree of error. This has been shown most convincingly by McConkie and his group (McConkie et al., 1988, 1994). A typical experiment involved a few participants reading a complete novel, so that analyses could be based on a large number of observations per person. One of the major analyses was the frequency distribution of the initial fixations on a word as a function of the launch site (i.e., the letter position relative to the target word centre, from which the eye movement started). Figure 1 depicts the prototypical findings. There are two main effects. First, the distribution of landing positions is well captured by a Gaussian curve, and second, the mean of the distribution is a function of the launch site. For each launch site one character position farther to the left, the mean of the landing position distribution moves leftward by about a third of a character position. McConkie attributed this to a range error, by which the system tends to overshoot near targets and undershoot far targets.

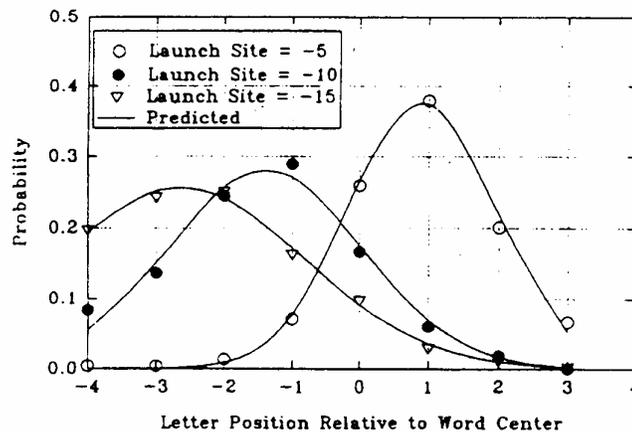


Figure 1 : Frequency distributions of the initial fixations on 7-letter words, following saccades launched from 5, 10, and 15 letter positions to the left of the centre of the target word (reprinted from McConkie et al., 1994).

There is no doubt that any comprehensive model of word skipping has to take into

account the existence of involuntary word skipping due to oculomotor error (as well as the fact that some words are involuntarily looked at because of a saccade undershoot). However, research (in particular, Reilly & O'Regan, 1998) has indicated that not all word skipping can be explained by oculomotor error alone. Some words are skipped, not because the saccade was badly programmed and/or executed, but because there never was an intention to fixate the words. As indicated above, the autonomous oculomotor scanning view claims that such voluntary word skipping happens because a word is too short and/or too close to the fixation location. According to the language control view, such skipping happens because the word was easy enough to be identified in parafoveal vision. In the next part, we will look at the effects of word length and launch site.

Word length and launch site

One of the most conspicuous aspects of word skipping is that it happens more often with short words than with long words. For instance, Vitu, O'Regan, Inhoff, and Topolski (1995) reported skipping probabilities of about 80% for one-letter words, 60% for three-letter words, 30% for five-letter words, and 10% for words of seven letters or longer. Interestingly, virtually the same skipping rates were obtained when the stimulus materials were changed into meaningless z-strings with the same lay-out as the original text, and participants were asked to pretend they were reading these letter strings.

Kerr (1992) was the first to note that the average word length effect hides another, equally strong effect, that of the launch site. Figure 2 shows some typical data. They are drawn from a study in which 24 participants read 120 sentences (see Brysbaert & Mitchell, 1996, Experiment 3 for further details), resulting in a total of more than 22,000 observations for words from two to nine letters. Skipping rate is plotted as a function of word length (2-9 letters) and launch site (1-15 letters; operationalised as the distance in letter positions from the blank space in front of the word). Although a two-letter word on average was skipped in 69% of the cases, this figure ranged from 90% at launch site one (the last letter of the previous word) to some 50% at launch site 15 (when the eyes already skipped one or two words). Similar data have been reported by Kerr (1992), Vitu et al. (1995), and Rayner, Sereno, and Raney (1996). In addition, Vitu et al. (1995) showed that the effect of launch site on skipping rate also applies for meaningless z-strings.

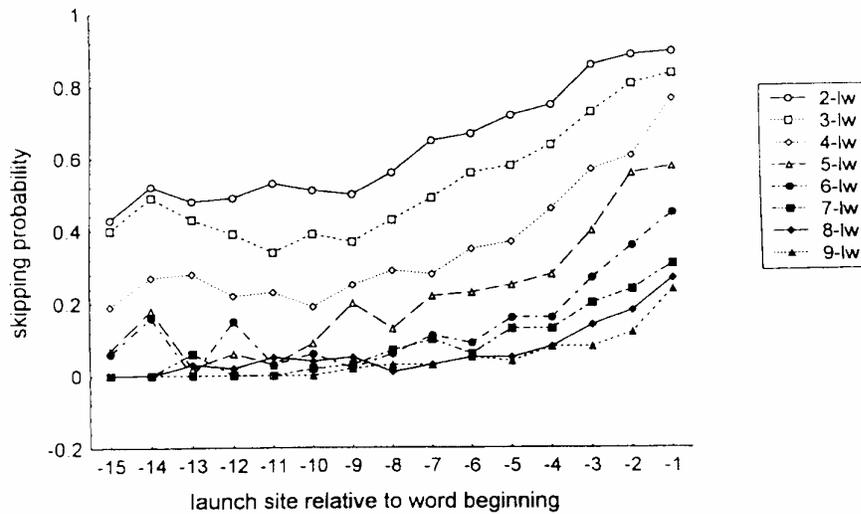


Figure 2 : Word skipping probability as a function of word length and launch site (defined in letter positions relative to the blank space in front of the target word)

It should be noted that the effects of word length and launch site are equally well explained by models that are based on autonomous oculomotor scanning strategies, and models that are based on language control. According to the oculomotor control models, short words and words close to the launch site are skipped because they lie in the area of high visibility around the fixation location and/or because their length and their distance make them less probable targets for a saccade. According to the language control view, short words and words close to the launch site are skipped because they are more likely to be identified before saccade onset. This is again due to the drop of visibility outside the fixation position and, in the case of word length, to the fact that short words in general are easier than long words (e.g., they usually have a higher frequency). In order to decide between both types of theories, researchers have tried to disentangle length and processing difficulty by looking at skipping rates for carefully controlled stimulus words and sentences.

Language factors

The only way to find out whether parafoveal words are skipped because they were identified during the previous fixation is to examine the skipping rate for stimulus materials that are identical except for the difficulty of the target word. Otherwise, it is impossible to disentangle the effects of the oculomotor scanning strategy (which can be a function of the difficulty of the text up to the target word and of the length of the words in front of the target word) from those of the language processing. So, the target words should be of equal length and be presented within the same text. The only variable on which they should differ is their identification difficulty. Target word difficulty has been manipulated in two different ways; either by manipulating the properties of the word itself, or by manipulating the extent to which the word was predicted by the previous words in the

sentence. As not all models predict an equal effect size for both cases (e.g., Hochberg and Shebilske predict a larger effect of contextual constraints than of word difficulty), we will discuss them separately.

Table 1 : Word skipping probabilities as a function of word characteristics

Study	manipulation	Word length	easy	difficult	diff
Blanchard et al (1989) exp 1 & 2	parafov preview	1 to 3 (value used: 2)	0.56	0.43	0.13
		4 to 5 (value used: 4.5)	0.20	0.10	0.10
		6 to 10 (value used: 8)	0.06	0.04	0.02
Pollatsek et (1992)	parafov preview	3 to 8 (value used: 5.5)	0.12	0.10	0.02
Henderson & Ferreira (1990)	word frequency	4 to 7 (value used, 5.5)	0.18	0.18	0.01
Inhoff & Topolski (1994)	word frequency	4 to 7 (value used, 5.5)	0.27	0.18	0.09
Rayner et al. (1996)	word frequency	5	0.20	0.14	0.06
		6	0.19	0.16	0.03
		7	0.13	0.12	0.01
		8	0.09	0.08	0.01
		9	0.06	0.06	0.00
		10	0.08	0.07	0.01
Rayner, & Raney (1996)	word frequency	6 to 9 (value used 7.5)	0.17	0.11	0.06
Rayner & Fisher (1996)	word frequency	5	0.18	0.08	0.10
		6	0.12	0.05	0.07
		7	0.05	0.01	0.04
		8	0.02	0.02	0.00
		9	0.03	0.02	0.01
Altaribba et al. (1996)	word frequency	5.8	0.15	0.12	0.03
Schilling et al. (1998)	word frequency	6 to 9 (value used: 7.5)	0.11	0.07	0.04
Kliegl et al. (2004)	word frequency	3	0.41	0.32	0.09
		4	0.30	0.20	0.10
		5	0.19	0.13	0.06
		6	0.21	0.11	0.10
		7	0.18	0.09	0.09
		8	0.06	0.04	0.02
		9	0.04	0.03	0.01
		means =	0.16	0.11	0.05

We were able to locate 10 studies in which skipping rates were compared for easy and difficult parafoveal words (see Table 1). In eight of these studies, the variable that was manipulated was the frequency of the word. For instance, Rayner and Fischer (1996) compared sentences like "He invested his money to build a *store* and was soon bankrupt." with sentences like "He invested his money to build a *wharf* and was soon bankrupt". In the other two studies, the manipulation was whether the word was visible in parafoveal vision or not up to the moment the eyes crossed the blank space in front of the word. As can be seen, in all studies and for all word lengths, skipping rate was higher or equal in the easy condition than in the difficult condition. This establishes beyond doubt that lexical variables do influence the probability of word skipping. On the other hand, it should be noted that the overall difference in skipping rate is rather small (5%) and tends to be

slightly larger for short words than for long words.

Table 2 : Word skipping probabilities as a function of context predictability

Study	manipulation	Word length	easy	difficult	diff
Ehrlich & Rayner (1981)	context constraint	5	0.41	0.35	0.06
Balota et al. (1985)	context constraint	4 to 8 (mean = 5.2)	0.11	0.02	0.09
Vonk (1984)	pronoun pred.	3	0.40	0.17	0.23
Schustack et al (1987)	context constraint	3 to 8 (value used: 5.5)	0.28	0.16	0.12
Hyoona (1993)	context constraint	7 to 10 (value used: 8.5)	0.04	0.00	0.04
Inhoff & Topolski (1994) exp 1	word consistency	4 to 7 (value used: 5.5)	0.13	0.07	0.06
Brysbaert & Vitu (1995)	pronoun pred.	3	0.49	0.40	0.09
Rayner & Well (1996)	context constraint	4 to 8 (value used: 6)	0.22	0.10	0.12
Altaribba et al. (1996)	context constraint	5.8	0.17	0.11	0.06
Rayner et al. (2001) exp 1	context constraint	4 to 8 (mean = 5.2)	0.30	0.18	0.12
Rayner et al (2001) exp 2	context constraint	4 to 8 (mean = 5.2)	0.23	0.13	0.10
Calvo et al. (2001)	context constraint	4 to 10 (mean = 6.6)	0.09	0.09	0.00
Calvo, & Meseguer (2002)	context constraint	4 to 11 (mean = 7)	0.09	0.07	0.02
Drieghe et al. (2004)	context constraint	2	0.79	0.74	0.05
		4	0.55	0.46	0.09
Kliegl et al. (2004)	context constraint	3 to 4 (value used: 3.5)	0.35	0.29	0.06
		5 to 6 (value used: 5.5)	0.21	0.14	0.07
		7 to 9 (value used: 8)	0.07	0.07	0.00
		means =	0.27	0.20	0.08

Fifteen other studies looked at the effects of contextual constraints on word skipping (see Table 2). Contextual constraints are usually measured by examining how many participants fill in a particular word in a cloze task. For instance, given the sentence "The man decided to shave his _____", participants are much more likely to fill in "beard" (83%) than "chest" (8%) (Rayner & Well, 1996). So, a language control view would predict more word skipping in the former case than in the latter. This is also what was found: In all studies, predicted words were skipped more often than unpredicted words. The mean difference amounted to 8%. The largest effect (of 23%) was reported by Vonk (1984) who (in Dutch) compared sentences like "Mary was envious of Helen because *she* never looked so good.", where the pronoun had no disambiguating value, with sentences like "Mary was envious of Albert because *she* never looked so good.", where the pronoun did disambiguate (in an unexpected continuation of the sentence). Brysbaert and Vitu (1995) used the same materials, but compared sentences with an expected continuation "Mary was envious of Marc because *he* always looked so good." and sentences with an unexpected continuation "Mary was envious of Marc because *she* never looked so good." They found a difference in skipping rate of 9%.

Rayner and Well (1996) pointed out that the difference in contextual constraints between predicted and unpredicted words has to be rather large in order to obtain an effect on skipping rate. For example, in their first experiment Ehrlich and Rayner (1981) had a difference between 93% and 15% continuations in the cloze task and reported skipping rates of 49% vs. 38%. In their second experiment, however, continuations were only 60% and 0%, and no difference in skipping rate was found (twice 32%). Similarly, Hyona (1993) compared conditions of 65% and 32% continuation and found virtually no effect on word skipping (4% vs. 0%). To test the effect of context constraints directly, Rayner and Well (1996) compared three conditions: one in which the target word had been given by 86% of the raters in a cloze task, one in which the target word had been given by 41% of the raters, and one in which the target word had been given by only 4% of the raters. Skipping rates were respectively 22%, 12%, and 10%; that is, virtually no difference was found between the 41% and the 4% condition.

In a final test of the influence of language factors on skipping rates, Rayner, Ashby, Pollatsek, and Reichle (2004) simultaneously manipulated the frequency of the target words and their predictability, to see what the combined effects of these two variables would be. The four conditions are listed below, together with the associated skipping rates:

High-frequency, predictable:	
Before warming the milk the babysitter took the infant's <i>bottle</i> out of the travel bag.	23%
High-frequency, unpredictable:	
To prevent a mess the caregiver checked the baby's <i>bottle</i> before leaving.	15%
Low-frequency, predictable:	
To prevent a mess the caregiver checked the baby's <i>diaper</i> before leaving.	14%
Low-frequency, unpredictable:	
Before warming the milk the babysitter took the infant's <i>diaper</i> out of the travel bag.	16%

The findings of this study are in line with those from the previous studies, because a predictability effect of 8% was found. In addition, however, the Rayner et al. (2004) study suggests that the predictability effect summarised in Table 2 is limited to target words of a reasonably high frequency. When the frequency of the target words is low, predictability is not strong enough to influence the skipping rate.

The relative importance of visual and linguistic variables

Thus far, we have shown evidence for oculomotor, visual, and language-related influences on word skipping. However, it should be noted that much of this evidence is not fully conclusive. For instance, the effects of word length and launch site (Figure 2) are usually reported without reference to the frequency of the words in the different cells. An exception to this can be found in Rayner et al. (1996, Figure 2) who looked at the effects of launch site and word frequency on the skipping rate for five- and six-letter words. They reported independent effects of word length and launch site, together with a frequency effect at close launch sites (up to three letter positions in front of the target word). However, even in this study, the text fragments on which the data were based may have been quite different in the various conditions (e.g., it is not unlikely to assume that certain sequences of word lengths resulted in far launch sites and others in near launch sites, or that high-frequency and low-frequency words appeared in different sequences of word

lengths).

Another question is how to interpret the language effects in Tables 1 and 2. Although these effects are undeniably and consistently there, they seem to be rather small (5-8%), certainly if we compare them to the effects of word length and launch site as shown in Figure 2. Remember that in Tables 1 and 2 we have skipping rates for words that were controlled for their length, that were presented in identical sentences, and that were constructed in such a way as to maximize their difference in processing difficulty (e.g., by having a large difference in frequency or in contextual constraint). So, for these stimuli, any language control model that defines word difficulty primarily in terms of word frequency and predictability, would have to predict that the effect of processing difficulty will be stronger than the effect of word length, because here we do not have the usual confound between word length and word difficulty (due to the fact that short words tend to be easier than long words). For these particular sentences, we would not predict that a difficult (low-frequency or unexpected) three-letter word is skipped more often than an easy (high-frequency or highly expected) five-letter word, because for these sentences the processing difficulty has been manipulated independently of the word length.

The relative contribution of word length and processing difficulty can be determined on the basis of Tables 1 and 2 by running multiple regression analyses with these two variables as predictors and skipping rate as the dependent variable. This is straightforward as the predictors in Tables 1 and 2 are orthogonal.

Although we could have taken the raw values of word length, we opted for an exponential transformation, which has the advantages that larger weights are given to differences between short words than between large words, and that the function asymptotes to 1 (for word length zero) and to 0 (for long words). As it turned out, only one free parameter was needed for a model based on word length (wl) alone. Below we list the equations for the four conditions (the high-frequency and low frequency words from Table 1, and the predictable and unpredictable words from Table 2) together with the variance explained by the model:

High-Frequency words : $P(skip) = e^{-.31wl}$	88% variance explained (27 data)
Low-Frequency words : $P(skip) = e^{-.39wl}$	82% variance explained (27 data)
Predictable words : $P(skip) = e^{-.26wl}$	75% variance explained (18 data)
Unpredictable words : $P(skip) = e^{-.35wl}$	55% variance explained (18 data)

These regression analyses teach us four things. First, when we want to predict the skipping rate of one of the studies listed in Table 1 or 2, knowing the length of the target word helps us a lot to improve our estimate. When the target word is short (e.g., 2 letters), the skipping rate will be high (e.g., $P(skip) = e^{-.31*2} = e^{-.62} = .54$ for the high-frequency words in Table 1). In contrast, when the target word is long (e.g., 9 letters), the skipping rate will be low ($P(skip) = e^{-.31*9} = e^{-2.79} = .06$ for the same type of words). The second thing these regression analyses show, is that word length is a better predictor for the studies of Table 1 than for those of Table 2. The reason for this might be that in Table 1 several

data came from the same studies, whereas in Table 2, there was more diversity in the origins of the data. Third, it can be seen that the difficult conditions resulted in a larger weight of the word length variable. As will be shown in Figures 3 and 4 below, this change in weight means that the skipping probability drops faster as a function of word length for difficult words than for easy words. Finally, the regression analyses show us that the difference between the easy and the difficult condition is not very big, meaning that not much prediction power is lost, if we fit a general model to all the data of Table 1 or Table 2. This is shown below:

High+Low Freq words : $P(skip) = e^{-.34wl}$	80% variance explained (54 data)
Pred+Unpred words : $P(skip) = e^{-.30wl}$	62% variance explained (36 data)

When we run similar regression analyses with the difficulty of the words as a predictor (i.e., D , defined as 0 for the easy condition and 1 for the difficult condition), we get the following results:

High+Low Freq words : $P(skip) = .16 - .05D$	5% variance explained (54 data)
Pred+Unpred words : $P(skip) = .27 - .08D$	5% variance explained (36 data)

The regression analyses on the basis of word difficulty leave little doubt that knowing the difficulty of the words is much less helpful to improve our predictions than knowing the word length (5% variance explained vs. 70% variance explained). Basically, information about word difficulty forces us to predict that all cells in the high-frequency row of Table 1 should have a value of .16 and all cells of the low-frequency words should have a value of .11. Similarly, our predictions of the values in Table 2 are that all cells in the first column have a value of .27 and all those of the second column have a value of .19.

Because word length and word difficulty are orthogonal variables in Tables 1 and 2, we can combine them into a single regression analysis to further improve our predictions. This is shown below:

High+Low Freq words : $P(skip) = e^{-(.31+.08D)wl}$	87% variance explained (54 data)
Pred+Unpred words : $P(skip) = e^{-(.26+.08D)wl}$	67% variance explained (36 data)

The lines in Figure 3 show the predicted values for Table 1 on the basis of the combined regression analysis with both word length and word difficulty as predictor variables. The figure also displays the observed data from Kliegl et al. (2004), Blanchard et al. (1989), Rayner et al. (1996), and Rayner and Fischer (1996). In this figure, we easily see that the predicted probability of skipping a high-frequency 2-letter word (.54 or 54%) is quite close to the value obtained in the Blanchard et al. study (.56). Similarly, we can compare the predicted probability of skipping a low-frequency 5-letter word (.14) to the empirical data reported by Kliegl et al. (.13), Blanchard et al. (.10), Rayner et al. (.14), and Rayner & Fischer (.08). Notice that in Figure 3 (and in Figure 4) skipping rates have been averaged over launch sites, as information about this variable was not available in the articles.

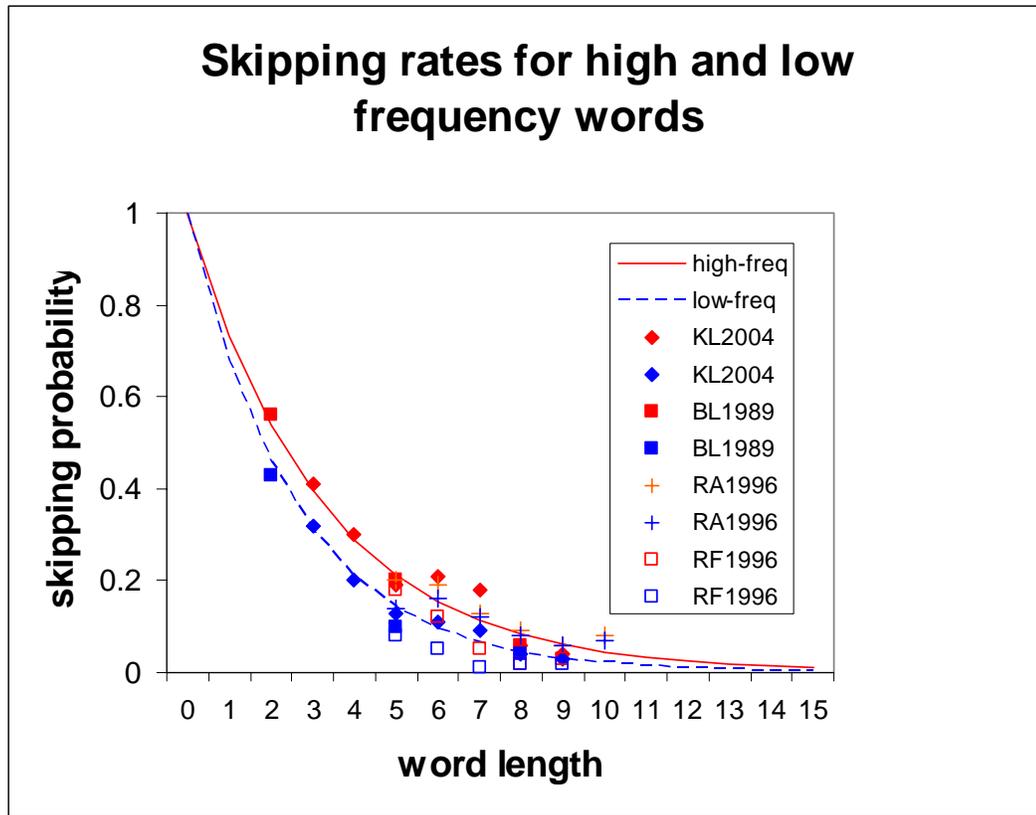


Figure 3 : Skipping rate as a function of word length and word difficulty (blue = easy condition; red = difficult condition). Empirical data from Table 1. Fitted curve based on nonlinear regression with word length and word difficulty as predictors.

Figure 4 shows the information for Table 2. The empirical data that have been included here, are Ehrlich & Rayner (1981), Rayner et al. (2001), Drieghe et al. (2004), Kliegl et al. (2004), and Vonk (1984). The figure shows the larger scatter in these data. At the same time, it illustrates how both word length and word difficulty (predictability) influence the skipping probabilities.

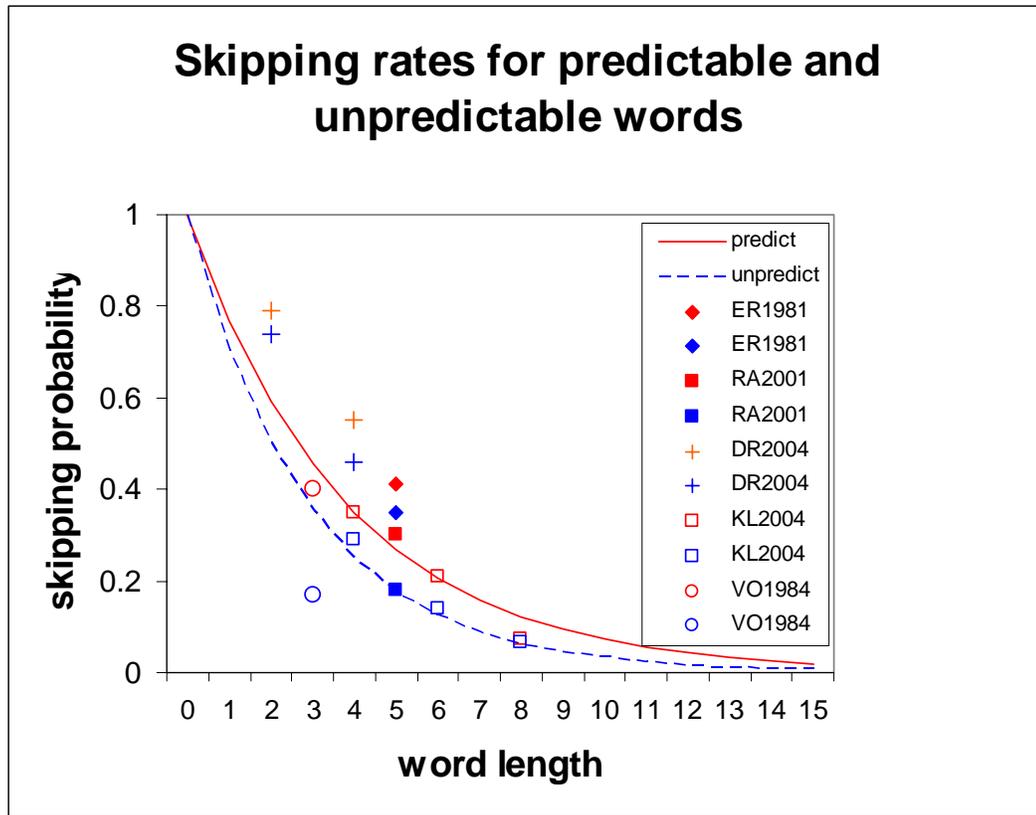


Figure 4 : Skipping rate as a function of word length and context predictability (blue = easy condition; red = difficult condition). Empirical data from Table 2. Fitted curve based on nonlinear regression with word length and context predictability as predictors.

The implications of our findings for theories of eye movement control

Making precise predictions about the impact of word length and processing load

The main conclusion from Figures 3 and 4 is that even for studies which specifically looked at the effects of processing difficulty on skipping rate, word length was a more important predictor of skipping rate than processing load. That is, to predict how often a word was skipped, it was better to know how long the word was than to know whether it was visible in the parafovea, of high frequency, or highly constrained by the preceding context. This is shown quite convincingly in a study reported by Drieghe et al. (2004). In this study, Dutch sentences of the following types were compared (presented together with their associated skipping rates):

1. The robber pointed the gun to the policeman and ordered him to put his hands *up* and face the wall. 79%
2. The robber pointed the gun to the policeman and ordered him to put his hands *in* and face the wall. 74%
3. He was very disappointed in his friends because he felt they had let him *down* when he was in trouble. 55%
4. He was very disappointed in his friends because he felt they had let him *stew* when he was in trouble. 46%

In one half of the sentences, a two-letter word was expected; in the other half, a four-letter

word was expected (82% continuation in the cloze-task; see sentences 1 and 3 for English counterparts of the type of stimulus materials used). In half of the trials, the expected words were replaced by an unexpected word of the same length (0.5% continuation; see sentences 2 and 4). These four types of sentences were then presented to the participants as part of a short paragraph of text, describing a familiar situation. When we look at the skipping rates for the different types of sentence, we see that the effect of word predictability was 7%, in line with the other studies of Table 2. At the same time, however, we see a whopping 26% difference between the two-letter words and the four-letter words. Because of this large effect, the totally unexpected two-letter word in sentence 2 was skipped more often (74%) than the highly expected four-letter word in sentence 3 (55%).

Our regression analyses not only establish the importance of word length and processing load for explaining word skipping rates, they also allow us to make precise statements about the magnitudes of the effects that will be found. On the basis of Table 1 and Figure 3, we can predict that studies which manipulate the difficulty of the target words will find an average difference in skipping rate of some 5%. The effect is maximal for word lengths of 2-4 letters, where it can be as high as 8%. For longer words, the effect is expected to be smaller. Similarly, Table 2 and Figure 4 inform us that a slightly larger difference of 8% will be found when the sentence context is manipulated. The difference will be at its maximum (10-11%) for word lengths of 3-5 letters, and slightly smaller for shorter and longer words. At the same time, the effect of word length can be estimated with the equation $P(\text{skip}) = e^{-.32wl}$, implying that a 2-letter word is expected to be skipped in 53% of the instances, a 4-letter words in 28%, and an 8-letter word in 8% (at least for the type of sentences and situations that have been used in the experiments reported in the Tables, and averaged over different launch sites).

In search of the underlying mechanisms

Although Figures 3 and 4 quite elegantly demonstrate the importance of word length and processing load for the understanding of word skipping rates, we must not forget that they only provide us with a description of the data. They do not tell us which underlying mechanisms give rise to these patterns. On their own, they certainly do not constrain the space of possible models to one single candidate. For instance, it may be possible to produce the curves of Figures 3 and 4 with a computer model of eye movement control that is entirely based on the language control view. If visual acuity outside the fixation location drops steeply enough, chances of identifying words in the parafovea will be a function of the word length rather than the easiness of the word within the sentence. Reichle et al. (2003) claim (but have not shown explicitly yet) that their E-Z reader model predicts a word length effect on skipping rate. The question then is whether the predicted word length effect is of the same size as the one found in the empirical studies listed in the present chapter. Similarly, one could imagine that a model of eye movement control based on the idea that on each fixation multiple words become activated and compete as the target of the next saccade could come up with curves very similar to the ones shown in Figures 3 and 4. This may be possible by implementing a sufficiently strong decrease in the activation gradient (or pulling strength) as a function of the distance from the fixation location.

Alternatively, one can imagine that our data also fit well within an autonomous oculomotor scanning model of word skipping. Such models capitalise on the lengths of the

upcoming word blobs and predict strong effects of word length (and launch site) in the absence of language-related influences. So, it may very well be that Reilly and O'Regan's (1998) strategy of targeting the longest word in the parafovea would result in a word length effect very similar to the one discovered here. Similarly, Brysbaert and Vitu (1998) showed that the word length effect (Figures 2-4) and the launch site effect (Figure 2) can easily be simulated by a simple scanning strategy that is based on the assumption of a normally distributed word recognition probability curve around the fixation location, and that uses this curve to quickly estimate the chances of recognising a word of a particular length at a particular distance by the end of the current fixation. Finally, McConkie (personal comment) rightfully pointed out that the word length data may even be compatible with a much cruder autonomous oculomotor scanning model that simply consists of selecting saccades from a frequency distribution without any attention to the actual word blobs in the sentence. If the selected saccade lengths are sufficiently long, such a blind saccade selection strategy would also predict more skipping of short words than of long words.

Although Figures 3 and 4 on their own may not refute any of the current models of eye movement control, they put strong constraints on the weights that should be given to the different components in the model. As such, they form a benchmark against which the performance of models should be evaluated, in very much the same way as the frequency distributions of fixation durations and landing positions are currently used. A model of eye movement control that does not predict a strong effect of word length and launch site on skipping probability is clearly at odds with human performance. At the same time, a model that predicts a word length effect but no effect of processing load, is at odds with the human data as well. It is our suspicion that all current models will fail on this double requirement. For instance, we believe that both the E-Z reader model and the SWIFT model overestimate the effects of word frequency and word predictability, because these variables have been included explicitly in the model, whereas the word length variable has been considered as a confounding variable (e.g., the E-Z Reader model claims to "successfully" simulate a 60% difference in skipping rate between high-frequency and low-frequency words, when words are averaged over different word lengths; see Figure 6 in Reichle et al, 2003). On the other hand, the models of word skipping that are based on an autonomous scanning strategy readily explain the word length effect (and the fact that very much the same length effect is observed when participants "read" meaningless z-strings), but face difficulties to incorporate the processing load component. Neither Reilly and O'Regan (1998) nor Brysbaert and Vitu (1998) offered detailed proposals about how to implement the effects of word frequency and word predictability in their mathematical models of word skipping. The future will have to show which adaptations must be made to the current models, so that they can account for the exact pattern of data presented in Figures 3 and 4.

What happens after a word has been skipped?

More information about what guides word skipping can be gained from analysing the consequences of such skipping. In a simple model where words are only skipped when they have been recognised in parafoveal vision, the only consequence one would expect is a slightly longer fixation duration following a skip, because skipping a word usually results in a long saccade, meaning that less information from the parafovea could be sampled on

the previous fixation. However, we have seen that this is unlikely to be a true account of human performance. Words are often skipped on the basis of incomplete information, because the initial decision to program a saccade needs to be taken at least 150 ms before the onset of the saccade. So, it may be worthwhile to have a detailed look at what happens when a word has been skipped.

A first informative observation is that quite some eye movements which resulted in word skipping are immediately followed by a regressive eye movement to the very same word $n+1$ that was skipped, sometimes after a short fixation on word $n+2$. Vitu and McConkie (2000) reported 19% immediate regressions to skipped words, compared to 11% immediate regressions to non-skipped words. Needless to say, such regressions are more common after a difficult word has been skipped than after an easy word has been skipped. Drieghe et al. (2004) reported 22% immediate regressions for unexpected words compared to 14% for expected words. This is a first indication that readers in a considerable number of cases immediately correct for word skipping, as if by the time the eyes landed, they realised the previous saccade was not what was needed.

Another observation is that the first fixation after a skipped word, when not followed, by a regressive eye movement, is longer when a difficult word has been skipped than when an easy word has been skipped. Again, this is an indication that readers are able to rapidly assess the consequences of skipping a wrong word.

These two observations are in line with the idea that as far as eye movements between words are concerned, the reader regularly is one saccade “too far” and needs to correct a decision made immediately before. Interestingly, as far as we know, this correction happens instantaneously, on the first fixation after the premature skipping. This is a good example of the tight coupling between oculomotor behaviour and the ongoing language processing. Although the literature on word skipping presents a case where eye movement control and language processing often are one step out of phase, there is no evidence that they ever get two steps out of phase. Apparently, it is more economical for a reader sometimes to make a wrong forward saccade that is immediately corrected, than to adopt a cautious strategy of always targeting the next word unless this word has already been identified (or passed the familiarity check). The most probable reason for the decoupling between language processing and target selection is the time delay between the initiation of a saccade program and its execution. This requires the reader to make “educated guesses” on the basis of incomplete information. The alternative, however, probably would be much slower reading.

Conclusion

It is tempting to think of eye movements during reading as an activity that is completely regulated by either a dumb oculomotor scanning strategy or by the ongoing text processing. In both cases, the pattern of fixations within a line of text seems needlessly complicated.

In this chapter we have reviewed the evidence for both positions with respect to word skipping, and we have noticed that some findings are more in line with the autonomous oculomotor view, and others with the language control view. This suggests that neither

approach at present gives a complete account of the phenomenon. To summarise, it has been established beyond doubt that word skipping depends on four variables: the length of word $n+1$ in the parafovea, the launch site of the saccade, the existence of oculomotor error in the programming and execution of saccades, and the difficulty of word $n+1$ within the sentence. In addition, it has been shown that the effects of word length and launch site cannot be reduced to the probability of identifying word $n+1$ in parafoveal vision. Rather, it looks like the decision to skip word $n+1$ is often based on incomplete information related to the length of the word and its distance from the fixation location.

There are two factors which in our view make that words are regularly skipped without being recognised in parafoveal vision. The first is the long programming time (100-150 ms) of a saccade. This forces the oculomotor system to select the target of the next saccade within the first 100 ms of a fixation. The second factor is the delayed recognition of words in parafoveal vision relative to central vision. This makes that verbal information about word $n+1$ is not available until reasonably late in the fixation.

At the same time, eye guidance in reading is closely linked to the ongoing language processing. Word frequency and word predictability have small but consistent effects on word skipping. In addition, when a word has been skipped without being fully recognised, remedial action follows immediately, either in the form of a regressive eye movement or in the form of a prolonged fixation on word $n+2$. These corrections ensure that eye movement control and language processing are never more than one step out of phase.

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