Word processing speed in peripheral vision measured with a saccadic choice task

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ABSTRACT

A saccadic choice task (Kirchner & Thorpe, 2006) was used to measure word processing speed in peripheral vision. To do so, word targets were accompanied by distractor stimuli, which were random strings of consonants presented in the contralateral visual field. Participants were also tested with the animal stimuli of Kirchner and Thorpe's original study. The results obtained with the animal stimuli provide a straightforward replication of prior findings, with the estimated fastest saccade latencies to animal targets being 140 ms. With the word targets, the fastest reliable saccades occurred with latencies of around 200 ms. The results obtained with word targets provide a timing estimate for word processing in peripheral vision that is incompatible with sequential-attention-shift (SAS) accounts of eye movement control in reading.

1. Introduction

How long does it take for the brain to detect the presence of a word in our visual field? How long does it take to identify a word in the visual periphery? Sequential-attention-shift (SAS) models of eye-movement control in reading (e.g., the E–Z Reader model: Reichle, Rayner, & Pollatsek, 2003) suggest that this might be achieved very rapidly. They posit that within the time course of an average eye fixation during natural reading (i.e. about 250 ms), there is often enough time for lexical processing of the fixated word (N) to be completed, and for the subsequent processing of the next word (N + 1) to be initiated and possibly reach an intermediate stage of lexical processing (i.e., the L1, word-familiarity check phase in the E–Z Reader model) that will influence where the eyes move next.

These assumptions are based on two sets of empirical findings. The first set of findings from eye-movement studies show that the eyes more frequently skip words that are easier to process in the periphery (e.g., high-frequency compared to low-frequency words), thus suggesting that peripheral word processing is sometimes quick enough to influence the length of the next saccade (for a review see Rayner, 1998). The second set of findings from electrophysiological studies suggests that foveal processing might be extremely rapid (Hauk et al., 2006; Sereno & Rayner, 2003; Sereno, Rayner, & Posner, 1998). These studies found that electrophysiological activity related to the orthographic processing of foveal words, when presented in isolation, can emerge as early as

about 100 ms, while word frequency and word regularity effects show up only slightly later, that is at about 132 and 160 ms respectively from stimulus onset. Following the assumptions of SAS models, and considering an average fixation duration of 250 ms (see Rayner, 1998), these results suggest that lexical information could be extracted very rapidly in peripheral vision, and particularly in those presumably quite frequent instances where such processing is sufficiently advanced to influence where the eyes move next (see Reichle, Rayner, & Pollatsek, 2003). The reasoning, to be developed in what follows, is summarized in Fig. 1.

While the eyes fixate word N, the processing on word N + 1 is distributed over two time intervals, as depicted in Fig. 1. The first 90 ms of processing is devoted to early visual extraction processes in both central and peripheral vision and is therefore shared with processing of word N. The second time interval, which corresponds to the final 90 ms of the fixation before a default saccade to word N + 1 is executed, is the time that remains after word N has undergone enough processing (i.e., completion of the L2 stage in E–Z Reader) for attention to shift to the next word (250 ms minus the 160 ms time estimated from the Sereno, Rayner, and Posner (1998) study for completion of both the L1 word-familiarity check stage and the L2 lexical processing stage). However, in order for the eyes to skip word N + 1, the default saccade has to be modified some 50 ms before the end of the fixation, given some time lag at the end of the fixation where saccade parameters can no longer be modified (i.e., the M2, non-labile stage of saccadic programming in opposition with M1, the labile stage of saccadic programming). Thus, in those specific, though quite frequent, instances where words are skipped, the L1 stage of lexical processing in the periphery, which is the trigger for a new saccade program, lasts no longer than 130 ms (i.e. the first 90 ms plus a later 40 ms time interval
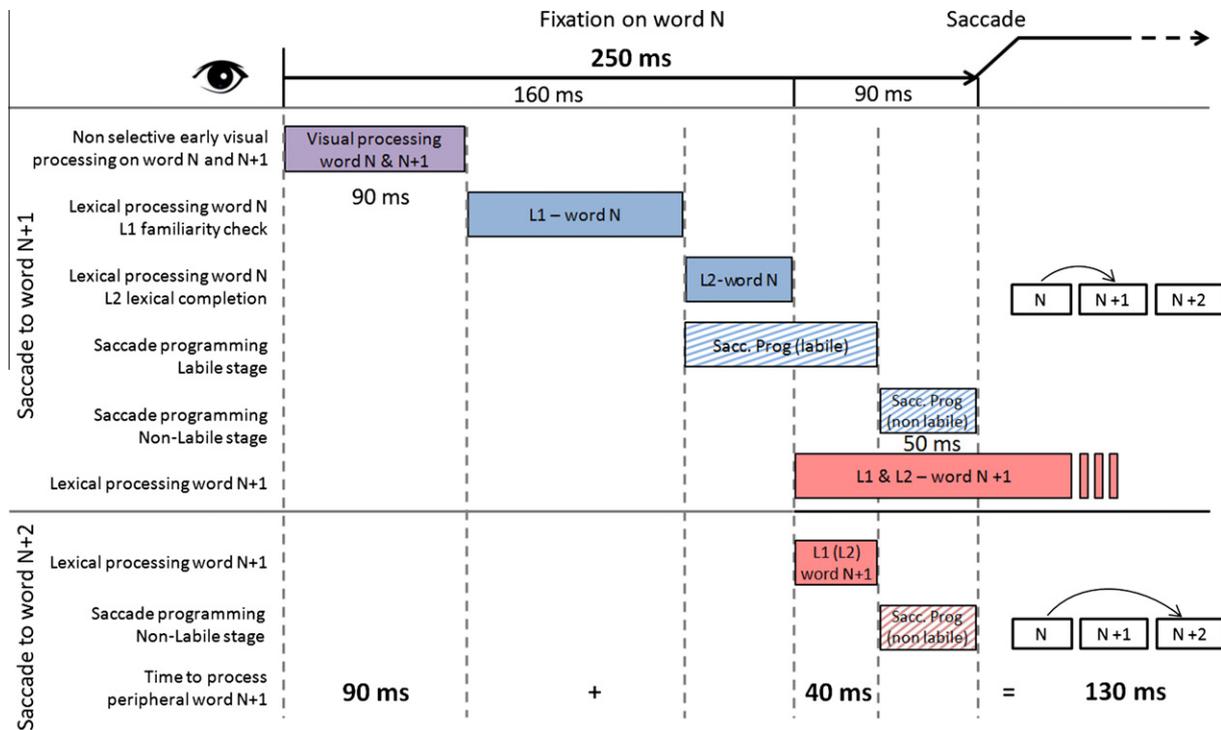
Fig. 1. Component processes of the E–Z Reader model of eye movement control in reading (Reichle, Rayner, & Pollatsek, 2003) described for when the eyes move from word *N* to word *N* + 1, and when the eyes move from word *N* to word *N* + 2 (i.e., word skipping). Upon fixation of word *N* there is an initial phase of early non-selective processing on both word *N* and word *N* + 1. This is followed by the L1 phase of processing on word *N* which leads to the programming of a saccade to word *N* + 1 that operates in parallel with the L2 phase of processing on word *N*. Completion of L2 processing on word *N* causes a shift of attention to word *N* + 1 and initiation of L1 processing on word *N* + 1. Word skipping (i.e., canceling of the saccade to word *N* + 1 and programming a new saccade to word *N* + 2) arises when the L1 phase of processing of word *N* + 1 is completed before the programming of the saccade to word *N* + 1 enters a non-labile stage and the saccade can no longer be modified. See main text for explanation of the time estimates associated with each processing stage.

which corresponds to the second 90 ms stage minus the 50 ms non-labile stage of saccade programming). This estimate should be even less given that information has also to reach the oculomotor centers within this time frame in order to modify the saccade program.

Several other findings and theoretical considerations however point to slower timing estimates for the processing of peripheral words. First, as revealed in meta-analyses of word skipping studies, only a small portion of variance in skipping likelihood is explained by peripheral preview (no greater than 5–8% on average), and this influence is unstable compared to the effects of visual variables such as word length (Brysbaert, Drieghe, & Vitu, 2005; Brysbaert & Vitu, 1998; see also O'Regan, 1990). And in fact, the typical relationship between word skipping and word length can also be observed when strings of identical consonants instead of normal words compose a pseudo-text to be scanned (Vitu et al., 1995). Altogether, these data suggest that peripheral word identification processes contribute only occasionally to determine saccadic behavior, and one possible explanation is that they are simply too slow to affect where the eyes move next (see Vitu (2003) for further discussion). Second, the assumption that adjacent words in reading are processed sequentially is challenged by several results showing that fixation times can sometimes be influenced by information extracted from word *N* + 1, and hence that peripheral processing may be initiated earlier during a fixation and benefit more fully from the time the eyes remain stable than assumed in SAS models (Kliegl, Nuthmann, & Engbert, 2006; for a review of earlier research see Vitu, Brysbaert, & Lancelin, 2004). The SWIFT model of eye-movement control accounts for these data based on the assumption that adjacent words in reading are processed in parallel, and not sequentially (Engbert et al., 2005). Finally, in natural reading, words are embedded in sentences and hence can

be predicted from the prior sentence context, and this may boost word identification processes in peripheral vision (see Lavigne-Tomps, Vitu, & d'Ydewalle, 2000). Indeed, given the rather drastic decrease of visual acuity with retinal eccentricity as well as the increase of visual crowding (Bouma, 1970; Legge, Mansfield, & Chung, 2001; Pelli et al., 2007), word identification accuracy rapidly diminishes as the center of a word is shifted away from fixation (Brysbaert, Vitu, & Schroyens, 1996; see also Nazir, O'Regan, & Jacobs, 1991; Rayner & Morrison, 1981; Stevens & Grainger, 2003). It remains therefore unclear how quickly lexical information associated with a peripheral word accumulates in the absence of linguistic context.

The present study was a first attempt to estimate the speed with which isolated word stimuli are processed in the visual periphery. To do so, we used a new behavioral paradigm for measuring peripheral object processing speed (Kirchner & Thorpe, 2006), applied here to measure how fast real words can be discriminated from nonwords (which were random strings of consonants) in peripheral vision. In the original study, Kirchner and Thorpe presented participants with two pictures of natural scenes, one to the left, the other to the right of a central fixation mark, and asked them to move their eyes as quickly as possible to the scene containing an animal. Animals were present on every trial, and randomly appeared in the scene to the left or the scene to the right of fixation, following a fixed gap interval of 200 ms (where the screen remained empty) after the offset of the fixation stimulus. The gap paradigm presents the advantage of greatly shortening saccadic reaction times by possibly squeezing/compressing early stages involved in saccadic programming, thus presumably facilitating estimation of the earliest possible discrimination responses associated with peripheral stimuli. This is due in particular to fixation disengagement occurring largely before peripheral target

onset, plus the use of two alternative responses (e.g., left vs. right) and a fixed gap interval (200 ms) that further shortens saccade latencies due to possible temporal and/or spatial expectation mechanisms (see Rolfs & Vitu, 2007; see also Findlay & Walker, 1999; Trappenberg et al., 2001). Kirchner and Thorpe found that the fastest saccades to animal targets were triggered as little as 120–130 ms post-stimulus onset, suggesting that the presence of an animal can be detected very rapidly. Considering that the shortest timing estimates for saccade generation are about 20 ms following brainstem stimulation (Schiller & Kendall, 2004), it thus appeared that enough processing can be performed within 100 ms or so for the presence of an animal to be detected. Here we used the same basic paradigm to estimate the time it takes to discriminate real words from nonwords in the periphery. Our estimate was based on measurement of saccade latency towards the target, a word, when presented simultaneously with a nonword in the contralateral hemifield.

In the present study, participants were also tested with the animal/non-animal scene stimuli used in the original Kirchner and Thorpe (2006) study, and for both word and animal stimuli, participants performed an additional control task in which a single word or a scene containing an animal was displayed either to the left or to the right of the initial fixation stimulus, and participants simply had to move their eyes to where the stimulus appeared. This was done in order to replicate Kirchner and Thorpe's original findings, and to ensure that our presentation conditions would allow us to investigate early effects in the experimental conditions by having a similar proportion of short-latency saccades irrespective of stimulus type (word or animal) in the control condition. To this end, the extent of the stimulation in the horizontal dimension was made comparable by magnifying word and nonword stimuli. Indeed, it is well known that the amount of stimulation in both the foveal and the peripheral regions greatly influences saccade latencies (Benson, 2008; Vitu et al., 2006; Walker et al., 1997; but see White, Gegenfurtner, & Kerzel, 2005). Letter size was also well-above the critical print size, that is the smallest print size that yields maximum reading speed (see Chung, Mansfield, & Legge, 1998). This ensured that, despite their eccentricity, the words would be sufficiently visible for the task to be performed accurately.

Finally, in order to provide the fastest possible estimate of word processing time we used five-letter words of high frequency of occurrence in order to optimize processing of the word stimuli.[1] Furthermore, we presented these words simultaneously with nonwords composed of random consonants as distractor stimuli, thus further facilitating the process of word/nonword discrimination. Indeed, using random consonant strings as distractors implies that word/nonword discrimination could be made on the basis of initial sublexical processing of word stimuli that is sensitive to orthographic structure. Therefore, the combination of the saccadic choice paradigm, the enlarged size of the stimuli, plus the use of relatively short high-frequency words as targets and random consonant strings as distractors, should all help provide the fastest estimate of word processing speed in peripheral vision, thus providing a strong test of SAS models of eye movement control in reading. According to one specific version of these models, the E–Z Reader model, the L1 stage or word-familiarity check involves the kind of processing that enables accurate discrimination of words from random strings of letters in peripheral vision, and this stage is assumed to take less than 130 ms, particularly in the case of short and frequent words which end up being skipped in the course of normal reading. We might therefore expect, under the specific conditions tested in the present study where saccade programming probably overlaps in time with visual and decisional processes, that saccades to word targets could be triggered as quickly as the saccades to animal targets in the Kirchner and Thorpe (2006) study.

2. Method

2.1. Participants

Eighteen volunteers between 21 and 28 years old took part in the experiment. All were native speakers of French and reported having normal or corrected-to-normal vision.

2.2. Stimuli

For the animal detection task, 500 photographs were selected from the set of natural scenes used by Kirchner and Thorpe (2006). One hundred of these photos that contained an animal were used in the control condition. The remaining 400 photos were used in the experimental condition. Half of them contained an animal and served as target images, and the other half were distractor images with no animal. The target images included photographs of scenes with various kinds of animals, such as mammals, birds, insects, and reptiles, while the distractors included photographs of scenes with mountains, city-scapes, fruits, and plants. The two sets of 200 photos were respectively divided in two equal subsets of 100 images. For the word detection task, a total of 500 items were used, including 300 words and 200 nonwords (consonant strings). Words were five letters in length and were selected from the French corpus Lexique (New et al., 2001). Their frequency of occurrence was relatively high, ranging between 1.6 and 700 per million (median = 23.1). The 100 words with the lowest frequency (median = 16.55) were assigned to the control condition. The remaining 200 words were presented in the experimental condition (median frequency = 59.52),[2] simultaneously with a distractor string that was a random string of five different consonants. Care was taken that none of the sequence of consonants formed an acronym. The two lists of 200 words and nonwords were divided respectively into two separate lists of 100 items each. Care was taken that the range of word frequencies in the two word lists was comparable (median = 58.11 vs. 60.17). For the animal-detection and word-detection tasks, an additional list of 40 target items and an additional list of 40 distractor items were prepared for the training phases that preceded the experimental blocks of trials. An additional list of 20 target items was used for training before the control blocks of trials. None of these items were presented during the experimental trials.

2.3. Apparatus

Participants' eye movements were recorded and analyzed online, using a Desktop, Head-supported, EyeLink 1000 (SR Research) device that samples the right-eye position every millisecond, with an average spatial accuracy of 0.5°. An automatic saccade-detection algorithm based on a velocity threshold of 30°/s and an acceleration threshold of 8000°/s^2 (i.e., the cognitive configuration for the EyeLink 1000) was used. Stimulus presentation was controlled using the Experiment-Builder software supplied with the Eyelink 1000. Stimuli were presented on a CRT screen on a black background with a resolution of 640 × 480 pixels and a refresh rate of 100 Hz. Presented at a distance of 80 cm from the participant's eyes, each image subtended 10.8 × 15.7° of visual angle, and each

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[1] In an analysis of lexical decision RTs to a very large set of French words presented foveally in a standard lexical decision experiment, Ferrand et al. (2011) reported a minimum RT for words of five-letters in length, which generated slightly faster RTs than four-letter words, which in turn were faster than three-letter words.

[2] In a post-hoc analysis of our stimuli we examined the RTs for these same words in the French Lexicon Project database for lexical decisions to 1482 French words (Ferrand et al., 2011). 80% of the 200 experimental words were among the fastest 30% of all words.

word 9.3 × 2.7° of visual angle. Words and nonwords were presented in lowercase Courier-New font, with each letter subtending about 1.7° of visual angle. A chin-rest was used to stabilize the participants' head. The room was dark, except for a dim, indirect, light source. Viewing was binocular.

2.4. Design

Participants were tested in the animal detection and word detection tasks in separate blocks, with the order counterbalanced across participants. The results for the animal and word targets were analyzed separately. In each task, there were two conditions, (1) a control condition where participants were presented with a single animal or word displayed randomly to the left or to the right of fixation, and (2) an experimental condition where a target animal/word was presented randomly to the left or to the right of fixation, but simultaneously with a contralateral distractor image/letter-string. Note that the control condition provides a baseline measure of simple detection latencies in the present testing conditions, given that participants simply had to move their eyes to where the stimulus was located independently of the nature of the stimulus. Half of the participants started with the control condition (one training block then the control block) and the other half with the experimental condition (one training block then the two experimental blocks). Across participants, all words and animals assigned to the control and the experimental conditions respectively were seen in both left- and right-presentation conditions (Latin Square design). Participants ran a total of five blocks of trials in both the animal and the word detection tasks: one control block of 100 trials which was preceded by a training block of 20 trials, and two experimental blocks of 100 trials each that were preceded by a training block of 40 trials. Within each block, an equal number of targets were presented to the left and to the right in random order.

2.5. Procedure

As shown in Fig. 2, in each trial, participants were first presented with two vertically aligned bars at the center of the screen. They were instructed to fixate the gap in between the two bars. When their eye was detected to be within a horizontal region of ±1° around the bars (i.e. 1° to the right and 1° to the left) for a minimum of 20 ms, the bars were removed and replaced with a fixation cross (horizontal and vertical size: 0.7°). As in Kirchner and Thorpe's original paradigm, the fixation cross disappeared after a random time interval (800–1600 ms), followed by a 200 ms gap interval during which the screen remained empty. The stimuli (one target, or one target and a distractor, in the control and experimental conditions respectively) were then displayed for 400 ms to the left and/or to the right of the initial fixation cross. Stimuli (words or animals) were centered at an eccentricity of 6°, and word and animal stimuli extended respectively from 1.35° to 10.65° and 0.6° to 11.4° to the right or to the left of fixation. Then, two gray fixation crosses were presented simultaneously for 1000 ms at the corresponding eccentricities. Participants were asked to move their eyes as quickly and as accurately as possible to the side where an animal (in the animal detection task) or a word (in the word detection task) was presented. The onset of the peripheral stimuli was the go-signal for a movement to be initiated. A training phase preceded the control trials as well as the first experimental block of trials for each task. The training block was repeated until the participant's performance reached 75% correct (with a maximum of six repetitions).

3. Results

3.1. Data selection

On each trial, a saccade was selected for analysis if it met each of the four following criteria: (1) stimuli were displayed during the fixation preceding the saccade, (2) the saccade was launched from within a ±1° horizontal region around the center of the fixation cross, (3) it moved the eyes more than 3° to the left or to the right of fixation, and (4) it was not preceded by a blink. After selection, 27% (7–64%) and 21% (2–56%) of trials were rejected in the animal detection and the word detection tasks respectively. Trials rejected because of a blink (criterion 4) represented about half of the rejections, but note that for these blink-related trials, accuracy was about the same as for trials selected on the basis of the other three criteria. Quite a large proportion of the rejected trials (29%) were due to the participant's eyes not being in the 1° fixation area before the saccade. Saccadic reaction time (SRT) was defined as the time difference between the onset of the target stimulus (animal or word and accompanying distractor) and the start of the saccade.

We first checked the overall level of accuracy of each participant in each task, using Chi-square tests. The performance of three participants did not differ significantly (at the $p < 0.05$ level) from chance (50%) in the word detection task. The average performance of these three participants on the animal targets was 87%, 88%, and 89% accuracy, with corresponding mean RTs of 175, 181, and 177 ms. This is already an indication of the difficulty of discriminating words from nonwords in the periphery in our experiment. The data of these three participants were excluded from analysis in both the animal and the word detection tasks.

3.2. Overall performance

In the control condition with no distractor, mean accuracy was 99.8% for animal targets and 100% for word targets, and mean SRTs were 153 ms and 149 ms for animal and word targets respectively. As expected, these simple detection latencies did not differ as a function of the type of stimulus. In the experimental conditions, accuracy was 92.2% for animal targets, and 75.2% for word targets, and there were no effects of visual field for either type of target (mean accuracy to the left and to the right of fixation was 92.9% and 91.4% for animals, $t(14) = 0.84$, $p = 0.41$, and 73.5% and 76.8% for words, $t(14) = 0.77$, $p = 0.45$). The mean SRT on correct trials was 204 ms for animal targets and 235 ms for word targets, and again there was no effect of visual field (mean SRT to the left and to the right of fixation was 202 ms and 206 ms for animals, $t(14) = 1.31$, $p = .21$, and 232 ms and 239 ms for words, $t(14) = .99$, $p = .34$).
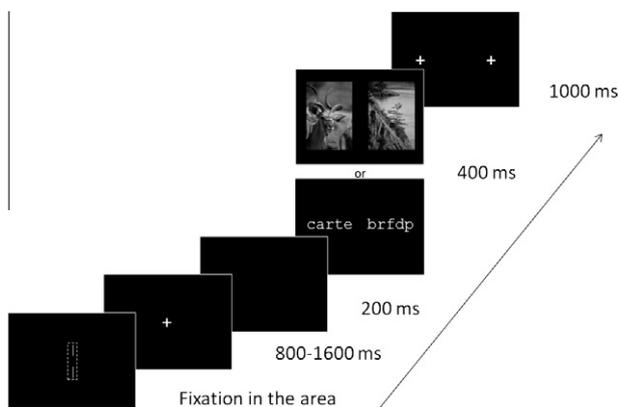

Fig. 2. Sequence of events on an experimental trial.

3.3. SRT distributions

The distributions of SRTs obtained with animal and word stimuli were first plotted across participants. As can be seen in Figs. 3 and 4, the distributions corresponding to the two control conditions, where a target stimulus (animal or word) was presented with no distractor, were very similar, being both unimodal and peaking at about 140 ms. When the target was presented with a distractor in the experimental conditions, the distributions were shifted towards longer latencies, with the mode varying between 180 ms and 200 ms for animal and word stimuli respectively. The important fact however is that the distributions associated with correct and incorrect responses separated at different points in time for animal and word stimuli, that is at an estimated 140 ms for animals and no earlier than 200 ms for words.

To estimate more precisely the minimum SRT value at which the proportion of correct responses was significantly higher than

the proportion of incorrect responses, we adapted Kirchner and Thorpe's (2006) analysis procedure. We divided the saccade latency distribution of each participant, in each condition, into 20-ms time bins. We then searched for the first bin containing more correct than incorrect responses, using Chi-square tests. As soon as a minimum of three subsequent tests reached significance (at the .05 level), the first of the corresponding bins was considered as being the minimum SRT for the corresponding condition and participant. With this procedure, a minimum SRT was obtained for each participant in the animal detection task, but for only 11 out of 15 participants in the word detection task even though the overall performance level of the four remaining participants was better than chance. As shown in Table 1, individual minimum SRTs varied between 120 ms and 200 ms in the animal detection task and 180 ms and 240 ms in the word detection task. The same procedure applied to the SRT distribution across all participants yielded a similar pattern. The minimum SRT was about 140 ms
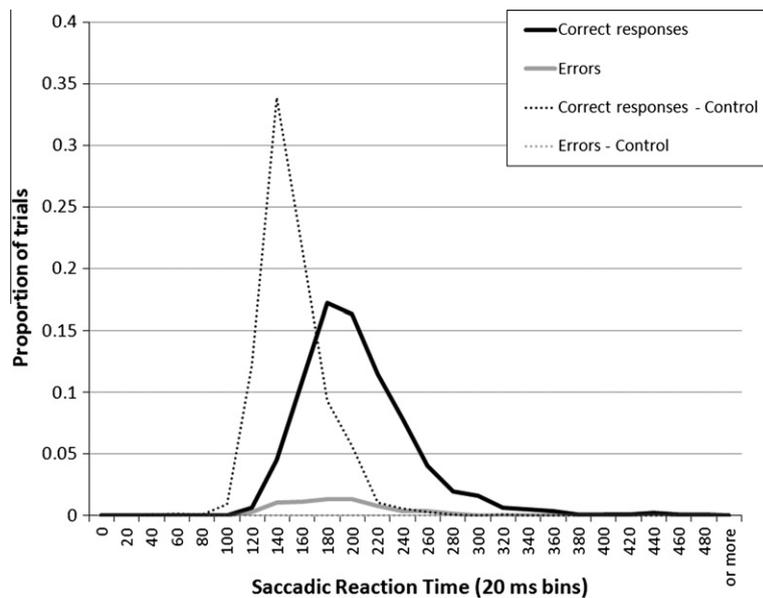

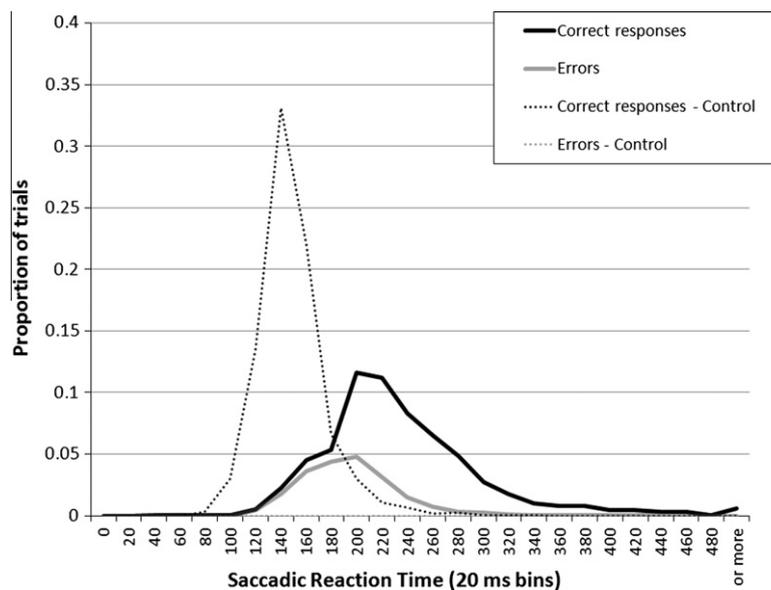**Fig. 3.** SRT distributions for animal targets.

Fig. 4. SRT distributions for word targets.

Table 1
Summary of individual results. Mean SRTs in the experimental and the control condition were computed over correct responses only.

Subject	Animals					Words				
	Accuracy (%)	Mean SRT (ms)	Min. SRT (ms)	Accuracy at min. SRT (%)	Control mean SRT (ms)	Accuracy (%)	Mean SRT (ms)	Min. RT (ms)	Accuracy at min. SRT (%)	Control mean SRT (ms)
1	93.1	173.93	120	100.0	136.28	63.6	156.52	×	×	117.11
2	91.7	201.41	160	87.5	151.82	78.0	258.77	200	71.4	166.95
3	96.5	209.99	160	94.7	160.36	74.5	231.66	200	68.9	165.06
4	91.2	194.62	160	81.2	146.16	75.0	259.20	240	86.6	147.09
5	92.9	239.88	180	100.0	168.24	76.9	223.86	180	76.4	147.55
6	82.2	168.07	140	70.4	125.81	69.6	216.45	220	76.9	149.54
7	95.3	188.79	140	100.0	156.67	77.3	210.09	180	68.4	150.71
8	89.2	197.64	160	86.6	142.40	74.3	231.25	200	75.0	145.00
9	90.9	222.05	160	100.0	151.49	68.4	243.13	×	×	136.69
10	92.0	204.91	180	97.5	169.46	79.7	253.51	200	72.5	170.96
11	89.9	188.89	140	93.3	139.22	68.2	278.38	×	×	134.65
12	97.7	219.71	180	100.0	163.89	90.8	251.21	220	86.6	159.51
13	94.0	209.06	160	100.0	147.56	73.4	216.83	200	73.7	146.29
14	87.0	172.85	140	82.9	139.19	63.4	188.51	×	×	133.82
15	99.3	265.32	200	100.0	191.28	95.0	299.73	200	100.0	166.14
All	92.2	203.81	140	81.3	152.65	75.2	234.61	200	70.8	149.14

(i.e., it corresponded to the bin interval going from 131 to 150 ms) in the animal detection task, and about 200 ms (191–210 ms) in the word detection task.[3] At this minimum SRT, accuracy was 81.3% for the animal targets and 70.8% for the word targets. As can be seen in Fig. 5, which re-plots individual accuracy data as a function of SRTs, accuracy tended to increase with SRT. However, note that the accuracy level for words remained overall lower than that for animals over the whole saccade latency range, and that it was only after 250 ms that for two participants performance with word targets matched their performance with animal targets.

4. Discussion

In the present study participants had to move their eyes as rapidly as possible to a peripherally located target stimulus situated to the right or left of a central fixation point. Accurate central fixation was ensured. The target could either appear alone in the control condition, or simultaneously with a distractor stimulus in the contralateral hemifield. The target stimuli were scenes containing an animal for the animal detection task, and five-letter words in the word detection task. The distractor stimuli were natural scenes not containing an animal for animal targets, and random strings of five consonants for the word targets.

The results obtained with the animal stimuli provide a straightforward replication of the findings reported in the original Kirchner and Thorpe (2006) study, with quite similar timing estimates for animal detection. The authors originally reported that participants can accurately direct their eyes to a scene containing an animal presented simultaneously with a scene without an animal, with a minimum latency of 120–130 ms. Here, the minimum SRT was only slightly longer, i.e. 140 ms, and this was most likely due to our participants being slightly slower in initiating their saccades, as mean SRT in the corresponding single-target control condition

was 153 ms in our study and 133 ms in the original study. However, the key result of the present study concerns the word targets, which required a minimum SRT of 200 ms (mean SRT 235 ms) to be accurately targeted when presented with nonwords, while the same stimuli presented in isolation gave rise to a mean SRT of 149 ms, thus quite like the animal stimuli.

The present findings provide further evidence concerning the relative difficulty of processing words in peripheral vision, while providing estimates of processing times that are relevant for evaluating models of eye movement control in reading. The difficulty of peripheral word processing was primarily reflected in the minimum (200 ms) and the mean latency of correct saccades towards target words (235 ms) in the present study. These latencies were well above the minimum and mean SRT obtained with animal targets in the present study as well as with a variety of other scene-type stimuli in previous studies using the same saccadic choice task (Crouzet, Kirchner, & Thorpe, 2010; Kirchner & Thorpe, 2006). Moreover, performance remained rather poor, as average accuracy levels reached 75% only after removing three participants who failed to achieve above chance performance in this task, while performance in the animal condition was 92%. Note that the difference in overall accuracy between the word and animal conditions was still present when mean saccade latency was comparable in the two conditions. In fact, in the word condition, only one participant had an overall accuracy greater than 95% correct, and her mean SRT was about 300 ms. There were of course gross physical differences between the animal and word stimuli, and so one must be cautious in drawing conclusions from a comparison of performance in these two conditions. However, the high level of performance (in terms of speed and accuracy) obtained with animal targets clearly suggests that the bilateral presentation of stimuli, and hence the uncertainty of where targets would appear, cannot be entirely responsible for the slowness and inaccuracy of responses in the word condition.

The earliest non-random oculomotor responses in the word/nonword discrimination task occurred at about 200 ms after stimulus onset. If one considers a minimal 20 ms delay for the efferent signal,[4] this means that word/nonword discrimination influenced saccadic activity in oculomotor center maps only around 180 ms

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[3] In a complementary analysis we used signal detection theory to estimate the point in time during stimulus processing where word/nonword and animal/non-animal discrimination differed significantly from chance. Proportion of hits, misses, correct rejections and false alarms were used to compute d' values at 20 ms intervals for each type of stimulus. Since a target was present on every trial, either to the left or to the right, we arbitrarily chose one side to represent target location (left) such that hits were defined as "target left–saccade left", misses as "target left–saccade right", false alarms as "target right–saccade left", and correct rejections as "target right–saccade right". For word targets, d' values started to increase sharply at around 200 ms, rising from .17 to .76 between 191 and 210 ms. For the animal targets, d' values started to increase at around 140 ms, rising from .94 to 1.28 between 131 and 150 ms.

[4] Robinson (1972) and Schiller and Kendall (2004) reported that a saccade can be elicited as fast as 20 ms following electrical stimulation of the Superior Colliculus, an integrative midbrain structure, which receives afferents from various cortical areas and whose topographically-organized neuronal activity determines saccade parameters.
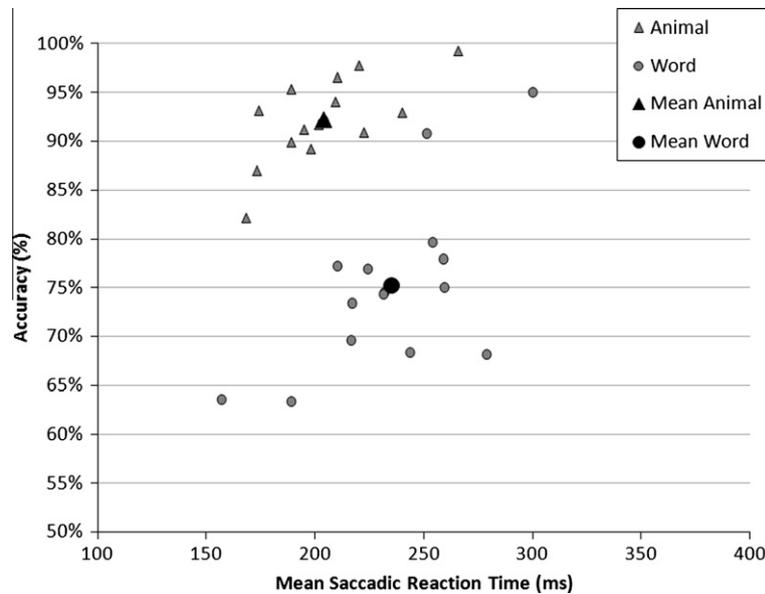
Fig. 5. Speed-accuracy trade-off functions (re-plotted from the individual data presented in Table 1).

after stimulus onset. Given the early fixation disengagement associated with the offset of the fixation stimulus (200 ms before peripheral stimulus onset), and possibly preparatory activity at the potential target locations in the motor map of the superior colliculus (see Rolfs & Vitu, 2007), it is indeed quite reasonable to assume that discrimination processes performed in higher cortical areas overlapped in time with saccadic programming. This could reinforce neuronal activity at the target location, and saccades may be elicited on that basis. Note that the efferent signal may take slightly longer, but even if it is increased to 50 ms as suggested by Reichle, Rayner, and Pollatsek's (2003) estimate of the non-labile stage of saccadic programming in E–Z Reader, this would still leave us with a minimal delay of 150 ms for an influence of word/nonword discrimination processes on saccadic activity. Furthermore, it is important to point out that we are only speaking of the minimal delay here. The mean discrimination delay was much longer, being in the order of 185 or 215 ms, depending on the chosen estimate of the efferent delay (235 ms − 50 ms or 235 ms − 20 ms).

The present estimate of 180 ms (or estimated range, 150–215 ms) for the time for word/nonword discrimination processes to begin to influence the saccadic orienting response is well above the timing estimate derived from the E–Z Reader model for processing of words in the periphery. This model relies on the general assumption that words are processed sequentially over the time course of an eye fixation during reading, with the processing of the next word (N + 1) being initiated only after lexical processing of the fixated word (N) is complete. Peripheral word processing can often influence the amplitude of the next saccade, by making it skip over word N + 1. For this to happen, the first stage of processing, the L1 or the word familiarity check stage in E–Z Reader, must have been completed before the point in time that the saccade under preparation can no longer be modified (i.e., the non-labile stage of saccade programming has been reached). This means that this first stage of processing of word N + 1 has to be achieved in between completion of lexical processing of fixated word N (for attention to be shifted to word N + 1), and the non-labile stage of saccade programming, thought to last about 50 ms. Applying the fastest possible estimate of completion of lexical processing of the foveal word as 160 ms from fixation onset (Sereno, Rayner, & Posner, 1998), and an average fixation duration of 250 ms (see Rayner, 1998) minus the 50 ms of non-labile saccade programming

time, we obtain an estimate of 40 ms. As the peripheral word also benefits from early visual processing during the first 90 ms of fixation on the foveal word, one is left with a total of 130 ms (90 ms + 40 ms) for the first, L1 phase of processing of the peripheral word (N + 1) to be completed and to influence the next saccade (see Fig. 1 for more details).

Thus, according to the E–Z Reader model, the first stage of lexical processing, which corresponds to the identification of the orthographic form of the word, should therefore take less than 130 ms for words in peripheral vision which end up being skipped. This is much shorter than the fastest estimate of word/nonword discrimination time obtained in the present study. The estimated timing of processing in E–Z Reader for the particular case where word N + 1 is skipped, occurs mainly, as noted by Reichle, Rayner, and Pollatsek (2003), when the peripheral word is "high frequency, predictable from prior context and/or short" (p. 454). However, the fact is that in the present study, target words were relatively short (five letters long) and of high printed frequency (see Footnotes 1 and 2 for further information about the ease of processing of the words tested in the present study). Furthermore, the visibility of the words in the present study was enhanced as compared to the visibility of the words in normal reading, in that letters were more than three times larger than letters in normal reading conditions (i.e. usually subtending 0.25–0.5° of visual angle). Note also that although our words extended further towards the periphery than words in normal reading, their initial letter(s) were presented no further from fixation than in normal reading (1.35° compared to 1.5–3° in normal reading, considering that saccades are initiated on average at a distance of about six letters from the beginning of a word in reading), and all the letters, even those at the most eccentric locations, were above the critical print size (CPS), that is the smallest print size that yields maximum reading speed (1.7° compared to a CPS of 1.3° for the most eccentric letter displayed at a distance of about 11° from fixation; see Chung, Mansfield, & Legge, 1998). Furthermore, unlike words in reading, our words were not flanked by other words. Thus, the level of visual crowding was certainly not higher than in normal reading.

More critically, the type of nonword (random consonant strings) used in the word/nonword discrimination task of the present study, means that the task could be performed accurately following the detection of an orthographically regular and

pronounceable combination of letters. This presumably occurs well within the early phase of lexical processing, the L1 or word familiarity check phase, that triggers saccade programming in the E–Z Reader model, and this amounts in any case to an easier decision to make than the decision that triggers saccade programming during normal reading. Thus, the present study probably underestimates the time it actually takes for lexical information to accumulate in the periphery during normal reading. Three additional observations point towards such an underestimation.

First, the fact that performance to word targets did not differ significantly as a function of visual field (targets presented to the left or to the right of fixation) could be taken as evidence that it is indeed sublexical information that is driving the word/nonword discrimination process in the present study. Given the well-established fact that visual word identification is more efficient (faster and/or more accurate) in the right visual field compared with the left visual field (e.g., Brysbaert, Vitu, & Schroyens, 1996; Ducrot & Grainger, 2007; Jordan, Patching, & Milner, 2000), the lack of a significant effect of visual field in our study suggests that word identification is unlikely to be a major factor governing saccadic choice. Furthermore, the mixed evidence concerning visual field effects on letter-in-string identification with nonword stimuli (e.g., Chanceaux & Grainger, 2010; Grainger, Tydgat, & Isselé, 2010) is consistent with the idea that sublexical orthographic processing is less sensitive to visual field differences than lexical processing (e.g., Jordan, Patching, & Thomas, 2003).

Second, the data of a pilot study suggest that our data might seriously underestimate lexical processing time per se. In this study, we used the saccadic choice task to measure the time to detect a five-letter target word presented simultaneously with one of two types of five-letter distractor stimuli, a nonword (i.e., random consonant string as in the present study) or a pronounceable pseudoword (Bendahman, Vitu, & Grainger, 2010). Stimuli were presented in conditions more similar to normal reading conditions, that is, closer to fixation than in the present study (4° instead of 6°), and they were smaller in size, each letter subtending about .5° of visual angle. Participants’ overall performance in the non-word distractor condition (82%) was only slightly higher than in the present study (75%), but the estimated minimum SRT was much longer than in the present study (380 ms vs. 200 ms). In addition, when target words were presented with pronounceable pseudowords, overall performance level was greatly reduced (58%), and the estimated minimal SRT greatly increased (431 ms). These data therefore suggest that it takes far more time to access lexical information than is assumed in E–Z Reader, and it is quite unlikely that the possibility to predict words from prior context in natural reading would boost lexical processing enough to make it occur as fast as within a 130 ms time window.

Third, the results of studies using the eye-movement contingent boundary technique (Rayner, 1975) speak to the issue of exactly what kind of information is available from word $N + 1$ while the eyes are fixating word N (so-called parafoveal preview effects) in conditions that are closer to normal reading. The evidence at present suggests that orthographic and phonological information, but not semantic information, can be extracted from word $N + 1$ (see Rayner (1998) for a review). Most important, however, is that there is little, if any, evidence for activation of lexical representations. The key finding in this respect is the fact that a very brief preview of an orthographically similar word interferes with target word processing in central vision (e.g., Segui & Grainger, 1990), and although the inhibition is reduced at the shortest preview durations, it never becomes facilitatory as in the case of orthographically similar nonword previews (De Moor, van der Herten, & Verguts, 2007; Grainger, 1992). This inhibitory effect of orthographically similar words is therefore taken to reflect activation of the corresponding lexical representation, which results in an

inhibitory influence on target word processing as these compete for identification. Now, when such orthographically similar words serve as previews in peripheral vision, facilitatory effects are systematically found (e.g., Johnson & Dunne, 2012; Williams et al., 2006). This can therefore be taken as evidence that there is little activation of lexical representations from peripherally located words.

Proponents of the E–Z Reader model could still argue that spatial uncertainty in our task (i.e., targets could appear left or right of fixation) lead to an overestimation rather than an underestimation of lexical processing time compared to normal reading. We acknowledge that our paradigm may have prevented the deployment of visual attention to the right of fixation that is assumed to intervene in normal reading. The lack of visual fields effects with both animal and word stimuli further comforts this assumption, particularly given that the right visual field advantage typically observed for isolated word recognition is presumably driven mainly by attentional biases induced by reading habits (see Ducrot & Grainger, 2007). However, as already noted above, this suggests that the word/nonword discrimination task tapped into an earlier processing level than lexical processing, and hence that it underestimated rather than overestimated the time it takes for a word to be identified in the periphery. In addition, the data of our preliminary experiment (Bendahman, Vitu, & Grainger, 2010) summarized above, did reveal a standard right-field advantage for word targets presented with pronounceable pseudoword distractors. Still, words presented in the right visual field were discriminated from pseudowords no earlier than 394 ms on average, thus comforting the idea that the slowness of peripheral word processing is a reality and not an artifact arising from bilateral stimulation. In line with this conclusion, it must also be recalled that despite bilateral stimulation, animal targets were detected extremely rapidly.

Therefore, although it is clear that words benefit from some form of peripheral processing during reading and that words can sometimes be identified in the periphery, our main conclusion, in contradiction with the dominant cognitive-control view, is that peripheral word processing must in general be too slow to be used to guide eye movements. Peripheral information is simply not detailed enough and does not accumulate rapidly enough for word identification processes to be a principal source of guidance for eye movements in reading (Vitu, 2003; see also O’Regan, 1990; Yang & McConkie, 2001). Poorly-detailed peripheral information may at best provide global visual clues (e.g. word length information) and form the basis of educated guesses relative to the ease of processing of peripheral words, thus allowing some minimal cognitive control of eye guidance (Brysbaert, Drieghe, & Vitu, 2005; Brysbaert & Vitu, 1998; Hochberg, 1975, 1976; Kerr, 1992; McDonald, Carpenter, & Shillcock, 2005; Shebilske, 1975). However, the possibility remains that the eyes move along the lines of text without searching or aiming for specific words or visual blobs, being primarily under the influence of low-level visuomotor processes (Vitu, 2003; Vitu & Blanes, 2009).

Nevertheless, although peripheral word identification may not be the main source of eye movement control of expert readers during reading, it still remains a good candidate for people with visual deficits. Patients with Age-related Macular Degeneration (AMD) have lost the ability to extract information in their central visual field and must rely on the processing of peripheral word information to read a text and guide their eyes through the text. Mr. Chips is an example of a model that uses peripheral word information to guide eye movements, and that can account for reading behavior with macular scotomas (Legge, Klitz, & Tjan, 1997; Legge et al., 2002; see also Bernard et al., 2009). Note however, that reading with a central scotoma very much slows down reading speed and greatly increases fixation durations (Rayner & Bertera, 1979). Given the slowness of peripheral word processing, longer fixation

times make it more likely that lexical processing of peripheral stimuli could influence where the eyes move next. This would be compatible with the finding from studies using artificial blocking of central vision, that reading rate is determined more by the number of masked letters rather than mask size per se (Fine & Rubin, 1999).

Finally, we will briefly speculate as to the possible reasons for why it might be so hard to identify words in peripheral vision. We suggest that it might be due to the limited information carried by global shape on the one hand, and local features (i.e., individual letters) on the other, with respect to other kinds of visual object (such as the animal stimuli in the present study). Peripheral vision would exaggerate the impact of these two factors via the increased sensitivity to low spatial frequency information (Hilz & Cavonius, 1974) and increased crowding (e.g., Bouma, 1973; Grainger, Tydgat, & Isselé, 2010; Legge, Mansfield, & Chung, 2001; Pelli et al., 2007). Therefore, not only would peripheral words be deprived of the kind of fast-guess mechanism proposed by Bar et al. (2006) for object identification, but the processing of individual letters would be handicapped by increased crowding. It might therefore be the case that peripheral word processing retains much of the same qualitative characteristics as word processing in central vision (Lee, Legge, & Ortiz, 2003), and as such does not benefit from the kind of compensatory mechanisms that might be operational with other kinds of visual object. Given the evidence that semantic information can be extracted from Chinese logographs in the periphery (Yan et al., 2009, 2010), future research could investigate the extent to which the above account might only apply to words written in alphabetic script. More generally, the results of the present study suggest that the saccadic choice task could be usefully employed in future research to investigate the processing in peripheral vision of various kinds of linguistic stimuli, including single letters.

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