Orthographic regularity gradually modulates saccade amplitudes in reading

Ralph Radach
University of Aachen, Germany

Albrecht Inhoff
SUNY Binghamton, New York, USA

Dieter Heller
University of Aachen, Germany

The present research tested the hypothesis that variations in the orthographic regularity of word beginnings influence landing positions and amplitudes of interword saccades in continuous reading. Participants were asked to read sentences including target words of low, medium, and high frequency of initial quadrigrams that were either single-root nouns or noun-noun compounds. Saccades landed further into words with more regular beginnings, irrespective of whether the target was a compound word or not. Critically, the orthographic landing site effect was graded, suggesting that orthographic information continuously modulates saccade amplitude before and after the decision to move has been made.

Fluent reading can be seen as a dual task where the main process is the extraction of meaning from print and the secondary task is the planning and execution of adequate oculomotor behaviour. Consequently, information beyond a fixated word is used for two distinct purposes: First, it can be used to initiate letter and word processing before a word is fixated and, second, it can be used to guide the eye movement programming system. In classic research both of these aspects have been related to the concept of the perceptual span. It is the total perceptual span within which word length information critical for saccade programming can be acquired, while letter and word information can only be

Correspondence should be addressed to R. Radach, Institute of Psychology, University of Aachen, Jaegerstr. 17, 52056 Aachen, Germany. Email: ralph@psych.rwth-aachen.de

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extracted from a smaller region around the current fixation, which includes the
fixated word and generally the next (parafoveal) word in the text. This range is
occasionally referred to as a letter identification span (see Rayner, 1998, for a
recent review).

Parafoveal letter and word processing is often quantified in terms of a para-
foveal preview benefit, determined as the difference in fixation or gaze dura-
tion on a target word between conditions with versus without useful parafoveal
target previews. Key results have shown that readers acquire useful orthographic
and phonological information from a parafoveal word. Yet, as shown by
McConkie and Zola (1987), there is a rather sharp drop-off in letter identifi-
cation performance from the centre of fixation toward the parafovea. Related to
this is the fact that more useful parafoveal letter information is extracted from
the beginning letters of a to-be-fixated word in comparison to centre or ending
letters (Briihl & Inhoff, 1995; Inhoff, 1989; Rayner, Well, Pollatsek, & Bertera,
1982).

The second aspect of parafoveal information processing in reading is related
to its use in the control of eye movements. There is broad consensus that the
visual configuration around the current fixation position provides the primary
base for the decision which word should be the target for the next saccade
(O’Regan, 1990; Rayner, Sereno, & Raney, 1996). For example, McConkie,
Kerr, Reddix, and Zola (1988) proposed that text is parsed by routines of low
level vision into an array of low spatial frequency word-objects that the eye
movement control system can select as targets for saccades. The choices that can
be made during this targeting process are quite limited. The most likely alter-
natives are the execution of a refixation on the same word, a saccade to the
adjacent parafoveal word or a saccade that “skips” this word and goes further to
the right. Empirically, this selectivity is reflected in the multimodality of landing
site distributions including cases of refixations, interword saccades, and “word
skipping” (Inhoff & Radach, 2002; Radach & McConkie, 1998). There is a
substantial body of literature indicating that saccade targeting decisions are
codetermined by low-level visual and linguistic processing. One example is the
discussion on the relative contributions of both components to the probability of
fixating a word (see Brysbaert & Vitu, 1998, for a review).

In addition to selecting the next to-be-fixated word, the spatial parameters for
a saccade aiming at this word need to be specified. It is widely assumed that the
intended target position of these saccades is the centre of the selected word. Two
major lines of evidence support this view. One includes results from research on
the processing of briefly presented single words (Brysbaert, Vitu, & Schroyens,
1996; O’Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; Nazir, Heller, &
Sußmann, 1992; O’Regan & Jacobs, 1992; Stevens & Grainger, 2003), indi-
cating the existence of an optimal viewing position at or slightly left of the word
centre. The counterpart of these effects for the case of continuous reading can be
seen in the fact that the probability of refixating the current word follows a
u-shaped function with a minimum at locations close to its centre. This phenomenon was first demonstrated by McConkie, Kerr, Reddix, Zola, and Jacobs (1989) and has been replicated in numerous reading studies (see Vitu, McConkie, Kerr, & O’Regan, 2001, for a recent discussion of issues related to the optimal viewing position in text reading).

However, if the centre of the to-be-fixated word is the optimal target for reading saccades, why are saccade landing positions not distributed accordingly? For example, when an initial interword progressive saccade is made, the peak of the landing site distribution, referred to as the “preferred viewing position” (Rayner, 1979), lies about halfway between word beginning and word centre. McConkie et al. (1988) have proposed that this apparent deviation between optimal and actual landing positions is the result of a small set of basic visuomotor principles. The most important of these principles, termed the saccadic range effect, consists of a tendency for saccades directed at near targets to overshoot and for saccades directed at far targets to undershoot the intended position, with the overall mean being diverted substantially to the left of the centre. For a range of launch sites relative to a target word, there is a linear relation between launch distance and mean landing position. This “landing site function” (Radach & McConkie, 1998) is now generally accepted as a fundamental property of eye movement control and has been implemented in several recent computational models (Rayner, Reichle, & Pollatsek, 2000; Reichle, Rayner, & Pollatsek, 1999; Reilly & O’Regan, 1998; Reilly & Radach, 2003). A second important low-level determinant for landing positions of initial interword saccades is word length. For each 1 letter increment in word length the mean landing position moves about 0.2 letters to the right, whereas for each letter variation in launch site the shift is in the order of about 0.5 letters. The word length effect can be attributed to a centre of gravity phenomenon (O’Regan, 1990; Vitu, 1991). Interestingly, parafoveal word length information appears not to be used to constrain orthographic or lexical word processing (Inhoff, Radach, Eiter, & Juhász, 2003).

If there is consensus about the fact that visuomotor factors are the main force determining saccade amplitudes in reading, the question arises as to whether and how the programming of a saccade to the next word in the text is influenced by linguistic processing. Historically, the notion of linguistic control can be traced back to Hochberg (1970, 1976) who proposed that a process labelled “peripheral search guidance”, together with “cognitive search guidance”, controlled saccade amplitude programming. In the current literature, possible modulations of saccade amplitudes or landing positions as result of linguistic processing are often referred to as “cognitive landing site effects” (Underwood & Radach, 1998).

The hypothesis that linguistic properties of a parafoveal word may modulate the amplitude of interword saccades was first directly investigated in a series of studies by Everatt and Underwood (1992), Hyönä, Niemi, and Underwood
(1989) and Underwood, Clews, and Everatt (1990). For these experiments, stimuli were developed either by dictionary counts or by asking participants to guess words on the basis of their first or last five letters. Stimulus words that were beginning-informative (e.g., “seamanship”) versus end-informative (e.g., “microwave”) were then presented in reading experiments. The main result obtained in these studies was that the eyes landed further into words when the informative part was at the end of the word as opposed to its beginning (see our discussion below for dissenting evidence).

At the time the effect of informativeness was interpreted as a consequence of lexical-semantic processing, claiming that fixations were “attracted” further into words with an informative ending. This position has been criticised on several levels. For example, Hyönä (1993) has questioned the methodology of the experiments, arguing that a number of linguistic variables were not well controlled. For example, in one study by Hyönä et al. (1989) stimulus words with informative beginnings had a productive derivational ending, whereas all words with informative endings were compounds consisting of two noun lexemes (generally referred to as NN-compounds). The proposal that lexical-semantic information may be acquired from the second half of a paraparoleal word and used for saccade amplitude programming is also in conflict with a large body of data on paraparoleal semantic preprocessing in both single word recognition and reading (Balota & Rayner, 1991; Inhoff, 1982; Rayner, Balota, & Pollatsek, 1986; Rayner, White, Kambe, Miller, & Liversedge, 2003).

Hyönä (1993) has proposed “orthographic saliency”, denoting the orthographic regularity of a word beginning as the factor most likely to

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1 It is useful to distinguish between the notions of orthographic saliency and informativeness of a word beginning. Saliency is usually computed as the frequency of the occurrence of a word initial N-gram among all entries (tokens) in a word form count. In contrast, the number of different word forms (types) in which a word initial N-gram occurs can be seen as a measure of informativeness with respect to the lexical identity of the word. As could be expected, token and type n-gram frequencies are correlated in natural text (r = .62 for the initial quadrigrams of the target words used in this study). However, at least for languages like German containing a multitude of derivational endings it may be more appropriate to determine “informativeness” in terms of the number of word stems or lemmata a word beginning corresponds to. Despite these problems of defining an appropriate statistical measure, it appears reasonable from a theoretical point of view to assume that informativeness plays a relatively late role during the time course of orthographic word processing. Thinking in the framework of a multilevel interactive processing model, activation within and feedback from the level of lexical representations will be needed for informativeness to have an effect on further word processing and/or eye movement control.

2 The terms saliency and regularity both carry a certain bias of interpretation. “Saliency” may suggest that a word with a rare N-gram, by definition, should be more noticeable. “Regularity” usually refers to the fact that a word conforms to the rules of orthography, in contrast to an irregular string, hence, the expression “high regularity” is problematic. Since no clear preference for either concept seems to have emerged so far, both terms are used in this paper, with “low regularity” being equivalent to “high saliency” and vice versa.
be able to “pull” the eyes towards a critical region within a target word. He tested this hypothesis in an experiment using three types of stimuli: words with a derivational ending, compound words containing an identical first half but an orthographically less frequent ending, and words with an orthographically infrequent beginning (Hyönä, 1995). The main result was that saccades into words with more irregular beginnings landed about 0.3 letter spaces closer to the left word boundary. Much of this effect was due to fixations made on the space before the target word with a less frequent beginning. The interpretation suggested by Hyönä (1995) is that an extremely rare word beginning leads to a difficulty in parafoveal processing, triggering the occurrence of atypical saccades. The specific version of this hypothesis that he favoured was that instead of attempting to go to the centre of the next word, the system selects the space before the word as a saccade target that is both easy to attain and useful for further processing of the difficult letter cluster. A shift of saccade landing positions towards less regular word beginnings was also reported by Beauvillain, Doré, and Baudouin (1996; see also Beauvillain & Doré, 1998). They used an orthographic decision task involving the recognition of single words displayed to the right of a central fixation mark. In this task saccade landing positions were again further to the left for target words with orthographically irregular beginning characters. A similar effect was also obtained in a recent word recognition study by Kennedy, Pynte, and Ducrot (2002). Another way of looking at effects of orthography on initial landing positions is to introduce misspellings at word beginnings. In this case it is not regularity but the level of irregularity in terms of the difference to correct spelling that is varied. While White and Liversedge (2004) report a substantial leftward shift of landing positions effects for misspelled and thus orthographically illegal word beginnings, Pynte, Kennedy, and Ducrot (2004) did not obtain such an effect.

Reviewing the literature on the issue, Vonk, Radach, and van Rijn (2000) noted that cognitive landing site effects had so far only been obtained in studies where single sentences were presented, whereas attempts to find such effects in studies involving larger amounts of text had failed (Kerr, 1992; Radach & Kempe, 1993). This led them to consider the hypothesis that reading strategies used in particular experimental situations may play a role in the use of linguistic information for saccade programming. To test this idea, they embedded target words with a low versus high frequency initial trigram into story frames with either a neutral or a high degree of contextual constraint. The results were straightforward: There was a clear effect of orthographic regularity, amounting to a shifting of 0.3 letters in the initial saccade landing position to the word beginning for words with less regular trigrams. In contrast, there was no effect of
contextual constraint, a finding that has been confirmed by Rayner, Binder, Ashby, and Pollatsek (2001).\textsuperscript{3}

Another type of linguistic landing site effect appears to have been found by Inhoff, Briihl, and Schwartz (1996) in a study designed to investigate the processing of word morphology in reading and naming tasks. They asked participants to read sentences containing three classes of target words: monomorphemic words (cathedral, arthritis), suffixed words (sainthood, heartless) and compound words with two 3- to 5-letter first constituents (timetable, gunpowder). An unexpected result emerged with respect to the initial interword saccades toward these target words. They went significantly further into compound words (mean landing position 4.4) as compared to suffixed (mean landing position 3.9) and monomorphemic words (mean landing position 3.7). We have recomputed the initial token and the type trigram and the first two bigram frequencies of the target words used by Inhoff et al. with the result that the observed effect is unlikely to be due to differences in orthographic saliency.

An alternative hypothesis that may account for this type of effect was first discussed by Rayner and Morris (1992), who considered the possibility that the initial part of a parafoveal word may be successfully processed and then skipped in some cases, creating the observed small shift in mean landing position. Further results suggesting the possibility of landing site effects on the level of morphemes or lexical constituents of complex words have been provided by Hyönä and Pollatsek (1998). In a series of experiments on the reading of Finnish noun-noun compounds, they found in one experiment that the initial saccade into 12–14 letter target words landed slightly closer to the word beginning when the lexical frequency of the initial constituent was low. To account for this result, they proposed a processing difficulty hypothesis, according to which a parafoveal low frequency word (or lexeme) will narrow down the span of effective preprocessing which in turn will lead to a shorter forward saccade (Hyönä & Pollatsek, 2000).

Looking at the literature, it is obvious that the evidence for cognitive landing site effects on saccades directed to the next word in the text is far from unequivocal. Even in the initial series of studies by Underwood et al. there was one experiment which showed no effect (Underwood, Bloomfield, & Clews, 1988). Using the same set of stimuli, Rayner and Morris (1992) failed to replicate the results of Underwood et al. (1990). In a more recent study,

\textsuperscript{3} There is one paper by Lavigne, Vitu, and d’Ydewalle (2000) suggesting that information on the semantic level may influence interword saccade landing positions. They found that when high frequency target words are in a prime–target relation with preceding words, saccades launched from near distances go further into these words. However, Rayner et al. (2001) did not get such an effect. Even if the Lavigne et al. results could be replicated, they would represent a rather infrequent exclusion in which several circumstances must act together to create an effect that would only very rarely occur in the reading of normal text.
Liversedge and Underwood (1998) attempted to test the hypothesis that a cognitive landing site effect may be increased when syntactic processing load on the foveal word is low and more resources can be allocated to parafoveal processing. However, in one experiment there was no main effect of word beginning saliency (initial trigram frequency) on the landing position of the initial saccade into target words. In a second experiment a small effect emerged only in a subanalysis including items with the shortest versus longest gaze durations in the pretarget region. With respect to the occurrence of higher order linguistic landing site effects, the situation is also contradictory. In contrast to the results of Hyönä and Pollatsek (1998) mentioned above, Andrews, Miller, and Rayner (2004) found no differences in landing positions for NN (noun-noun) compounds with varying lexical frequency.

Given this situation, it is obvious that more empirical evidence on the issue is needed. In addition to contributing to the empirical base for the discussion about cognitive landing site effects, the current study has two specific purposes. The first of these objectives originates from an observation made by Vonk et al. (2000). They varied the regularity of word beginnings in a far less extreme way than Hyönä (1995), who had used a number of loan words whose beginnings are virtually nonexistent in the rest of the Finnish vocabulary. Yet, in the Vonk et al. study a reliable cognitive landing site effect emerged that manifested itself in a shift of the whole distribution of landing sites rather than an increase of fixations at the very beginning of the less regular words. This appears to be in contradiction to Hyönä’s proposal that cognitive landing site effects are due to a discrete deviation from normal oculomotor behaviour in cases where very unusual letter clusters are encountered. However, it does not address the related, more general issue of whether these effects are an exclusion from or, alternatively, part and parcel of normal reading behaviour. Typical for the prevailing view on this issue is the statement by Reichle, Rayner, and Pollatsek (in press) that ‘‘there appears to be general agreement that an orthographically irregular letter cluster at the beginning of a word results in the eyes’ initial landing position deviating toward the beginning of the word’’ [italics added].

The alternative to this position is that orthographic landing site effects are of a graded nature: If there is a medium level of orthographic regularity for a certain class of words, it is possible that differences in either direction would lead to corresponding alterations in mean incoming saccade amplitude. It is quite obvious that such a result would have substantial theoretical implications. To allow for the investigation of this possibility, the present research used a variation of orthographic saliency on three rather than two levels.

The second purpose of this experiment was to reinvestigate the possibility that there are landing site effects at the lexico-morphological level. To this end, two classes of target words were used. One type of targets were morphologically regular single root nouns. The second class of target words consisted of noun-noun (NN) compounds that included four-letter initial lexemes that were
matched on a number of linguistic properties to the first four letters of the single root nouns. In the case of words with medium orthographic regularity, it was even possible to create pairs of regular and compound words with identical initial quadrigrams (e.g., the medium-regular single root noun “Autopsie” and the medium-regular compound noun “Autokino”). Since the orthography of the first half of these two types of words was identical, differences in saccade landing positions between these two types of words could thus be attributed to their morphological structure.

METHOD

Participants

Twenty-four participants, all students at the University of Aachen, volunteered to take part in the experiment or received credit toward the fulfilment of a course requirement. All had normal or corrected-to-normal vision and were native speakers of German. Since the experiment was advertised as a study on semantic sentence processing, all participants were naïve about its purpose.

Materials

A total of 144 German target words served as stimuli, including 72 morphologically simple single root nouns and 72 NN compounds (see Appendix for sample sentences). Word length ranged from 8 to 10 letters with the distribution of lengths being exactly matched in all cells of the 3 (Regularity) × 2 (Word type) design (cell means: 8.7 letters). In the case of the NN composita, the first stem was always four letters long. Word statistics on the orthographic, morphological, and lexical level were computed on the basis of the German CELEX word form corpus (Baayen, Piepenbrock, & van Rijn, 1993). The lexical frequency of the target words was relatively low, with means between 1.04 and 9.42 per million, and did not differ between the cells of the 3 (Regularity) × 2 (Word type) design. For both classes of target words the first four and three letter positions were used to compute the token quadrigram frequency and the token trigram frequency of word beginnings. Within each type of target words there were 24 stimuli with low, medium, and high saliency. As an example, for the regular nouns quadrigram frequency per million tokens was lower than 10, between 11 and 288, and larger than 288 for the low, medium, and high orthographic saliency stimuli respectively (see Table 1 for means and standard deviations). A group of 20 participants who did not take part in the reading experiment was asked to rate potential target words on a 7-point scale of subjective word familiarity from 1 (ubiquitous) to 7 (completely unknown). Only targets that were rated as relatively familiar (cell means between 2.28 and 2.69, no significant differences) were included into the final sample. Since one of the two factors varied in the present design is directly related to morphological complexity, the number of morphological components
TABLE 1
Token frequency of word beginning quadigrams and trigrams, mean ratings of word familiarity and mean number of lexical components for all cells of the 3 (Orthographic regularity) × 2 (Word type) design. Word statistics are based on the German CELEX corpus. Standard deviations are given in parentheses.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Example</th>
<th>Initial quadigram frequency</th>
<th>Initial trigram frequency</th>
<th>Word familiarity</th>
<th>Number of morphological components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nouns</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low regularity</td>
<td>Rhabarber</td>
<td>5</td>
<td>41</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5)</td>
<td>(70)</td>
<td>(0.6)</td>
<td>(0.5)</td>
</tr>
<tr>
<td>Medium regularity</td>
<td>Autopsie</td>
<td>129</td>
<td>369</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(93)</td>
<td>(379)</td>
<td>(0.7)</td>
<td>(0.7)</td>
</tr>
<tr>
<td>High regularity</td>
<td>Geschirr</td>
<td>900</td>
<td>2564</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(747)</td>
<td>(2742)</td>
<td>(0.6)</td>
<td>(0.5)</td>
</tr>
<tr>
<td><strong>Compounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low regularity</td>
<td>Filzstift</td>
<td>5</td>
<td>56</td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3)</td>
<td>(75)</td>
<td>(0.6)</td>
<td>(0.2)</td>
</tr>
<tr>
<td>Medium regularity</td>
<td>Autokino</td>
<td>129</td>
<td>369</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(93)</td>
<td>(379)</td>
<td>(0.7)</td>
<td>(0.2)</td>
</tr>
<tr>
<td>High regularity</td>
<td>Haustier</td>
<td>790</td>
<td>2049</td>
<td>2.4</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(655)</td>
<td>(2746)</td>
<td>(0.6)</td>
<td>(0.2)</td>
</tr>
</tbody>
</table>

(according to the CELEX definition) should differ substantially for the two types of target words. However, within the levels of orthographic saliency, the mean values in this measure were kept nearly identical. Table 1 gives an overview of the cell values for the most important linguistic parameters together with examples for the target words in each condition.

All targets were embedded in one-line declarative sentences with a line width between 71 and 84 characters. The critical words occupied sentence positions between four and six relative to the line beginning. The word preceding the target was an adjective of 5–9 characters length (mean length 7.46 letters, mean lexical frequency 25.4 per million, no significant differences between cells) and the word preceding this adjective was an article. The word length range for the adjectives was chosen on the basis of analysing a large corpus of reading data to maximise the proportion of cases with one fixation on the word before the target. The next word after the target was always a three-letter function word, followed by a noun. Sentences were presented in fixed random order with the constraint that two items belonging to the same condition would not be at adjacent positions within the list. Participants were asked to read at their normal pace such that they would be able to understand the main content of the text. To make sure that readers would follow this instruction, catch trials including sentences with a semantic inconsistency were added and participants asked to indicate the
occurrence of gross irregularities in sentence meaning. These semantic irregularities only became apparent at the end of the respective sentences, whereas the initial part of the sentences that contained the target words was always correct.

Apparatus

Sentences were displayed on a Nokia 19-inch crt monitor running at a pixel resolution of 1024 × 768. Stimuli were shown in dark grey on a white background near the vertical centre of the screen. Text was displayed in non-proportional Courier font such that each letter maximally occupied 15 pixels horizontally and 25 pixels vertically. At a viewing distance of 71 cm, each character subtended approximately 0.33° of visual angle. Eye movements were recorded via an Eyelink I video-based pupil tracking system. Viewing was binocular but eye movements were recorded from the right eye only. The recording system included a high speed video camera positioned below the monitored eye and held in place by head-mounted gear. The system has a relative spatial resolution in the order of a few minutes of arc and its absolute accuracy is better than 0.33°. Its output is linear over the vertical and horizontal range of the display. Fixation locations were sampled every 4 ms and used to determine basic measures of oculomotor activity during reading. The on-line saccade detector of the eye tracker was set to detect saccades with an amplitude of 0.15° or greater, using an acceleration threshold of 8000°/s² and a velocity threshold of 30°/s.

Procedure

Participants were tested individually. To avoid gross head movements, the reader’s head was stabilised by a chin rest. Head position was recorded by an additional head mounted camera and small movements were compensated online. At the beginning of the experiment a one-dimensional horizontal calibration routine was initiated when the participant pressed the space bar of a keyboard. During calibration, the reader was asked to fixate a sequence of three fixation markers as they appeared in fixed order at the horizontal midline of the screen. One of these markers was located near the left side of the screen, one at the horizontal screen centre and one near the right side of the screen. Calibration was immediately followed by a validation routine that determined the stability and accuracy of the initial measurement. Successful calibration was followed by the presentation of a fixation marker, consisting of a plus sign, that was shown at the left side of the screen. A second pressing of the space bar replaced the fixation marker with a line of text which remained visible until the sentence was read, which was signalled by the reader with a second space bar pressing. This self-paced sentence reading procedure was used throughout the experiment. The experimental session consisted of a training block with 28 practice trials including 4 semantically inconsistent sentences. The experimental sentences
were divided into three blocks of 48 items plus 8 inconsistent sentences that were presented in a counterbalanced order. The experiment lasted between 45 and 60 min.

**Data selection and data analyses**

A target word was considered fixated when a fixation fell on one of its constituent letters or the blank space preceding it. Target fixation durations of less than 70 ms and of more than 1500 ms were removed from analyses. Also excluded were trials in which the first fixation on the target word was not preceded by a progressive saccade. Together with cases of blinks or track losses, these restrictions resulted in the rejection of 3.6% of all observations. Saccade landing positions, denoting the letter at which the eye landed, saccade amplitude, consisting of the number of letter spaces the eyes traversed to reach the target, and launch site, consisting of the distance (in letter spaces) between the last fixation location prior to the target’s fixation and the blank space preceding that target, served as dependent variables to test for the occurrence of cognitive landing site effects. Landing positions of incoming saccades were rounded to a tenth of a character before averaging, with the space preceding the target word coded as position 0.1 to 0.9. Two commonly reported measures of target viewing durations were computed: First fixation durations consisted of the duration of the initial fixation on the word, irrespective of whether the target was subsequently refixated. Gaze durations included the time spent viewing the target, including the time spent refixating it during first pass reading, but excluding the duration of saccadic movements (see Inhoff & Radach, 1998, and Rayner, 1998, for discussions of oculomotor measures). Spatial and temporal eye movement parameters were subjected to 3 (Orthographic regularity) × 2 (Word type) analyses of variance (ANOVA) using subject (F1) and item (F2) variability in the computation of error terms.

**RESULTS**

The spatial measures of the saccade that placed the eyes on a target word, launch distance, saccade amplitude, and the resulting initial landing position, together with the duration of the first fixation on the target and the target’s gaze duration are shown in Table 2. As can be seen, orthographic regularity had a profound effect on saccade amplitude specification. This was expressed in a highly significant main effect for landing positions of initial saccades into target words, $F(2, 46) = 11.47, p < .01; F(2, 138) = 5.81, p < .01$, and in a corresponding highly reliable main effect for saccade size, $F(2, 46) = 7.10, p < .01; F(2, 138) = 3.67, p < .05$. Moreover, the orthographic regularity effect could not be attributed to spatial properties of the pretarget fixation, as orthographic regularity had no effect on launch distance, $F(2, 46) = 0.71, p = .50; F(2, 138) = 0.77, p = .46$. 
TABLE 2
Spatial parameters of incoming progressive saccades and viewing duration measures for initial fixations on target words. Standard errors of means are given in parentheses

<table>
<thead>
<tr>
<th>Condition</th>
<th>Landing position</th>
<th>Saccade amplitude</th>
<th>Launch distance</th>
<th>Fixation duration</th>
<th>Gaze duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nouns</td>
<td></td>
<td></td>
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</tr>
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<td>(1.6)</td>
<td>(34)</td>
<td>(76)</td>
</tr>
</tbody>
</table>

In contrast to this, word type did not influence spatial saccade parameters in any of the analyses, including landing position, saccade amplitude, and launch site, all $F$1 and $F$2 < 1. The interaction between orthographic regularity and word type also did not approach statistical significance in the landing position data, $F$1(2, 46) = 1.81, $p = .18$; $F$2 < 1, or saccade size data, $F$1 and $F$2 < 1. There was, however, a marginally significant interaction in the launch site data, $F$1(2, 46) = 2.80, $p = .07$; $F$2(2, 138) = 1.55, $p = .22$. The reason for this marginal effect becomes apparent when looking at Table 2. In the case of low regularity single root nouns, the mean launch position was relatively near, such that the modulation of saccade amplitude had to work against an opposing tendency. Consequently, the difference in landing position was somewhat smaller for simple nouns as for compounds while the difference in saccade amplitude showed the opposite (nonsignificant) tendency.

Initial fixation durations and gaze durations for the target indicated that orthographic regularity and the morphological status of the target influenced the time spent viewing it. Specifically, first fixation durations and gaze durations increased as the orthographic regularity of the beginning letter sequence decreased, $F$1(2, 46) = 12.04, $p < .01$; $F$2(2, 138) = 6.37, $p < .01$, and $F$1(2, 46) = 44.22, $p < .01$; $F$2(2, 138) = 8.56, $p < .01$, respectively. Furthermore, first fixation durations and gaze durations were shorter when the fixed target noun contained one root morpheme than when it was a compound, $F$1(1, 23) = 46.66, $p < .01$; $F$2(1, 138) = 20.89, $p < .01$, and $F$1(1, 23) = 47.79, $p < .01$; $F$2(1, 138) =
17.41, p < .01, respectively. Effects of orthographic regularity tended to be smaller for nouns with a single root morpheme than for compounds but the corresponding interactions did not approach significance in the items analyses, $F1(2, 46) = 2.35, p = .11; F2 < 1$, for first fixation durations, and $F1(2, 46) = 7.10, p < .01; F2 < 1$, for gaze durations.

Supplementary analyses

Landing site distributions are strongly affected by the fixation pattern on the previous word (Radach & Kempe, 1993; Vonk et al., 2000). Even when launch distance is controlled, landing sites are slightly shifted to the right when the prior word has been refixed and are substantially shifted to the left when the prior word has not been fixated (skipped). In the present data in 61.1% cases the prior word received one fixation, in 28.5% cases it was refixed, and in 10.4% it was skipped. To control for possible effects of this factor, the analyses of landing sites and saccade amplitudes were repeated for the subsample of cases with at least one fixation on the preceding word. For these data, the effect of orthographic regularity on landing positions was significant, $F1(2, 46) = 11.85, p < .01; F2(2, 138) = 5.57, p < .01$. The effect of word type was negligible, $F1$ and $F2 < 1$, as was the interaction of orthographic regularity and word type, $F1(2, 46) = 2.10, p = .13; F2 < 1$. Similarly, the regularity of word beginnings significantly influenced saccade amplitude, $F1(2, 46) = 9.22, p < .01; F2(2, 138) = 2.77, p = .06$, but the effect of word type and the interaction of regularity and word type were negligible, all $Fs < 1$. The distance from which the incoming initial saccade was launched was again neither related to regularity, $F1$ and $F2 < 1$, nor to word type, $F1$ and $F2 < 1$, and the corresponding interaction once more did not reach statistical significance, $F1(2, 46) = 2.32, p = .109; F2(2, 138) = 1.05, p = .35$. Overall, this subanalysis thus revealed an even more clear-cut effect pattern than the full set of data. Also, the suggestion of a slightly greater launch distance for saccades toward low regularity nouns with a single root morpheme had disappeared. In a further set of supplementary analyses including only cases where exactly one fixation was made on the preceding word essentially the same pattern of results was obtained. Means and standard errors for observation with at least one and exactly one fixation on the previous word are listed in Table 3.

One further key question about cognitive landing site effects is whether they are restricted to relatively near launch distances or generalise to the full range of launch sites. To address this issue, launch site distributions were computed individually and partitioned such that for each subject approximately half of the observations would fall into a “near” versus “far” launch category. This procedure resulted in mean launch distances of 3.7 letters ($SD = 1.7$) for near launches and 7.8 ($SD = 2.9$) letters for far launches, representing 53% and 47%
of the total data set. Table 4 reports mean landing positions, saccade amplitudes and launch sites for far versus near launch distances.

This supplementary analysis also confirmed the results of the main analyses with effects of orthographic regularity irrespective of launch distance. For near launches, the main effect of orthographic regularity on both landing position, $F(2, 46) = 7.86, p < .01; F(2, 138) = 3.08, p < .05$, and saccade amplitude, $F(2, 46) = 4.98, p < .05; F(2, 138) = 2.61, p = .07$, was significant, while there was no effect of word type: landing position: $F1$ and $F2 < 1; $ saccade amplitude: $F1(1, 23) = 2.40, p = .13; F2(1, 138) = 2.68, p = .10$. The interaction of orthographic and word type properties was also not significant for landing position, $F1$ and $F2 < 1$, and saccade amplitude, $F1$ and $F2 < 1$. In the case of far launches, again, a significant effect of regularity on landing position was present, $F(2, 46) = 9.64, p < .01; F(2, 138) = 3.69, p < .05$, but there was neither an effect of word type, $F1(1, 23) = 1.24, p = .28; F2(1, 138) = 3.46, p = .07$, nor an interaction of regularity and word type, $F1$ and $F2 < 1$. Saccade amplitudes showed a robust regularity effect in the $F1$ analysis, $F(2, 46) = 4.42, p < .05$, and a marginal effect in the $F2$ analysis, $F(2, 138) = 2.15, p = .12$. Word type again did not influence saccade amplitude, $F1$ and $F2 < 1$, and the interaction of the two factors was once more negligible, $F1$ and $F2 < 1$. 

<table>
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<th>Condition</th>
<th>Landing position</th>
<th>Saccade amplitude</th>
<th>Launch distance</th>
<th>Landing position</th>
<th>Saccade amplitude</th>
<th>Launch distance</th>
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<td>5.0 (1.3)</td>
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<td>8.2 (1.5)</td>
<td>5.5 (1.2)</td>
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<tr>
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<td>3.6 (0.9)</td>
<td>8.2 (1.5)</td>
<td>5.1 (1.5)</td>
<td>3.4 (1.0)</td>
<td>8.4 (1.5)</td>
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<td>5.1 (1.5)</td>
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<td>8.6 (1.6)</td>
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<td></td>
</tr>
<tr>
<td>Low regularity</td>
<td>3.4 (0.9)</td>
<td>8.0 (1.6)</td>
<td>5.1 (1.3)</td>
<td>3.2 (1.0)</td>
<td>8.2 (1.6)</td>
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</tr>
<tr>
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<td>3.7 (0.97)</td>
<td>8.3 (1.6)</td>
<td>5.1 (1.5)</td>
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<td>8.3 (1.6)</td>
<td>4.9 (1.4)</td>
<td>3.6 (0.9)</td>
<td>8.4 (1.5)</td>
<td>5.3 (1.2)</td>
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Spatial parameters of incoming progressive saccades for initial fixations on target words computed separately for near versus far launch distances relative to the word beginning. Standard errors of means are given in parentheses.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Near launches</th>
<th>Far launches</th>
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<td>Landing position</td>
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<tr>
<td>(1.0)</td>
<td>(1.3)</td>
<td>(1.3)</td>
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</tbody>
</table>

Spatial distributions of saccade landing positions are depicted in Figures 1 and 2 as a function of orthographic regularity. In addition to exhibiting the typical truncated normal distributions (Rayner, 1979; McConkie et al., 1988) the figures show the expected large effect of launch distance on landing position. For near launches, the mean landing position was 4.2, whereas for far launches incoming saccades on the average landed at position 2.8. Thus, a difference of 4.1 in launch distance (see above) led to a difference in landing positions of 1.4. The proportion of about 0.35 between these two values is in the order of what would be predicted on the basis of results from large corpora of reading data (Radach & McConkie, 1998). More importantly, it is evident from the figures that in both launch distance ranges the effect of orthographic regularity is a graded one; the distributions appear to be shifted as a whole. Only for far launches there is a suggestion of some extra fixations on the first letter and on the space preceding the target word as reported by Hyönlä (1995).

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\[4\] In the present study mean landing positions are computed empirically on the basis of saccades that actually landed on the target word. When taking into account cases of under- and overshooting the target word boundary by estimating the central tendencies of the respective normal distributions, a ratio of about 0.5 between variations in launch distance and landing position would be predicted (McConkie et al., 1988).
Figure 1. Spatial distributions of landing positions for saccades into target words with low, medium, or high orthographic regularity. Data for saccades that were launched from positions relatively near to the left boundary of the target word (mean launch distance: 3.7, standard deviation: 1.7).

Figure 2. Spatial distributions of landing positions for saccades into target words with low, medium, or high orthographic regularity. Data for saccades that were launched from positions relatively far to the left boundary of the target word (mean launch distance: 7.8, standard deviation: 2.9).
DISCUSSION

The main purpose of the current study was to determine the influence of two types of linguistic information, orthographic regularity and morphological word structure, on saccade amplitudes and landing positions in normal reading. Toward this goal, a three-step variation of orthographic regularity was implemented by varying the token frequency of word initial quadrigrams and trigrams while the lexical frequency and familiarity was controlled. An analysis of word viewing time measures showed that this manipulation strongly influenced target processing. When it was fixated, readers spend more time on the target as the degree of orthographic regularity of the target's beginning letter sequence decreased. This confirms earlier studies that also found that words with a rare initial letter cluster require longer viewing durations (Lima & Inhoff, 1985; Vonk et al., 2000). In addition, readers spent more time viewing compound words than words with a single root morpheme, as reported in Inhoff et al. (1996).

Spatial properties of the saccade that reached the target revealed a different pattern of effects. Here, it was of no substantial consequence whether the critical word was a simple noun or a compound. Therefore, the current findings are not in harmony with another aspect of Inhoff et al.’s (1996) results, that showed larger incoming saccades for compounds than for monomorphemic controls. Our data are also difficult to reconcile with a particular interpretation of Hyönä and Pollatsek’s (1998, 2000) findings, according to which interword saccades land further into words with a more frequent first constituent (see Andrews et al., 2004, for a compound reading study that does not find this effect). In the present experiment, the beginning quadrigram frequency is equivalent to the lexical frequency of the first constituent. Since landing positions were shifted to the right as orthographic regularity increased, it may appear as if landing position was modulated by word frequency. Critically, however, the shift in landing position was present to an equal degree when the beginning quadrigram was not a word. This is particularly compelling in the case of the medium regularity items where word beginning quadrigrams were identical. A similar result was obtained by Hyönä (1995) who compared Finnish compounds versus derived words with identical beginnings and also found no difference in landing positions. Taken together, these findings provide solid evidence against the idea that parafoveal lexical or morphological processing may have a modulating effect on saccade amplitude specification.\(^5\) From a more methodological point of view

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\(^5\)One might argue that, if the beginning letter sequence corresponded to a lexeme, readers may have assumed that the parafoveal string is a "word", irrespective of the actual whole-word type (compound or single root noun). However, in this case landing positions should have been further to the left in the low or high regularity simple noun conditions where initial quadrigrams never corresponded to a potential lexeme. Also, if readers incorrectly assumed that the parafoveally visible beginning quadrigram of a single root noun was a morpheme, then subsequent viewing durations should have been relatively long—as there was a need to recover from garden pathing (see also Inhoff, 1989, and Lima, 1987, for evidence against morphological processing in the parafovea).
they also suggest that in studies using comparisons between NN compounds, it may be quite difficult to exclude the possibility that a seeming morpho-lexical effect of initial constituent frequency on spatial saccade parameters is in fact due to processing on the orthographic level.

The data presented in this paper add to a growing body of evidence in favour of orthographic landing site effects. We have shown that saccades into orthographically more regular (less salient) words have longer amplitudes and the landing positions of these saccades are located further to the right. The size of this main effect (about 0.3 letters) is in the order of what has been reported before in studies that also found orthographic landing site effects in continuous reading (Hyönä, 1995; Vonk et al., 2000). Our results indicate that the effect is of a graded nature in two related but different respects: First, as in Vonk et al., the distributions are shifted as a whole rather than showing a discrete deviation from the norm in the case of irregular word beginnings as found by Hyönä (1995). Second, since our study used a three-level variation of orthographic regularity, we were able to demonstrate that the differences between low versus medium regularity words, and medium versus high regularity words, were in the same order of magnitude. Hence, there is good reason to assume that the effect is continuous over a wide range of orthographic processing load. In our view this excludes all accounts on the basis of visual or preattentive processing (see below). Our supplementary analyses of observations with saccades coming from relatively near versus relatively far launch positions further indicated that this influence of parafoveal word-beginning orthography on saccade specification is not restricted to targets that are very close to the current fixation (see Vonk et al. for a converging result).

Focusing on the fact that parafoveal orthographic processing influences the programming of saccades, the question arises how this effect can be accounted for. Current proposals on this issue have taken several routes. First, Hyönä (1993) suggested that irregular letter clusters may “pop out” and “attract” saccades towards them. This idea has also been promoted by Beauvillain and Doré (1998). This proposal is certainly appealing, as the notion of “pop out” has high face validity. However, going back to its original definition in the area of visual search, the concept was developed to account for the automatic and parallel detection of critical targets in an array containing distractors that differ on a physical feature dimension or visual feature changes in two successively shown displays (e.g., Treisman & Gelade, 1980). To our knowledge there is no direct evidence suggesting that this type of pop-out effect can also apply to visually similar letter strings with variations in particular linguistic properties.

Findlay and Walker (1999), in the framework of their saliency map theory of saccade generation, proposed that modifications of saccade amplitudes due to parafoveal processing may be accounted for in terms of an intrinsic saliency that a stimulus may carry. The current results are also difficult to reconcile with this view, unless one would want to claim that we keep in memory a specific
repertoire of rare letter clusters that are unlikely to form word beginnings. Another interpretation of intrinsic saliency could be to claim that all possible letter clusters are salient for a beginning reader and that the saliency is reduced with repeated encounters of a particular visual pattern (see Pollatsek & Rayner, 1989, for a critical discussion of visual template matching accounts of visual word recognition). However, any means of gradually differentiating a “salient” word beginning from a background of less salient letter strings must necessarily require a minimum of orthographic processing. However, as soon as the orthographic processor is activated, processing is no longer confined to the level of visual perception and concepts like “pop out”, preattentive processing, and “intrinsic” saliency lose much of their explanatory appeal.

An alternative hypothesis was put forward by Hyönä and Pollatsek (1998, 2000) to account for their effect on landing position of initial compound constituent frequency. They suggested that high parafoveal processing load may reduce the extent of the perceptual span, which in turn would lead to a shortening of saccades. However, applying such a proposal to parafoveal processing may carry the danger of logical circularity: In the present context the perceptual span would be defined as the region around the current fixation position within which foveal and parafoveal letter discrimination takes place. Only as a result of this parafoveal orthographic letter processing can the system know that the beginning of the next word “does not compute”. Also, there is direct empirical evidence according to which orthographic properties of the beginning letters of a parafoveally visible word do not influence the acquisition of useful letter-level information from the parafovea (Lima & Inhoff, 1985). In the experiment readers could or could not obtain useful parafoveal letter or word information from a parafoveally visible target word, and eye-movement-contingent display changes were used to show the intact target when it was fixated. In addition, the study controlled orthographic properties of the target’s onset trigram so that it was consistent with a large number of words (e.g., roo) or with a relatively small number of words (e.g., dwa). The target words themselves (rooster and dwarf in the example) were matched on a wide range of lexical properties. Analyses of target viewing durations as the function of the type of previously visible target preview revealed virtually identical benefits from common (roo) and rare (dwa) word onset trigrams, suggesting that the processing of rare parafoveally visible word onset letters did not narrow the perceptual span. Consistent with this view, van de Weijgert (1993) found a uniform decrease in visual discrimination performance over a range of eccentricities rather than evidence for “tunnel vision” (see also Williams, 1988) in a memory comparison task that sought to manipulate nonvisual processing load.

Looking at basic oculomotor research there is a body of evidence dealing with graded effects on saccade amplitudes. In so-called double step experiments, two targets are shown in rapid succession and participants are asked to follow this seeming two-step movement as fast as possible. If the second target
displacement goes in the same direction (e.g., to the right on a horizontal plane) and occurs within an interval approximately 70–180 ms before the onset of the first saccade, this saccade consistently lands in between the first and the final target location (Becker & Jürgens, 1979; Ottes, van Gisbergen, & Eggermont, 1984; see Becker, 1989, for a review). As shown by Findlay and Harris (1984), for step eccentricities similar to the amplitude of reading saccades there is a continuous transition of the saccade amplitude toward the second target location, as the available reprocessing time increases.

This line of evidence was ingeniously applied to reading by Morrison (1984). Considering lexical access of a fixated word as the trigger for an attention shift and subsequent saccade initiation, he described a scenario where lexical access of an adjacent word N+1 has taken place but the information about this arrives relatively late. Hence, a saccade that is being programmed to go to word N+1 cannot be cancelled and replaced with a saccade to word N+2. However, the critical information may arrive early enough to allow for the kind of spatio-temporal averaging described above, leading to a lengthening of the next saccade amplitude. Also, since in this case the subsequent saccade to word N+2 is already programmed, the fixation duration after the initial saccade can be reduced to a minimum latency, accounting for the very short fixation durations often observed in continuous reading (Radach, Heller, & Inhoff, 1999).

It is clear from the results obtained in research using the double step paradigm that the mechanism responsible for amplitude specification is prepared to take into account visual information before and after the decision to move has been made (see Deubel, O’Regan, & Radach, 2000, for a more detailed discussion). Cognitive landing site effects appear to suggest that this is true not only for visual but also for specific linguistic information. One way to implement such a mechanism would be to apply the Morrison scenario to data like those obtained in the present study. Assuming that the initial letter cluster is parafoveally processed, the system may sometimes make an attempt to “skip” over this word segment, initiating a saccade to go beyond these letters (Rayner & Morris, 1992). In the present experiment, mean initial fixation durations were indeed shorter for target words with more regular beginnings, as predicted by Morrison’s reprogramming hypothesis. On the other hand, an inspection of the distributions underlying these means indicated that there was no increased frequency of very short fixation durations for highly regular beginning words. Nonetheless, this line of reasoning may in principle open a way to accommodate saccade amplitude modifications as a result of sublexical parafoveal processing within attention-based sequential processing models of eye movement control (Reichle et al., in press).

A parsimonious way to explain the observed orthographic landing site effects may be in terms of continuous feedback from ongoing orthographic processing to saccade amplitude specification. A theoretical framework allowing for an integration of visual and cognitive processing in the process of saccade
generation has been proposed by Findlay and Walker (1999). They suggest that
the specification of saccade targets is based on parallel processing and com-
petitive inhibition within a spatial saliency map. In the recent Glenmore model
by Reilly and Radach (2003), this takes the form of a saliency vector initially
representing the visual configuration of letters within the perceptual span on a
line of text. The model also implements a linguistic processing module including
an interactive activation network for orthographic letter processing. Most
importantly, results of processing within this network are fed back continuously
to the saliency vector, leading to dynamic changes in local saliency values. In
the current version of the model, these saliency values are integrated for each
word, forming a preference list of potential target objects. When a saccade is
triggered, it is always directed to the centre of the word with the highest sali-
ency. Thus, the saccade generator is insensitive for properties of specific letter
clusters. In a future version of the model saccade amplitude adjustments as a
result of parfoveal orthographic processing could be made possible by taking
local saliency fluctuations into account when specifying the saccade goal. The
saliency maximum within the target word is likely to be further to the right for
high regularity word beginnings at the point in time when the impending saccade
to word N+1 is committed to action. This could effectively account for a graded
effect of word initial regularity on the resulting saccade amplitude.

In sum, the present study has reported evidence in favour of a graded mod-
ulation of interword saccade amplitude in response to variations in the ortho-
graphic regularity of parafoveal word beginnings. The modification of current
models of oculomotor control in reading to account for the relatively small
orthographic landing site effects appears to require changes in model architec-
ture and will certainly make these models more complex. More research into
graded orthographic landing site modulations is needed to establish the pheno-
momenon as an undisputed empirical fact. If this research leads to unequivocal
results, the investment to incorporate this effect into current theories of eye
movement control will begin to appear rewarding.

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ORTHOGRAPHIC REGULARITY


APPENDIX

Sample sentences for each condition in the 3 (orthographic regularity) × 2 (word type) design together with (literal) translations with target words written in italics. Note that in German all nouns have capital initial letters.

Simple noun target, low orthographic regularity
Er stellte das gläserne Aquarium ins Wohnzimmer seiner neuen Wohnung.
(He put the glass aquarium in the living room of his new apartment.)

Simple noun target, medium orthographic regularity
Nächsten Monat soll das komplette Fundament des Hochhauses fertiggestellt werden.
(By next month the complete foundation of the high-rise building should be finished.)

Simple noun target, high orthographic regularity
Überraschend gewann der junge Interpret den Musikpreis der Stadt Hamburg.
(Surprisingly the young interpreter [singer] won the music award of the city of Hamburg.)

Compound noun target, low orthographic regularity
Für Säuglinge ist weiches Lammfell als Schlafunterlage von Geburt an zu empfehlen.
(For babies soft lambskin as a sleeping pad from birth onwards is to be recommended.)

Compound noun target, medium orthographic regularity
Der Beamte schleppte den schweren Postsack vom Erdgeschoss bis in die siebte Etage.
(The clerk carried the heavy mailbag from the ground floor to the seventh level.)

Compound noun target, high orthographic regularity
Der Tourist genoss den schönen Rundblick vom Leuchtturm der Nordseeinsel Helgoland.
(The tourist enjoyed the nice roundview [panorama] from the lighthouse of the North Sea island of Helgoland.)

Example for a semantically inconsistent catch trial
Zum Glück verfehlte der rote Dachziegel den Termin zur Anmeldung.
(Fortunately the red roof tile missed the deadline for the registration.)