PSYCHOPHYSIOLOGY

Psychophysiology, 00 (2017), 00–00. Wiley Periodicals, Inc. Printed in the USA.

DOI: 10.1111/psyp.12849

Lateralization of posterior alpha EEG reflects the distribution of spatial attention during saccadic reading

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Abstract

Visuospatial attention is an important mechanism in reading that governs the uptake of information from foveal and parafoveal regions of the visual field. However, the spatiotemporal dynamics of how attention is allocated during eye fixations are not completely understood. The current study explored the use of EEG alpha-band oscillations to investigate the spatial distribution of attention during reading. We reanalyzed two data sets, focusing on the lateralization of alpha activity at posterior scalp sites. In each experiment, participants read short lists of German nouns in two paradigms: either by freely moving their eyes (saccadic reading) or by fixating the screen center while the text moved passively from right to left at the same average speed (RSVP paradigm). In both paradigms, upcoming words were either visible or masked, and foveal processing load was manipulated by varying the words' lexical frequencies. Posterior alpha lateralization revealed a sustained rightward bias of attention during saccadic reading, but not in the RSVP paradigm. Interestingly, alpha lateralization was not influenced by word frequency (foveal load) or preview during the preceding fixation. Hence, alpha did not reflect transient attention shifts within a given fixation. However, in both experiments, we found that in the saccadic reading condition a stronger alpha lateralization shortly before a saccade predicted shorter fixations on the subsequently fixated word. These results indicate that alpha lateralization can serve as a measure of attention deployment and its link to oculomotor behavior in reading.

Descriptors: Attention, Parafoveal vision, Saccadic reading, Rapid serial visual presentation, Eye tracking, Alpha lateralization

During reading, our eyes sample each line of text with a series of saccadic eye movements that is interrupted by fixation pauses lasting on average 200–250 ms. An important top-down mechanism that governs the uptake of new visual information during each reading fixation is covert visuospatial attention (e.g., Miellet, O'Donnell, & Sereno, 2009; see Schotter, Angele, & Rayner, 2012, for a review), which serves to enhance perception within the attentional focus and to inhibit processing outside of it. However, visual attention is subject to capacity limits (for a review, see Carrasco, 2011) and therefore has to be deployed efficiently by the reader. Given its central role in reading, researchers have long sought to understand the spatial and temporal dynamics by which attention is allocated to different regions of the visual field during reading. Goal of the present study was to explore the utility of EEG alpha-band oscillations to measure the distribution of attention in reading situations with and without saccades, and to investigate the relationship between the reader's covert attention and observable fixation behavior.

This work was supported by a grant (So177/19-2) from the German Research Foundation (DFG) within the Research Group 868. We thank Florian Niefind for conceptual discussions.

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Distribution of Attention in Reading

High-acuity visual information during reading is only extracted from the fovea, the central 2° of the visual field. However, eye-tracking studies have provided strong evidence that, over the course of an eye fixation, readers also take up information from the parafovea (eccentricity of 2–5°), which is used to preprocess upcoming words before they are directly fixated. This is most evident in the so-called preview benefit (Hohenstein, Laubrock, & Kliegl, 2010; McConkie & Zola, 1979; Rayner, 1975; Rayner, Balota, & Pollatsek, 1986; Rayner, McConkie, & Zola, 1980; Yan, Richter, Shu, & Kliegl, 2009): Fixation durations on a word are 20–50 ms shorter if that word had been visible in the parafovea (rather than masked with another string or word) during the preceding fixation.

In order to extract information from both the fovea and the parafovea during a single fixation, attention must be deployed to each of these regions. Since the pool of attentional resources is limited, foveal and parafoveal processing are not independent from one another, but have been shown to interact (Henderson & Ferreira, 1990). Specifically, if the currently foveated word requires more attentional resources because it is difficult to process (i.e., inducing high foveal load), fewer resources are left to preprocess upcoming words in the parafovea, resulting in a smaller preview benefit on the next word. Conversely, if the fixated word is easy to process (i.e., inducing low foveal load), this allows more preprocessing in the parafovea, resulting in a larger preview benefit on the next

word (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Kornrumpf, Niefind, Sommer, & Dimigen, 2016; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999; White, Rayner, & Liversedge, 2005). While these findings imply that attention is dynamically allocated between foveal and parafoveal information, they do not allow inferences about the dynamics of attention within a fixation.

Electrophysiological Studies on Attention in Reading

An alternative approach to study foveal and parafoveal processing is use of EEG recordings. Two basic reading paradigms have been used in this line of research: In the first paradigm, participants are allowed to move their eyes freely over the text. The EEG is then time-locked to the onset of the reading fixations, yielding fixation-related potentials (FRPs; Dimigen, Kliegl, & Sommer, 2012; Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Hutzler et al., 2007; Kornrumpf et al., 2016; Kretzschmar, Bornkessel-Schlesewsky, & Schlesewsky, 2009; Metzner, von der Malsburg, Vasishth, & Roesler, 2015; Niefind & Dimigen, 2016). In the second paradigm, reading is studied in the absence of eye movements with the rapid serial visual presentation-with-flankers paradigm (in the following, termed RSVP; e.g., Barber, Donamayor, Kutas, & Munte, 2010; Barber, van der Meij, & Kutas, 2013; Li, Niefind, Wang, Sommer, & Dimigen, 2015). Here, sentences are presented word by word in the screen center while the participants maintain a central fixation. To approximate the natural reading process and to allow parafoveal preprocessing, the preceding and upcoming words in the sentence are shown as flanker words to the left and right of the currently presented word. ERPs are then aligned to each stimulus onset.

Using both paradigms, several recent studies (Dimigen et al., 2012; Kornrumpf et al., 2016; Li et al., 2015; Niefind & Dimigen, 2016) found an electrophysiological manifestation of the parafoveal preview benefit in the time window of the N1 component of the ERP/FRP, providing a first insight into the time course of the integration of foveally and parafoveally acquired information within a given fixation. The N1 was consistently smaller after valid than invalid previews, and this preview positivity effect was considerably larger in saccadic reading compared to RSVP and when foveal processing load was low rather than high (Kornrumpf et al., 2016).

These results suggest that attention mechanisms are a critical factor in the interactions of preview and reading paradigms as well as preview and load. First, in saccadic reading, the preparation of an eye movement is preceded by a mandatory shift of visuospatial attention toward the saccade target (Deubel & Schneider, 1996; Hoffmann & Subramaniam, 1995; Rolfs & Carrasco, 2012), whereas in passive reading, the reader is required to maintain fixation. Second, processing an easy word in the fovea requires less attentional resources than processing a difficult word. As a consequence, any surplus resources can be deployed toward the parafovea and used for the preprocessing of the upcoming word. It remains unclear, however, whether this deployment occurs in the form of discrete attention shifts as proposed by "sequential-attention-shift" models (e.g., E-Z Reader; Reichle, 2011; Reichle, Pollatsek, & Rayner, 2006) or in the form of an expanding attentional "zoom lens" as proposed by "guidance by attentional gradient" models (e.g., SWIFT; Schad & Engbert, 2012) of oculomotor control. Ultimately, both the behavioral as well as the electrophysiological approach lack a direct measure of attention distribution.

Alpha Power as a Marker of Attention Distribution

So far, only a small number of studies have investigated oscillatory activity of the continuous EEG in the context of reading (e.g., Kretzschmar et al., 2013; Metzner et al., 2015; Vignali, Himmelstoss, Hawelka, Richlan, & Hutzler, 2016). Yet already, Metzner and colleagues (2015) have provided evidence that oscillatory EEG changes elicited by world knowledge violations in the delta, theta, alpha, and gamma range differ between saccadic reading and RSVP. In the present study, we are specifically interested in the alpha band (8–14 Hz), since it represents a potentially useful direct measure of attentional deployment. In contrast to most other frequency bands, alpha responds to task demands either with an increase (event-related synchronization, ERS) or a decrease (event-related desynchronization, ERD) in band power (Klimesch, 2012; Klimesch, Sauseng, & Hanslmayr, 2007). These dynamic fluctuations of alpha power have been related to attention in various tasks and situations (for a review, see Klimesch, 2012), including intermodal attention (Foxe, Simpson, & Ahlfors, 1998), somatosensation (Haegens, Luther, & Jensen, 2012), temporal order judgments (e.g., Babiloni et al., 2004), word recognition and semantic judgments (e.g., Klimesch, Doppelmayr, Pachinger, & Russegger, 1997), as well as the spatial cueing task, both in healthy participants (e.g., Gould, Rushworth, & Nobre, 2011; Worden, Foxe, Wang, & Simpson, 2000) and participants suffering from attention-deficit hyperactivity disorder (ter Huurne et al., 2013). Together, these studies show that both sustained and transient attention can modulate the power of tonic and phasic alpha oscillations during the anticipation and processing of a stimulus (for a review, see Klimesch, 1999).

The typically observed time course of alpha modulations involves three stages: an initial short-lasting burst in poststimulus alpha power reflecting a phase-locked visual response (evoked alpha), followed by a transient decrease in induced alpha power (ERD), and finally a sustained increase (ERS; Klimesch et al., 2007; Rihs, Michel, & Thut, 2009; Worden et al., 2000). Importantly, these changes in alpha power are topographically specific. In spatial cueing tasks, parietal-occipital alpha power is generally larger over recording sites ipsi- rather than contralateral to the attended hemifield; this lateralization increases with task difficulty (Roijendijk, Farquhar, van Gerven, Jensen, & Gielen, 2013) and with increasing certainty about the upcoming stimulus location (Gould et al., 2011). The most common view is that contralateral decrease reflects facilitated processing of attended locations (Kelly, Gomez-Ramirez, & Foxe, 2009; Rihs et al., 2009; Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Yamagishi, Callan, Anderson, & Kawato, 2008; Yamagishi, Goda, Callan, Anderson, & Kawato, 2005), whereas ipsilateral increase reflects inhibition of the unattended space (Kelly, Lalor, Reilly, & Foxe, 2006; Rihs, Michel, & Thut, 2007; Rihs et al., 2009; Worden et al., 2000). The occurrence of contralateral decrease and ipsilateral increase is commonly referred to as alpha lateralization. It has been suggested that an elevated level of tonic alpha power may be required for this decrease/increase pattern to show (Rihs et al., 2009), as is the case in more difficult tasks (Doppelmayr, Klimesch, Pachinger, & Ripper, 1998a; Kelly et al., 2006; Klimesch, 1999; Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999).

In addition to covert shifts of attention, alpha lateralization has also been linked to other processes such as language perception (McKee, Humphrey, & McAdam, 1973; Spironelli & Angrilli, 2010; Strauss, Kotz, Scharinger, & Obleser, 2014) and saccade

preparation (Kaiser, Brunner, Leeb, Neuper, & Pfurtscheller, 2009; Medendorp et al., 2007). Regarding language perception, there is a left-lateralized desynchronization in word recognition tasks that increases with the "wordiness" of a stimulus (Strauss et al., 2014). Regarding saccade preparation, there is a growing body of research suggesting that alpha dynamics related to visuospatial attention may covary with saccadic behavior (Hamm, Sabatinelli, & Clementz, 2012). Presaccadic desynchronization is strongest contralateral to the saccade goal (Medendorp et al., 2007), and emerges in a 500-ms period before the go cue for a saccade, reflecting gaze-centric stimulus gating (Van Der Werf, Jensen, Fries, & Medendorp, 2008). Conversely, presaccadic synchronization occurs when a reflexive saccade to a more salient distractor is prevented and a voluntary saccade to the target is executed instead (Mazaheri, DiQuattro, Bengson, & Geng, 2011).

Importantly, not only do experimental manipulations influence alpha, but alpha oscillations can also influence behavioral outcomes (for reviews, see Hanslmayr, Gross, Klimesch, & Shapiro, 2011; Mathewson et al., 2011). Since the momentary direction of attention predicts behavioral performance at different spatial locations and since attention can be estimated from alpha lateralization, alpha lateralization itself can in turn predict those biases in performance. In visual perception tasks, prestimulus alpha power over parieto-occipital brain areas is negatively correlated with various measures of performance, such as detection rates, reaction times, and line orientation judgments (Hanslmayr et al., 2005, 2007; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009; Yamagishi et al., 2008) and can even predict performance on a trial-by-trial basis (Ergenoglu et al., 2004; Kelly et al., 2009; Thut et al., 2006; Van Dijk, Schoffelen, Oostenveld, & Jensen, 2008).

The Present Study

The present study explored the use of alpha power as a new and possibly direct marker of attentional allocation during reading. To this end, we followed up on our previous work (Kornrumpf et al., 2016; Niefind & Dimigen, 2016) and reanalyzed data from two word-list reading studies with combined recordings of eye movements and EEG (Kornrumpf et al., 2016; Niefind & Dimigen, 2016). The design of both studies, termed Experiment 1 and 2, is highly similar, and the results of Experiment 2 are included here mainly for the purpose of replication and generalization. To isolate alpha-band oscillations with relatively high temporal resolution (Graimann & Pfurtscheller, 2006), we used a standard band-pass filtering method, temporal spectral evolution (TSE; e.g., Kelly et al., 2006, 2009; Rihs et al., 2007, 2009; Thut et al., 2006; Worden et al., 2000). We then calculated an alpha lateralization index to compare biases in spatial attention between several different reading situations: First, we compared saccadic reading (with eye movements) to the RSVP paradigm (without eye movements). Second, we contrasted situations with high versus low foveal processing load. Load was manipulated in two ways: by varying the lexical frequency of the words (i.e., how often a particular word occurs in the language) and by manipulating the parafoveal preview that was obtained for a word during the preceding fixation. In a final step, we investigated whether, during saccadic reading, the degree of alpha lateralization can be used to predict the duration of the following fixation.

We held three hypotheses about alpha oscillations and fixation behavior during left-to-right reading. (1) We assumed that, in left-to-right reading with saccades, attention is deployed to the upcoming parafoveal word to the right of fixation because eye movement preparation is accompanied by an obligatory attention shift toward the saccade goal (Rolfs & Carrasco, 2012). Thus, during saccadic reading, alpha power should be stronger over the right hemisphere while this lateralization should be weaker or even absent in the RSVP paradigm requiring steady central fixation. (2) In line with the foveal load hypothesis (Henderson & Ferreira, 1990), we expected that attention is biased more strongly toward the right hemifield whenever the currently fixated word is easy rather than difficult to process, because an easy word in foveal vision should free attentional resources to process parafoveal information. Along this line of argumentation, preview could have the same effect. If the fixated word had been parafoveally visible during the preceding fixations, this preprocessing should facilitate the subsequent foveal processing of that word and again reduce the processing load (preview benefit). Consequently, there should be a stronger rightward lateralization under conditions of low foveal load. (3) As a consequence of a stronger allocation of attention toward the right visual field, upcoming information should be preprocessed more efficiently, which, in turn, should lead to a shorter processing time during the subsequent fixation. Thus, we hypothesized that a stronger rightward lateralization of alpha should index a stronger deployment of attention to the right and, as a consequence, should predict shorter fixation times on the subsequently fixated word.

Method

Participants

Two nonoverlapping samples of 24 adults each participated in Experiment 1 (ages 18–34, $M = 24.8$ years; 10 women) and Experiment 2 (ages 18–34, $M = 26.12$ years; 13 women). All participants were native German speakers with normal uncorrected visual acuity (Experiment 1: $M = 1.29 \pm 0.33$; Experiment 2: $M = 1.55 \pm 0.26$; Bach, 1996). According to the Edinburgh Handedness Inventory (Oldfield, 1971), all participants in Experiment 1 were right-handed; in Experiment 2, 22 were right-handed and two were left-handed. Procedures had been approved by the local ethics committee, and participants provided written informed consent before the experiment. They received either course credit or 16–24€.

Task

Both reading experiments used the same task. In each trial, participants silently read a list of five German nouns and then indicated via a mouse click whether the list had contained the name of an animal or not. This task (e.g., Grainger, Kiyonaga, & Holcomb, 2006) requires the processing of all words at a semantic level. An animal name was included in 20% of the lists (henceforth called *animal lists*), whereas the other 80% did not contain an animal (*regular lists*). Only data from regular lists were analyzed.

Word Materials

The words for the regular lists were drawn from a pool of 1,000 German nouns between four and six letters long ($M = 5.1$, $SD = \pm 0.8$). For each word, we retrieved word form and lemma frequencies from the extended DWDS corpus (Geyken, 2007). According to the natural logarithm of these frequencies, the words were categorized into three frequency classes with both word form and lemma frequencies either < 1 (low frequency; $n = 400$ words), > 1 and < 2 (medium frequency; $n = 200$ words), or > 2 per million words (high frequency; $n = 400$ words). We created

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200 regular word lists with five words apiece for each half of the experiment. Word length was equally distributed across the five list positions, and orthographic overlap was minimized. To construct the 100 animal lists, an additional set of 400 German nouns with 4, 5, or 6 letters ($M_{word\ form} = 1.2 \pm 1.5$, $M_{lemma} = 1.6 \pm 1.3$) was used together with 100 animal names ($M_{word\ form} = 0.03 \pm 1.2$, $M_{lemma} = -0.4 \pm 1.1$; listed in the appendix of Dimigen et al., 2012). During the experiment, animal names appeared with equal probability at all five positions of the list. Fifty animal lists were shown in each half of the experiment. For further details regarding word materials, refer to Kornrumpf et al. (2016) and Niefind and Dimigen (2016).

Design

Three factors were manipulated within-subject: reading paradigm, foveal load, and preview. Reading paradigm had two levels and was manipulated blockwise. In the saccadic reading condition, participants read the lists from left to right at their own pace by executing saccades. In the RSVP condition, participants read the lists by fixating the screen center while the lists moved word by word from right to left through their foveal field. Based on fixation duration estimates taken from the results of Dimigen et al. (2012), we set the presentation speed in the RSVP condition to match the average duration of first fixations (FFD) in the saccadic reading condition.

The second factor—foveal load—had two levels and was operationalized as the lexical frequency of the fixated word: High-frequency words were considered to induce a low processing load, whereas low-frequency words were used to induce high processing load (Henderson & Ferreira, 1990). Load (low or high) varied randomly for word positions 1 to 4 (in Experiment 1) or 2 to 5 (in Experiment 2) in the list. The remaining position was occupied by a word of medium frequency. Note that in the present study we only analyzed words at list positions 2 to 5, but not at position 1, because we were also interested in alpha lateralization before fixation onset.

The third factor—parafoveal preview—had two levels. In the invalid preview condition, each word (e.g., "Tisch," *table*) was either completely masked by a string of the letter *x* (e.g., "*Xxxxx*," Experiment 1) or another noun (e.g., "Spalt," *gap*, Experiment 2) of the same length. In the valid preview condition, the word was not masked in the parafovea, but completely visible. See Kornrumpf et al. (2016) and Niefind and Dimigen (2016) for a complete description of other design details, which are of no importance for the present study. Once a word entered foveal vision, it was always fully visible to the reader.

The three factors paradigm, foveal load, and preview were counterbalanced across all trials of a given participant and over list positions. That is, each combination of factor levels was shown equally often at each position of the list (except for the position occupied by a medium-frequency word).

Procedure

After applying the electrodes, we first recorded the EEG during a 10-min calibration task in which participants produced typical eye movements in the four cardinal directions. These recordings of stereotypical ocular artifacts were used for ocular artifact correction offline (cf. Dimigen et al., 2011, 2012). Afterward, participants received instructions for the experiment.

The reading task and the physical stimulation properties were the same in both experiments. Words were presented in black monospaced font (Courier New) on a white background separated by one-character blank spaces. One character extended 0.43° visual angle horizontally. The visual angles between the center of one word and the left edge of the next word varied between 1.34 and 1.79° ($M = 1.59° \pm 0.17$), depending on word length. The trial schemes for Experiment 1 and 2 are illustrated in Figure 1. F1

In the saccadic reading condition, trials started with a fixation check near the left screen edge followed by the appearance of the complete word list with the first letter 9.4° to the right of the fixation point. By performing saccades, participants read the list from left to right. Once their eyes crossed an invisible vertical boundary located in the middle of each blank space in between adjacent words, the upcoming target word was uncovered if it had been masked before. Words that were directly fixated were fully visible. As soon as the eyes crossed the next boundary to the right, the previously fixated word was again covered with a mask, either consisting of *x* letters (e.g., "*Xxxxx*," Experiment 1) or random consonants (e.g., "*Jknpq*," Experiment 2), and remained masked for the rest of the trial.

The mean delay to implement the gaze-contingent display change (i.e., the delay between the eyes crossing the invisible boundary and the actual update of the display) was less than 11 ms (the *SD* between trials was 2.8 ms in both experiments). The response screen with the animal question ("Animal in the list?") was triggered by fixating another fixation point near the right edge of the screen for 800 ms. A *yes* or *no* response by pressing the left or right button of the mouse initiated the next trial.

In the RSVP conditions, the list was passively presented while the reader maintained a steady central fixation. Word presentation durations (300 ms) and interstimulus blank intervals (30 ms) were set such that they closely resembled the average duration of first fixations and saccades during saccadic reading. Each trial started with a fixation check in the screen center. Subsequently, the list appeared for 300 ms with the center of the first word presented at the point of fixation. In Experiment 1, the full list of five stimuli was shown at the first presentation. At the second presentation, following the 30-ms blank interval, the list reappeared, but now with the center of the second word shown in the screen center, and so on. Apart from the fixated word in the center and the word immediately to its right, all remaining words in the list were masked by *x* masks. In Experiment 2, rather than the entire five stimuli in the list, only three stimuli were shown at a time: a left flanker, the fixated word, and the preview of the next word to the right. At the next presentation, the triplet reappeared with the previously right word in the center, and so on. After presentation of the last word, a central fixation point replaced the list for 800 ms before the response screen appeared.

Each participant completed 500 trials. Trials were split into four blocks (one block per reading condition per half of the experiments with counterbalanced order) each containing 100 regular and 25 animal lists that were presented in a randomly intermixed order. Six practice trials before each block familiarized participants with the reading mode in the upcoming block.

Eye Tracking and EEG Recording

Participants were seated in a dimly lit, electrically shielded cabin at a viewing distance of 60 cm from a 22-inch CRT monitor (Iiyama Vision Master Pro 514, resolution 1,024 × 760 pixels, vertical refresh rate 160 Hz). Stimuli were presented using Presentation software (Neurobehavioral Systems Inc., Albany, CA).

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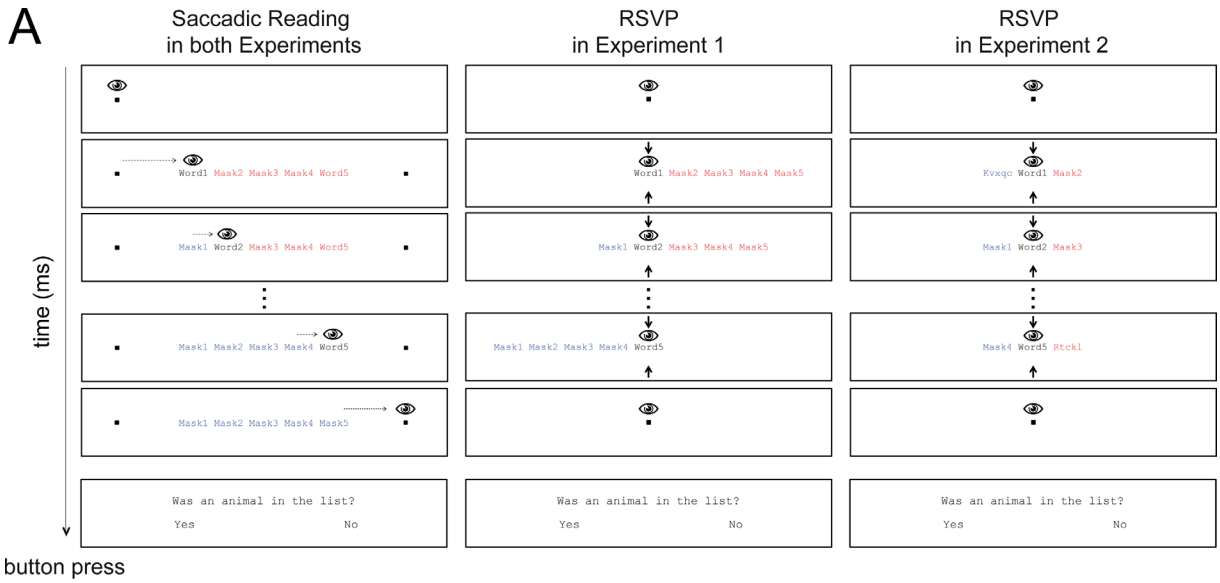

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Figure 1. Trial scheme. A: Left—In saccadic reading, the list of five words appeared on the midline of the screen, and participants moved their eyes to read it from left to right at their own pace. To finish reading, participants fixated a point on the right side of the screen and then responded with a mouse click whether the list had contained the name of an animal. Middle, Right—In RSVP, participants maintained central fixation throughout the trial. In Experiment 1 (middle), the word list first appeared with the center of the first word positioned at fixation. It remained on the screen for 300 ms, disappeared for 30 ms, and then reappeared but shifted so that the center of the second word was positioned at fixation, and so on. In Experiment 2 (right), a word triplet appeared with the first word of the list centered at fixation and flanked by a consonant string to its left and the next word in the list to its right. At the same stimulus-onset asynchrony of 330 ms as in Experiment 1, the next triplet appeared with the second word in the list centered at fixation, and so on. Small arrows were continuously presented above and below the screen center to aid maintaining a central fixation. After presentation of the fifth word, the list was replaced by a fixation point and the animal question appeared. B: The currently fixated word was always fully visible. The word to the right (i.e., the next word in the list) was either visible or (partially) masked with *x* letters (Experiment 1) or another noun (Experiment 2) and unmasked upon fixation of that word. The word to the left (i.e., the previously fixated word) was always masked.

In the following, we give only a short summary of the eye tracking and EEG hardware setup since details are provided in Kornrumpf et al. (2016). The hardware setup was identical in both experiments. Eye movements were recorded binocularly at a rate of 500 Hz with a high-resolution eye-tracker (iView-X Hi-Speed 1250; SMI GmbH, Teltow, Germany) that was recalibrated with a nine-point grid at least every 25 trials. Electrophysiological data were recorded from 46 Ag/AgCl electrodes at a sampling rate of 500 Hz and with a pass-band from 0.016250 Hz using BrainAmp amplifiers (Brain Products GmbH, Gilching, Germany). Electrodes were initially referenced against the left mastoid (A1), but the data were rereferenced to an average reference offline.

Eye tracking and EEG data were synchronized offline with the EYE-EEG extension (Dimigen et al., 2011; http://www2.hu-berlin.de/eyetracking-eeg/index.php) for EEGLAB (version 13.4.4b; Delorme & Makeig, 2004), based on common TTL (transistor-transistor logic) trigger pulses. Corneoretinal artifacts from eye movements were corrected using the surrogate variant of the multiple source eye correction method (MSEC; Berg & Scherg, 1994). Refer to Dimigen et al. (2011, 2012) for procedural details and an in-depth evaluation of the MSEC algorithm and its performance on natural reading data.

Data Preprocessing

In both experiments and reading conditions, trials containing an incorrect manual response, blinks, missing data in the eye track, or vertical gaze deviations $> 3.6°$ were discarded. Additionally, in the RSVP condition, a trial's data were rejected as soon as the horizontal gaze deviated $> 1.3°$ from the screen center (Kornrumpf et al., 2016; Li et al., 2015; Niefind & Dimigen, 2016). For the remaining trials, we identified fixations and saccades using the algorithm by Engbert and Mergenthaler (2006; vertical threshold = 5 *SD*s). Small saccades of less than one character were considered as part of the fixation. Note that in Experiment 1, only two of the original five preview levels (see Kornrumpf et al., 2016) were analyzed.

In saccadic reading, we excluded individual fixations if any of the following conditions were met: (a) The display change occurred > 20 ms after saccade offset ($n = 1{,}883$ in Experiment 1, $n = 2{,}738$ in Experiment 2). (b) The left and right eye fixated on

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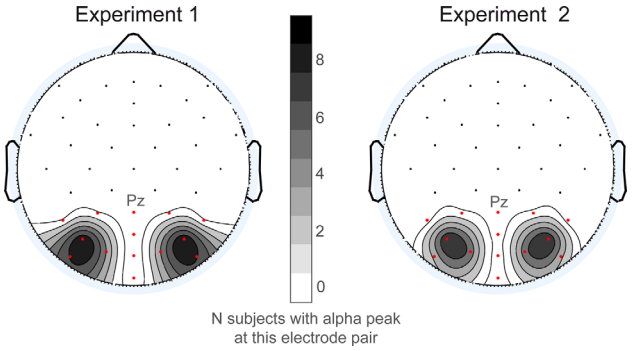

Figure 2. Electrodes used for alpha analyses. Red dots mark the electrodes used to determine the individual alpha frequency. The gray shading visualizes how often (i.e., in how many participants) a particular electrode pair served for the calculation of the LI.

different words ($n = 632$ in Experiment 1, $n = 774$ in Experiment 2). (c) Fixation durations lasted < 50 ms ($n = 14$ in Experiment 1, $n = 33$ in Experiment 2) or $> 1{,}000$ ms ($n = 42$ in Experiment 1, $n = 71$ in Experiment 2).

After rejections, 6,103 epochs (Experiment 1) and 13,709 (Experiment 2) epochs remained in the saccadic reading condition, and 6,537 epochs (Experiment 1) and 17,836 epochs (Experiment 2) remained in the RSVP condition for final analyses.

Determination of Individual Alpha-Frequency Band

To allow for individual alpha-band variations and to minimize interactions with other frequency bands (Doppelmayr, Klimesch, Pachinger, & Ripper, 1998b; Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998; Klimesch, Russegger, Doppelmayr, & Pachinger, 1998), we defined for each participant an individual alpha frequency (IAF) based on the posterior electrode showing the strongest alpha peak.

The 800-ms fixation interval preceeding the presentation of the first word in RSVP trials served as a neutral baseline to compute the IAF. For this purpose, these epochs of 800 ms (from 0 to +800 ms relative to the onset of the trial initial fixation point) were subjected to a fast Fourier transform using the newtimef function of EEGLAB with a frequency resolution of 0.63 Hz, a window size of 398 samples, a pad ratio of 2, and a Hanning taper. Each participant's IAF was defined as the frequency with the overall maximal power at any frequency between 8 and 14 Hz at any one of the following parietal, parieto-occipital, or occipital electrodes: P7/P8, P3/P4, Pz, PO9/PO10, PO7/PO8, POz, O1/O2, Oz, or Iz (the electrodes marked in red in Figure 2). In line with previous studies (e.g., Gould et al., 2011; Thut et al., 2006), the individual alpha band was defined as the IAF ± 2 Hz. The mean IAF was 10.3 Hz ($SD = 0.9$) in Experiment 1 and 10.2 Hz ($SD = 1.0$) in Experiment 2. The electrode defining the IAF and its symmetric counterpart over the opposite hemisphere was used to compute the alpha lateralization for each participant (see below).

Time-Frequency Analysis

To extract alpha power, we first band-pass filtered the continuous, artifact-corrected EEG by applying a Butterworth filter of the fourth order using EEGLAB's function basicfilter. The low-pass filter cutoff was set to IAF + 2 Hz and the high-pass filter cutoff to IAF − 2 Hz. After filtering in the alpha band, epochs were cut from −400 ms to +1,100 ms relative to the onset of all time-locking events (simply called events in the following), that is, fixation onsets in the saccadic reading condition and stimulus onsets in the RSVP condition. In addition, in order to subtract the evoked alpha activity from the overall alpha activity, we calculated for each participant and condition the mean band-pass filtered ERP, averaged across all of the band-pass filtered epochs. For each epoch, we then subtracted the evoked alpha activity from the respective condition, thereby preserving only induced activity not strictly time-locked to the event.[1] In a final step, the data were rectified, resulting in induced band power (Klimesch, Doppelmayr, Röhm, Pöllhuber, & Stadler, 2000; Klimesch, Doppelmayr et al., 1998; Klimesch, Russegger et al., 1998), and temporally smoothed with a moving average with a window size of 100 ms.

To investigate relationships between reading paradigm, fixation durations, and alpha lateralization, we calculated a lateralization index (LI) of alpha for each individual event on an event-by-event basis. The LI summarizes the relative distribution of alpha power over both hemispheres in one value and, therefore, allows for the investigation of differential changes over the left versus right hemisphere (e.g., Perez et al., 2009; ter Huurne et al., 2013; Thut et al., 2006). For each participant, we defined a bilaterally symmetric electrode pair, which included the IAF-defining electrode with the strongest alpha activity and its counterpart over the opposite hemisphere (e.g., if the IAF was detected at PO9, the individual electrode pair consisted of PO9 and PO10). If the IAF was detected at a midline electrode (e.g., Oz), we analyzed the bilateral electrode pair closest to that electrode (e.g., O1 and O2). A topographic illustration of which electrode pairs were chosen for the calculation of the LI in both experiments for how many of the participants is provided in Figure 2. The mean LI in four predefined time windows (see below) was then calculated according to the following formula (see also Perez et al., 2009; ter Huurne et al., 2013):

$$LI = \frac{IBP(right) - IBP(left)}{IBP(right) + IBP(left)}$$

Note that the LI is a relative measure: Positive values indicate that alpha power is stronger over the right than left hemisphere and negative values indicate the opposite. It does not inform about whether there is an increase in power over one hemisphere or a decrease over the other. To obtain the grand mean LI for each condition, LIs for individual events were first averaged within and then across participants.

Statistical Analyses

We used linear mixed effect models (LMMs) for statistical analyses. All models were run using the lmer function of the lme4 package (version 1.1-7; Bates, Maechler, & Dai, 2008) for R (version 3.1.1; R Core Team, 2013). In comparison to ANOVAs, LMMs provide three advantages: They do not lose statistical power due to (1) imbalanced amounts of observations per cell (Pinheiro & Bates, 2000), or (2) due to dichotomization of continuous variables, such as foveal load (Baayen, 2004; Cohen, 1983; MacCallum, Zhang, Preacher, & Rucker, 2002), and (3) the models allow us to include both participants and items as crossed random effects (Forster & Dickinson, 1976).

To investigate the influence of reading paradigm on alpha lateralization during a given epoch, we modeled the LI as a function of

1. For analyses focused on evoked activity in the time domain, refer to Kornrumpf et al. (2016).

Table 1. *Mean FFDs (in ms) in Saccadic Reading (and Between-Subject SDs)*

			Load		
			Low	High	Overall
Experiment 1	Preview	Invalid	305 (39)	338 (40)	321 (38)
		Valid	285 (36)	309 (40)	297 (36)
		Overall	295 (35)	323 (39)	–
Experiment 2	Preview	Invalid	331 (68)	335 (72)	333 (70)
		Valid	299 (53)	305 (53)	302 (53)
		Overall	315 (60)	320 (62)	–

four predictors: paradigm, preview, foveal load, and time. Paradigm was specified with a treatment contrast; according to our hypotheses, saccadic reading was compared to the reference level RSVP. Preview was specified with a sum contrast. The predictor foveal load was operationalized as the currently inspected word's lexical frequency (word form frequency). For statistical analysis, frequency was log-transformed, centered, and entered into the LMM as a continuous variable. The predictor time had four levels, which encompassed four different time intervals relative to event onset: pre-event (−300 ms to 0 ms), early (0 ms to 300 ms), middle (300 ms to 600 ms), and late (600 ms to 900 ms). Time was specified with a treatment contrast with the pre-event interval serving as the reference level.

To analyze the relationship between alpha lateralization and fixation behavior in the saccadic reading condition, we focused on fixation durations (FFDs) during first-pass reading as a dependent variable. FFD is defined as the duration of the initial fixation on a word, regardless of whether a word is refixated or not. FFD values were log-transformed and analyzed as a function of the average LI in the four time intervals relative to fixation onset: $LI_{pre\text{-}event}$, LI_{early}, LI_{middle}, and LI_{late}. Because LI serves as predictor in this model, LI values were centered (subtraction of mean value) for this analysis. Since the factors preview and foveal load have previously been shown to influence FFDs during list reading (see Kornrumpf et al., 2016; Niefind & Dimigen, 2016), both were included as covariates in the model for the purpose of statistical control.

Following recommendations by Barr, Levy, Scheepers, and Tily (2013), all models were run with a maximum random effects structure, but no correlations between random effects were included. The models contained random slopes for all fixed effects over participants and words, respectively. For all fixed effects of interest, we report regression weights (b), standard errors (SE), and t values (t). Any t values $> |1.96|$ are interpreted as significant since the t distribution approaches the normal distribution for large data sets like ours (Baayen, Davidson, & Bates, 2008).

Results

Task Performance and Reading Behavior

Accuracy in the animal detection task was generally high (94.4% ± 2.4 *SD* across both experiments), indicating that participants read and understood the meaning of the words. In Experiment 1, there was no difference in accuracy between saccadic reading ($M = 94.4\% \pm 2.2$ *SD*) and the RSVP condition ($M = 94.3\% \pm 2.9$ *SD*; $p = .70$). In Experiment 2, participants performed slightly better in the RSVP condition ($M = 95\% \pm 2.3$ *SD*) than the saccadic reading condition ($M = 93\% \pm 3.1$ *SD*; $p < .001$).

In the saccadic reading condition, participants needed on average 2.4 and 2.6 s in Experiment 1 and 2, respectively, to read the whole word list, with average FFDs of 309 and 304 ms per word and saccade durations of 32 and 35 ms. These mean FFDs (see also Table 1) and mean saccade durations closely resembled the fixed durations of word presentations (300 ms) and interword blank intervals (30 ms) in the RSVP condition. Thus, the overall reading speed was closely matched in the two reading paradigms.

Effect of Reading Paradigm on Alpha Lateralization

Figure 3 and 4 (Experiment 1 and 2, respectively) show the time courses of grand-averaged alpha-band activities at different pairs of posterior electrode sites for saccadic reading and RSVP. The lower panels show the time courses at the individually defined alpha peak electrodes as well as the LIs, which is the difference between the activities measured at the left and right peak electrodes. In saccadic reading, alpha amplitudes were mostly larger at electrode sites over the right compared to the left hemisphere. In RSVP, this difference was much smaller or even absent. As a consequence, the LIs consistently showed more positive values (i.e., rightward lateralization) in saccadic reading and more negative values (i.e., leftward lateralization) in RSVP.

Note that the absolute alpha power did not show a clear transient decrease and increase (i.e., ERD/ERS patterns) after event onset. This is most likely due to the fast pace of stimulation in the present experiments, that is, the short fixation periods (in saccadic reading) and short stimulus-onset asynchronies (in RSVP).

Figure 5 depicts the effect of paradigm on the average LI within the four time intervals. Since Experiment 2 served mainly for replication, we will primarily describe the results of Experiment 1 in the following and provide values for Experiment 2 in parentheses. Unless explicitly mentioned, the results of the two experiments did not differ.

For saccadic reading, there was a rightward alpha lateralization throughout the entire epoch. On top of this general rightward bias, we observed a pattern across time: The LI is largest prior to fixation onset; this is followed by a gradual drop and finally an increase toward the end of the epoch. This pattern was replicated in Experiment 2. The analysis of RSVP trials shows a slightly different pattern. Here, the LI is around zero prior to the onset of the stimulus. After stimulus onset, there is an increase in leftward lateralization followed by a return to zero and another leftward increase. In Experiment 2, lateralization did not change across the epoch.

These visual impressions are supported by the results of the LMMs. There was a main effect of paradigm on the LI. As expected from our first hypothesis, the pre-event LI (−300 to 0 ms) was more positive in the saccadic condition than in the RSVP condition (Experment 1: $b = 0.033$, $SE = 0.0075$, $t = 4.47$; Experiment 2: $b = 0.046$, $SE = 0.0069$, $t = 6.70$). As revealed by the intercept of the LMM (note that paradigm was treatment contrast coded with RSVP set as reference level), the pre-event LI did not differ from zero in the RSVP condition (Experiment 1: $b = 0.0017$, $SE = 0.011$, $t = -0.15$; Experiment 2: $b = -0.0045$, $SE = 0.0097$, $t = -0.46$).

There was a main effect of time. The averaged LI was smaller in the early ($b = 0.0078$, $SE = 0.0035$, $t = -2.20$) and the middle ($b = 0.0074$, $SE = 0.0035$, $t = -2.08$) time window than during the pre-event interval. As is also apparent from the similar time course of the LI in both paradigms, time did not interact either with paradigm or any other factor. Note that in Experiment 2 there was no effect of time, but an interaction between time and paradigm. This

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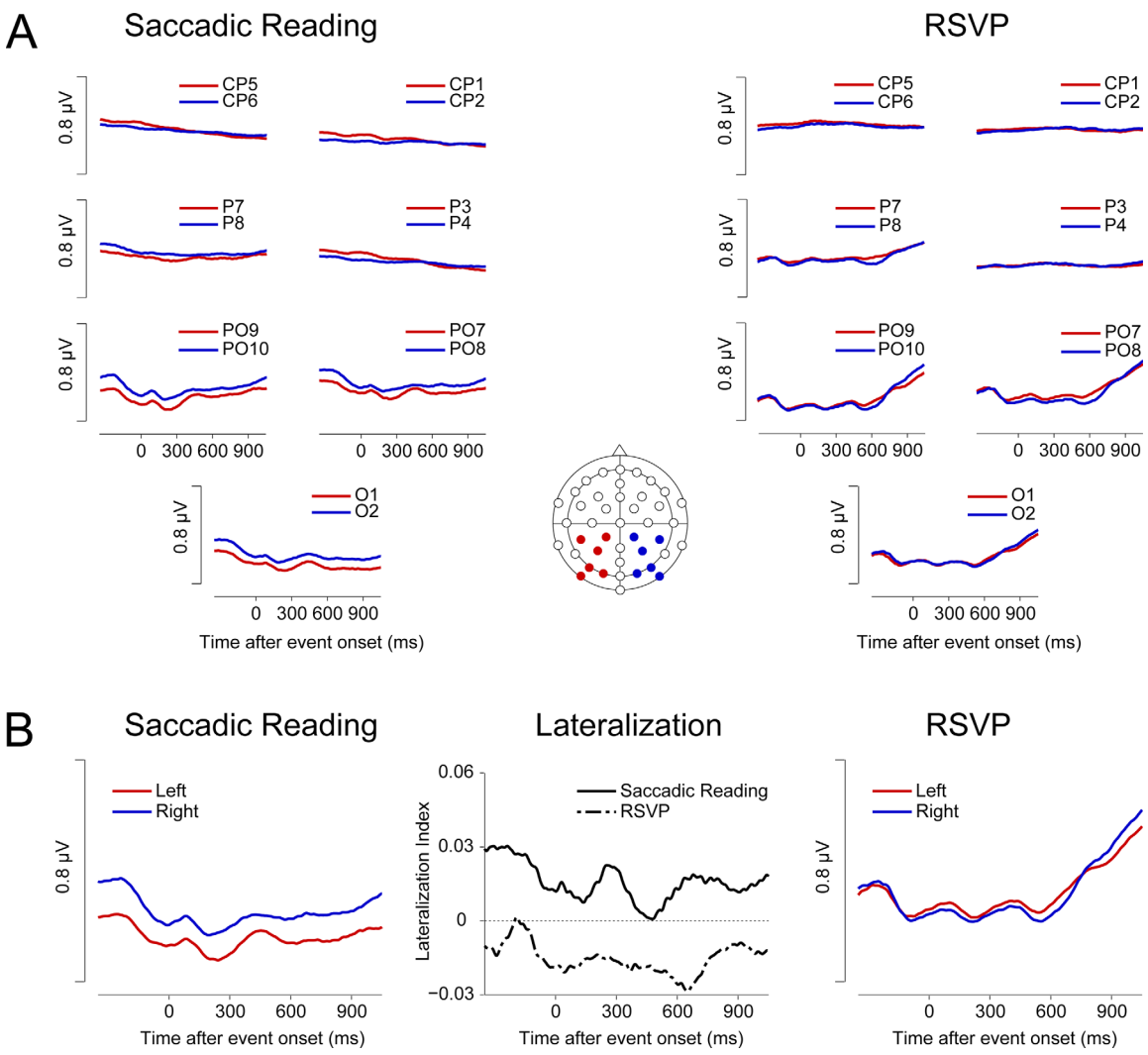

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Figure 3. Time course of grand-averaged alpha-band activity in Experiment 1 at pairs of posterior electrode sites for saccadic reading and RSVP (A), and for individual posterior electrode sites, averaged per hemisphere (B), which were derived from the determination of the IAF during the baseline interval and served for the calculation of the corresponding alpha lateralization index (B, middle).

means that the LI was smaller in the early ($b = 0.0077$, $SE = 0.0032$, $t = -2.40$), the middle ($b = 0.018$, $SE = 0.0032$, $t = -5.71$), and the late ($b = 0.012$, $SE = 0.0032$, $t = -3.68$) time window than during the pre-event time window, but this was only the case in saccadic reading.

In disagreement with our second hypothesis, there were no effects of foveal load or preview on the LI in either experiment. In contrast, foveal load and preview—as well as the LI—did affect fixation behavior. These results will be described in the following.

Relationship Between Alpha Lateralization and Fixation Duration

In a second set of analyses, we investigated whether LI is a significant predictor of oculomotor behavior during reading. For this purpose, we analyzed only the fixation data from the saccadic reading condition. Preview and foveal load were entered into the model as covariates, and the mean FFDs in the resulting four crossed conditions are summarized in Table 1.

In accordance with previously reported behavioral results (Kornrumpf et al., 2016; Niefind & Dimigen, 2016), the models showed the expected main effects of preview (Experiment 1: $b = 0.040$, $SE = 0.007$, $t = 6.12$; Experiment 2: $b = 0.041$, $SE = 0.006$, $t = 6.75$), such that invalid preview led to longer FFDs (Experiment 1: $M = 320.6$ ms, $SD = 18.6$; Experiment 2: $M = 322.7$ ms $\pm$ 29.8) than valid preview (Experiment 1: $M = 307.3$ ms $\pm$ 18.0; Experiment 2: $M = 310.8$ ms $\pm$ 23.4). Similarly, a main effect of foveal load (Experiment 1: $b = -0.009$, $SE = 0.003$, $t = -3.22$; Experiment 2: $b = -0.005$, $SE = 0.002$, $t = -2.73$) reflected the fact that FFDs were shorter when the currently fixated word was frequent (Experiment 1: $M = 306.4$ ms $\pm$ 18.1; Experiment 2: $M = 315.4$ ms $\pm$ 25.9) rather than infrequent in the language (Experiment 1: $M = 311.9$ ms $\pm$ 20.3; Experiment 2: $M = 317.9$ ms $\pm$ 27.0). There were no significant two-way or three-way interactions.

Figure 6 illustrates the effect of alpha lateralization during the pre-event period before fixation onset on the duration of the subsequent fixation. The plot depicts the FFD values estimated by the LMM, which are therefore already controlled for contributions of the other covariates entered into the model, preview, and foveal load. F6

Confirming our third hypothesis, we found that, with increasing rightward lateralization of alpha power during the pre-event

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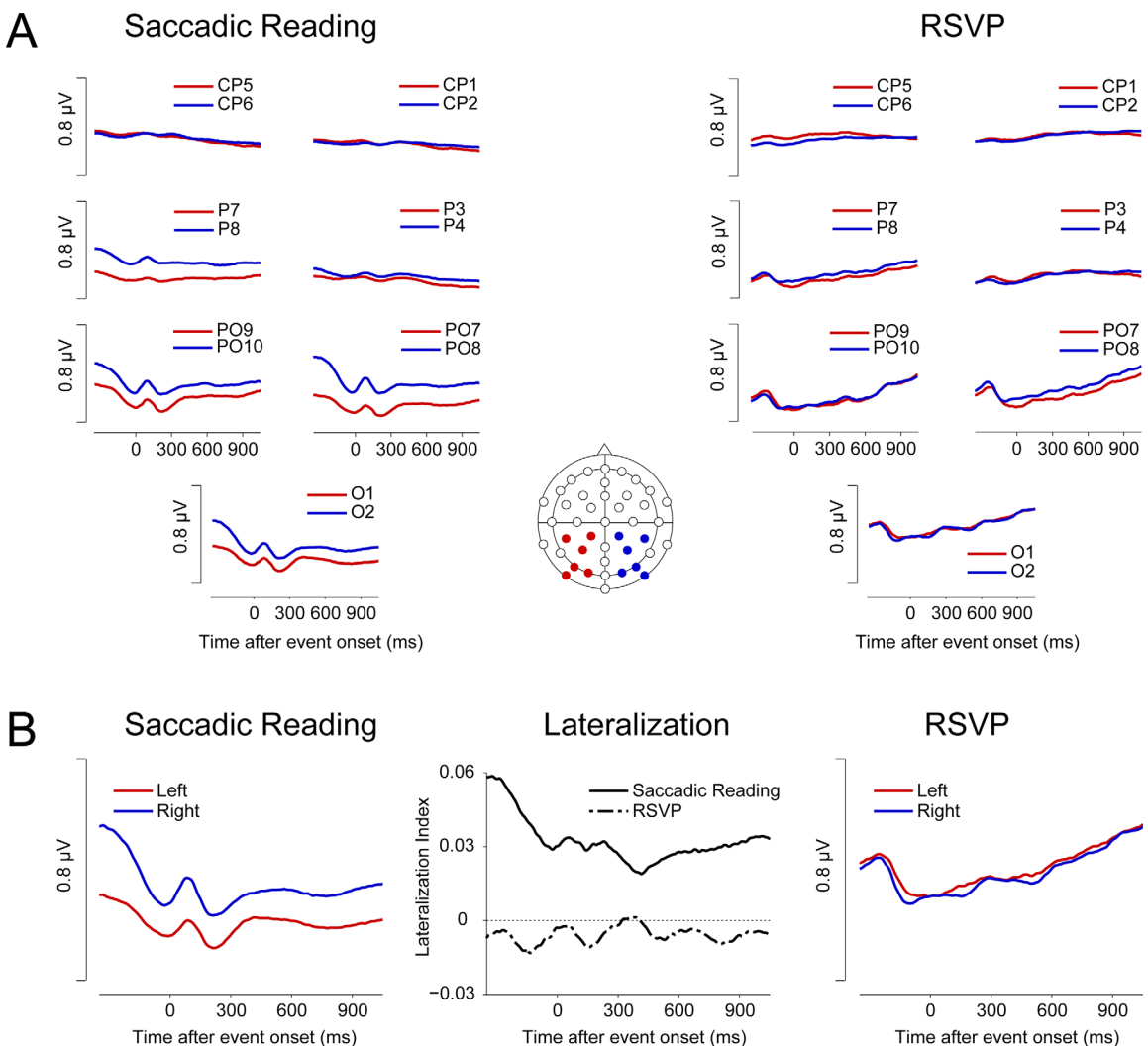

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Figure 4. Time course of grand-averaged alpha-band activity in Experiment 2 at pairs of posterior electrode sites for saccadic reading and RSVP (A), and for individual posterior electrode sites, averaged per hemisphere (B), which were derived from the determination of the IAF during the baseline interval and served for the calculation of the corresponding alpha lateralization index (B, middle).

interval, FFD decreased. This relationship was supported by the fixed effect coefficients, which showed a main effect of $LI_{\text{pre-event}}$ (Experiment 1: $b = -0.045$, $SE = 0.022$, $t = -2.03$; Experiment 2: $b = -0.036$, $SE = 0.017$, $t = -2.07$). In contrast, LI in the three later time windows did not predict FFD in either experiment.

Discussion

The current study investigated the spatial distribution of attention in saccadic reading and in the RSVP paradigm. We reanalyzed two independent data sets from word-list reading experiments with regard to the lateralization of posterior alpha activity. In two analyses, we investigated (1) the influence of reading paradigm, foveal load, and preview on alpha lateralization, as well as (2) the relationship between alpha lateralization and fixation durations. Overall, we found a rightward lateralization of alpha in saccadic reading, but no such asymmetry in RSVP. Superimposed on the general rightward bias in saccadic reading was a temporary and gradual decrease of alpha lateralization at the beginning of the fixation followed by a rebound toward the epoch's end. In the RSVP paradigm, alpha power became left-lateralized after stimulus onset in Experiment 1, whereas it remained symmetrical in Experiment 2. Also, alpha lateralization before fixation onset predicted the fixation duration on the following word. In contrast, attentional differences related to differences in foveal load or the validity of the preview were not reflected in the lateralization index, presumably because these changes take place on shorter time scales or because they only modulate evoked ERP activity (Kornrumpf et al., 2016; Niefind & Dimigen, 2016), but not the induced alpha-band oscillations analyzed here. Notably, almost all results of Experiment 1 were replicated in Experiment 2 with an independent sample of participants, suggesting that our findings are reliable. In the following, we will discuss each of these main results.

Alpha Lateralization Reflects Attention Bias in Saccadic Left-to-Right Reading

Posterior alpha power showed a clear rightward lateralization in saccadic reading, but not in RSVP, implying that in the former situation attention was directed more strongly toward upcoming parafoveal information in the right visual hemifield. This finding adds to recent findings by Kornrumpf et al. (2016) and Niefind and

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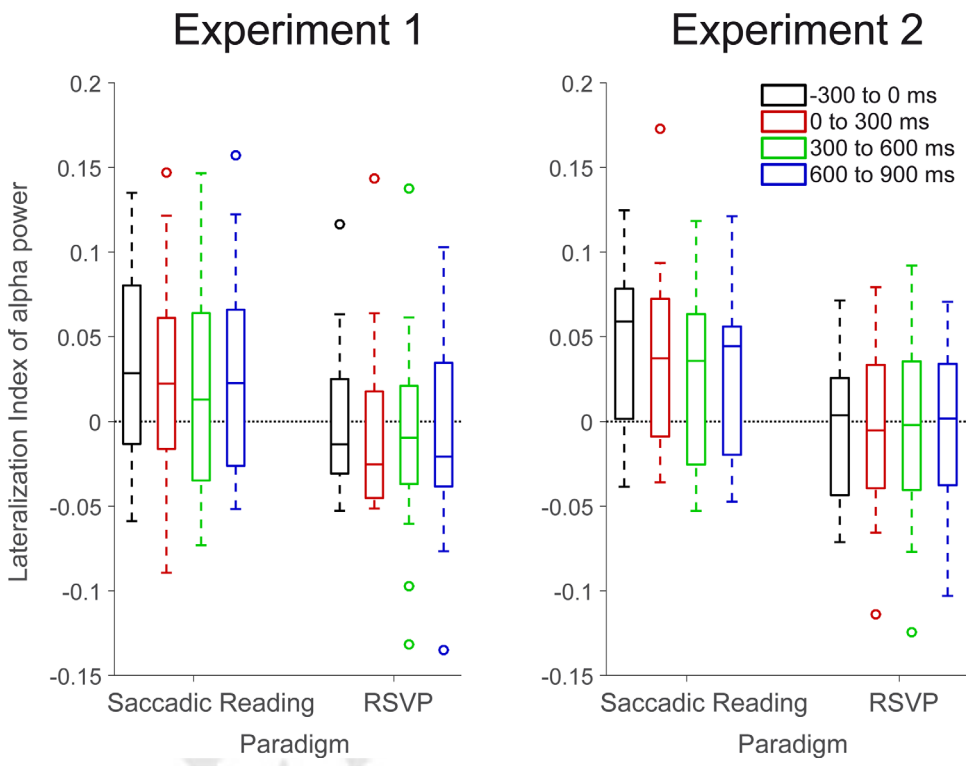

Figure 5. Effect of paradigm and time on alpha lateralization. For Experiment 1 (left) and Experiment 2 (right), the lateralization index of alpha power for the four levels of time is depicted separately for saccadic reading and RSVP. Positive values reflect stronger alpha power over the right hemisphere, and negative values reflect stronger alpha power over the left hemisphere, respectively. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers depict ± 2 *SD*s, and the circles depict subject averages considered outliers.

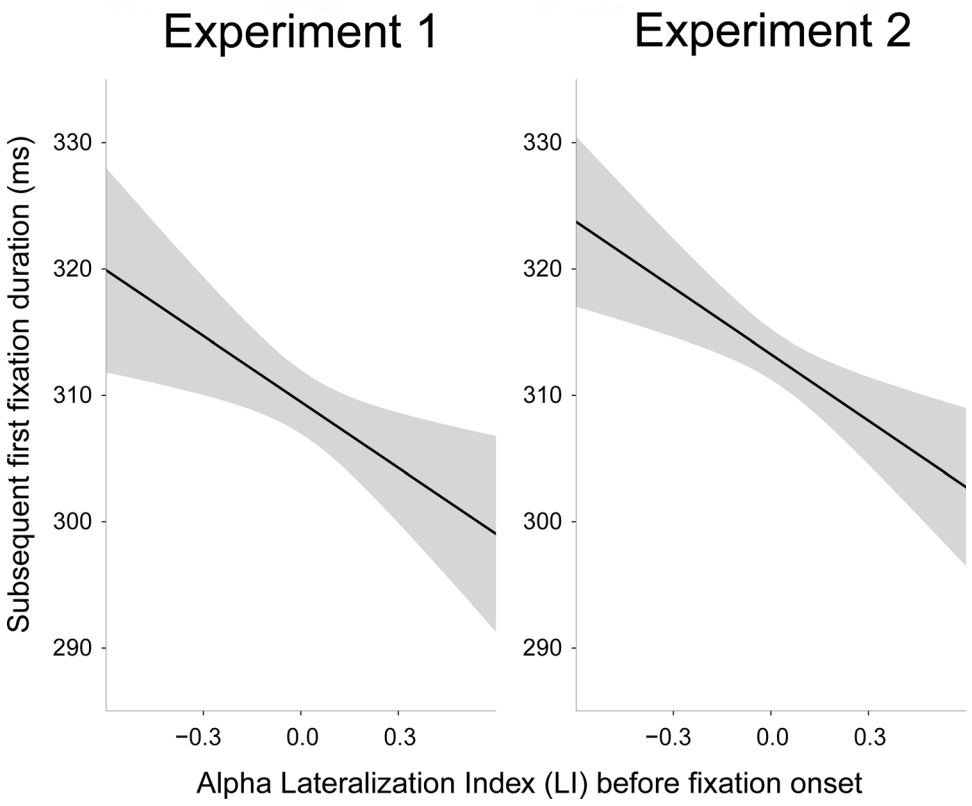

Figure 6. Effect of alpha lateralization on FFDs. For Experiment 1 (left) and Experiment 2 (right), the estimated FFDs are plotted as a function of the (centered) lateralization index within the pre-event time window before fixation onset (−300 ms to 0 ms). Gray areas indicate the 95% confidence interval of the estimated values.

Dimigen (2016), showing that brain-electric correlates of the preview benefit, in particular, the preview positivity effect on the N1 component, are significantly larger in saccadic reading than in RSVP, even though the parafoveally available visual information is the same in both situations. In Kornrumpf et al. (2016), we offered two explanations for this difference: The first is that there is a general attentional bias into the reading direction when reading naturally, probably caused by presaccadic attention shifts that enhance preprocessing of the saccade target. The other explanation is that this bias is artificially suppressed during RSVP due to the task requirement of maintaining central fixation. Below, we address these two explanations in turn.

Parietal-occipital alpha power has been linked to the direction of (covert) visuospatial attention in a variety of situations, most often in spatial cueing tasks. The commonly observed pattern is a lateralization of alpha as a function of attention direction: There is a power decrease contralateral to the attended space, presumably reflecting enhanced processing (Kelly et al., 2009; Rihs et al., 2009; Sauseng et al., 2005; Thut et al., 2006; Yamagishi et al., 2005, 2008), and a power increase ipsilateral to the attended space, presumably reflecting an inhibition of processing (Kelly et al., 2006; Rihs et al., 2007, 2009; Worden et al., 2000). In addition, tasks in which internally represented or maintained information has to be selected seem to lead to a general increase in alpha power (Benedek, Schickel, Jauk, Fink, & Neubauer, 2014; Foxe et al., 1998; Van der Lubbe, Bundt, & Abrahamse, 2014).

Our results reveal a sustained rightward alpha lateralization in saccadic reading. This lateralization was particularly pronounced prior to fixation onset, but lasted for the entire epoch and covered the time range of several subsequent fixations. We interpret this finding to reflect a general attention bias in saccadic reading toward the right visual hemifield and into the predominant direction of reading. A similar sustained adjustment of attention has previously been observed by Kornrumpf and Sommer (2015) in a readinglike situation that required participants to read only the central word or the central and right parafoveal word of a word triplet while maintaining fixation. In this study, the N1 elicited by task-irrelevant probe stimuli that were flashed near the central and parafoveal word also revealed an increased attention deployment to the parafovea that persisted across trials in blocks where the parafoveal word was task relevant. In accordance with the well-established asymmetry of the perceptual span in reading (McConkie & Rayner, 1975, 1976), the attentional bias indexed by alpha lateralization in the present analysis may serve the perceptual enhancement of upcoming information allowing for efficient processing in a highly overlearned task. This overall rightward bias was superimposed by a relative decrease in rightward lateralization after fixation onset. Plausibly, this pattern could reflect the initially stronger focusing and prioritized processing of the foveated word during the beginning of the fixation, before attention is shifted toward parafoveal information.

Moreover, eye movements—especially in the horizontal direction—are correlated with parieto-occipital alpha desynchronization (Kaiser et al., 2009) both prior to and during saccade execution. The desynchronization prior to saccades is stronger contralateral to the saccade goal (Medendorp et al., 2007). Since the brain networks recruited during covert and overt shifts of attention mostly overlap (Corbetta et al., 1998; de Haan, Moryan, & Rorden, 2008; Ikkai & Curtis, 2008; Nobre, Gitelman, Dias, & Mesulam, 2000), the alpha dynamics of visuospatial attention allocation may covary with saccadic behavior (Hamm et al., 2012). This could explain why we observed an overall rightward lateralization in left-to-right reading, but not in RSVP. In the RSVP paradigm, an attentional reorienting toward the upcoming word is not required since no saccade follows. It is therefore possible that the attentional bias toward the right is much weaker in reading situations without saccades and that the RSVP paradigm fails to capture this typical aspect of reading.

Alternatively, it could be that the rightward orienting of attention needs to be actively suppressed in order to meet the task requirements of RSVP, namely, maintaining central fixation. Such an active suppression of attention shifts would bind additional resources and also add an unnatural element to RSVP reading with flankers. Kornrumpf et al. (2016) suggested that the apparent motion of the word list from right to left in the RSVP-with-flankers paradigm may have actually biased attention toward the left due to the tendency of our eyes to follow the movement of visual objects. To explicitly avoid this confound, Niefind and Dimigen (2016) presented only three word stimuli at a time rather than all five. Our result patterns in the two experiments support the view of these authors. While alpha power remained symmetrical throughout the entire epoch in Experiment 2, there was a significant lateralization to the left following stimulus onset (i.e., around the time the entire list of words shifts one position to the left) in Experiment 1, indicating that attention is indeed drawn leftward before returning to the center prior to the next event.

It is noteworthy that the saccadic reading and RSVP condition involved the same language processes, namely, to read words and to judge their meaning. Any left-hemispheric desynchronization due to the brain's left-hemispheric specialization for language should have occurred similarly in both paradigms and can therefore be ruled out as an explanation for the observed difference in lateralization.

Taken together, reading with saccades strongly biases alpha lateralization. This indicates a disparity in attention allocation such that there is comparatively rightward attention direction in saccadic reading and a more central attentional focus in RSVP. This sustained bias is most likely due to the left-to-right reading direction acquired over the reader's lifetime, the tight link between attention and saccade preparation, or both.

Alpha Lateralization Predicts Fixation Behavior

To relate alpha to oculomotor behavior during saccadic reading, we computed the alpha lateralization in the 300-ms interval before fixation onset. Because the average fixation in our reading task lasted around 300 ms, this interval corresponds approximately to the duration of the preceding fixation. Interestingly, in both data sets, prefixation alpha lateralization was a predictor for the duration of the following fixation: The larger the LI during a given fixation, the shorter the next fixation. There was no connection between fixation duration and alpha lateralization in later time windows, which indicates that the relationship between prestimulus alpha lateralization and the subsequent fixation duration is specific and directional. This result adds to a body of research demonstrating relationships between trial-by-trial variability in the amplitude of ongoing alpha oscillations before stimulus onset and the subsequent behavioral performance (Ergenoglu et al., 2004; Kelly et al., 2009; Mathewson et al., 2009; Thut et al., 2006; Van Dijk et al., 2008). Most closely related to our findings, Thut et al. (2006) reported that alpha lateralization predicts the processing of upcoming visual targets in a Posner cueing task, such that reactions are faster when alpha power is stronger ipsilateral to the target. While in their analysis trials were split into bins according to the lateralization index, we could show the same pattern here with a continuous predictor. Our results therefore provide further evidence that alpha lateralization indicates

attentional processes that can predict behavioral outcome at a single-trial level. If we assume that alpha lateralization indicates the momentary attention deployment, this finding implies that attention distribution is, in fact, one of the factors that contributes to subsequent word processing.

Surprisingly, there was no interaction between prestimulus alpha lateralization and the size of the preview benefit in reading. Attentional deployment to the right visual field enables preprocessing of the upcoming word, which then results in faster processing during the next fixation (Rayner, 1975). One would expect that stronger alpha lateralization is only beneficial if useful information, rather than a mask, is presented in the parafovea.[2] In contrast, our results would suggest that stronger alpha lateralization is generally beneficial for reading performance, possibly because preparatory attentional processes or increased efficiency of the saccadic system contribute to improved perception and processing of the soon-to-be fixated stimulus (Van Petten, 2014). Evidence for the former interpretation has been provided by fMRI studies observing enhanced cue-related activity in visual cortex contralateral to the expected location of an upcoming stimulus (e.g., Hopfinger, Buonocore, & Mangun, 2000). Furthermore, fluctuations and perceptually relevant shifts in alpha-band activity have been shown to occur spontaneously, that is, without experimentally manipulating the attentional focus (Ergenoglu et al., 2004; Romei et al., 2008). It has been suggested that these functionally significant fluctuations are generated automatically rather than voluntarily, and may account for the variability in behavioral responses to physically identical stimuli. Romei and colleagues (2008) investigated the link between spontaneous alpha-band fluctuations and variability in visual cortex excitability via transcranial magnetic stimulation (TMS)-induced visual percepts (i.e., in the absence of actual visual stimulation). They found that the visual cortex was more excitable by TMS when prestimulation posterior alpha-band activity was low. The spontaneous fluctuations in alpha power occurred on a subsecond time scale, and contralaterally to the induced percept. This is similar to alpha-activity changes during active covert attention shifts, suggesting that trial-by-trial variability in visuospatial attention is the source of these fluctuations.

Since attentional mechanisms and saccade preparation could not be isolated from one another in the present study, further investigations are necessary to understand the beneficial effect of alpha lateralization in the absence of preview. Given that alpha lateralization predicted fixation behavior regardless of preview, it seems also possible that alpha lateralization reflects fluctuations in the general efficiency of the saccadic system. If this is the case, one should observe a similar relationship between alpha lateralization and fixation duration also in nonlinguistic scanning tasks that do not allow for parafoveal preprocessing of the next item (e.g., a visual search task with large saccades).

Alpha Lateralization May Not Reflect Attention Dynamics on Short Time Scales

There was no effect of preview or foveal load on alpha lateralization. Based on proposals by Kornrumpf et al. (2016), we expected attention to be oriented more strongly toward the right visual field after a valid preview and when foveal load was low because, in these cases, the foveal processing is easy and the reader has more attentional resources to preprocess parafoveal information. Vice versa, in situations with an invalid preview and high foveal load, attention should remain more centrally focused in order to process the currently fixated difficult word and to inhibit irrelevant parafoveal information. If these attentional dynamics exist, they did not manifest in alpha lateralization.

There are two possible reasons for the absence of both effects. First, it is conceivable that foveal load and preview produce reliable electrophysiological effects only in evoked activity (like ERPs; see Kornrumpf et al., 2016), but not in induced oscillations. Second, the temporal resolution of alpha lateralization might be too coarse. Since preview and foveal load varied randomly from word to word, any dynamic adaptation of the distribution of attention would need to happen fast and, in contrast to the blockwise manipulation of the reading paradigm, should vary from fixation to fixation. On top of that, each word was only inspected for about 300 ms in both paradigms. Most other studies on alpha oscillations have used longer presentation intervals lasting up to several seconds to account for the relatively long wavelength of alpha oscillations (Graimann & Pfurtscheller, 2006; Roach & Mathalon, 2008), as well as the sluggish onset of alpha power responses (Klimesch, Russegger et al., 1998). There is evidence that alpha lateralization can indeed index the dynamics of voluntary attention shifts within short intervals, provided that there is a sufficiently long baseline period before stimulus onset (e.g., Perez et al., 2009; ter Huurne et al., 2013). Naturally, this is not possible in natural reading situations, in which a new saccade is initiated every few hundred milliseconds. Even though TSE provides a measure of alpha-power fluctuations over time, the filtering of the data introduces some temporal spread and smearing (Worden et al., 2000). In contrast to the aforementioned spontaneous fluctuations in alpha lateralization that predicted the duration of the subsequent fixation, the stimulus-induced changes in alpha power in response to a word's properties like foveal load might be too short or too small in amplitude to be visible in induced alpha oscillations or the lateralization index (which was averaged across time windows of 300 ms).

Conclusion

Taken together, our results indicate that alpha lateralization can serve as a marker for attention distribution during natural reading and as a new electrophysiological predictor of fixation duration. In two experiments, we observed a general and sustained rightward alpha lateralization in saccadic left-to-right reading, but a symmetrical distribution in the RSVP paradigm. We believe that this shows a natural tendency to allocate attention toward the reading direction that is likely suppressed in variants of the RSVP paradigm. The larger the alpha lateralization, the shorter was the subsequent fixation duration. In contrast, alpha lateralization was no suitable indicator for the kind of quick and stimulus-related attentional adaptations required by changes in foveal load or preview. Taken together, lateralized alpha oscillations seem to be a useful tool to study the distribution of attention; this tool could hence be applied to various reading situations (e.g., proofreading versus speed reading), individual differences in reading skill or reading acquisition, and to the investigation of visual spatial processing outside of the reading domain.

2. Note that there is evidence that invalid previews in the parafovea, in particular the kind of visually salient x-letter masks used in Experiment 1, can lead to additional processing costs (Kliegl, Hohenstein, Yan, & McDonald, 2013; Marx, Hawelka, Schuster, & Hutzler, 2015). It is therefore important to stress that all results of Experiment 1 were replicated in Experiment 2, which used different words rather than *x* letters as the mask for the parafoveal word.

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(Received July 20, 2016; Accepted January 31, 2017)

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