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Frequency-based foveal load modulates semantic parafoveal-on-foveal effects

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ABSTRACT

During reading, we can process words allocated to the parafoveal visual region. Our ability to extract parafoveal information is determined by the availability of attentional resources, and by how these are distributed among words in the visual field. According to the foveal load hypothesis, a greater difficulty in processing the foveal word would result in less attentional resources being allocated to the parafoveal word, thereby hindering its processing. However, contradictory results have raised questions about which foveal load manipulations may affect the processing of parafoveal words at different levels. We explored whether the semantic processing of parafoveal words can be modulated by variations in a frequency-based foveal load. When participants read word triads, modulations in the N400 component indicated that, while parafoveal words were semantically processed when foveal load was low, their meaning could not be accessed if the foveal word was more difficult to process. Therefore, a frequency-based foveal load modulates semantic parafoveal processing and a semantic preview manipulation may be a suitable baseline to test the foveal load hypothesis.

1. Introduction

Reading is a complex activity that involves the integration of several perceptive and cognitive processes. During visual language perception, not only do we process the word fixated at the fovea, but also the words positioned in the parafoveal region, which is located between 2 and 5° away from the fixated point. This parafoveal region, despite being more poorly perceived, can facilitate the processing of incoming words. Therefore, when we fixate a new word in a sentence, this word has already been partially processed parafoveally. This facilitation effect is known as the preview benefit effect. Additionally, words allocated in the parafoveal region can affect the processing of the currently fixated word, located in the foveal region, i.e. a parafoveal-on-foveal effect (for a review, see Schotter, Angele, & Rayner, 2012).

Our ability to extract parafoveal information is determined by our ability to attend to it. We distribute our attention asymmetrically across the words located in the fovea and parafoveal regions, knowing that attention is distributed up to 15 characters to the right of fixation and between 3 and 4 characters to the left in alphabetic languages (for reviews, see Rayner, 1998; or Clifton Jr et al., 2016).

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The region in which attentional resources are distributed during reading has been classically referred to as the perceptual span (McConkie & Rayner, 1975) and its size depends on properties of the text. Among these properties we can refer to syntactic ambiguity (Apel, Henderson, & Ferreira, 2012), the difficulty of the text (Rayner, 1986) and, more classically established, the lexical frequency and syntactic complexity of the fixated word, i.e. the foveal load (Henderson & Ferreira, 1990). According to the foveal load hypothesis, when the fixated word is more difficult to process, less attentional resources are available to process upcoming words, therefore hindering parafoveal processing.

In the original experiment reporting this foveal load hypothesis, Henderson and Ferreira (1990) recorded eye movements of subjects who were reading sentences. They were interested in discovering if foveal processing difficulty could affect our perceptual span and, therefore, our ability to extract parafoveal information. To control the availability of parafoveal information, they used a well-known technique in reading research, i.e. the boundary paradigm (Rayner, 1975). In this paradigm, the display was changed when eyes crossed an invisible boundary located right before the parafoveal word, meaning that different words could be presented in the parafoveal region before actually fixating it. More importantly, to control the foveal processing difficulty, they manipulated word frequency and syntactic complexity. They found that increasing the foveal load hampered the processing of the parafoveal word, therefore demonstrating that the perceptual span was reduced, since not enough attentional resources were allocated into the parafoveal region. This theory has been widely considered in reading research (see Schotter et al., 2012). However, evidence supporting the foveal load hypothesis has been contradictory. Even though the same manipulation has been replicated with even stronger effects (White, Rayner, & Liversedge, 2005; Veldre & Andrews, 2018), others failed in finding such outcomes (Findelsberger, Hutzler, & Hawelka, 2019). Other authors found foveal load effects with less subtle preview manipulations, such as visually degrading the previews (Findelsberger et al., 2019; Marx, Hawelka, Schuster, & Hutzler, 2017; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999) or by using "X" masks (Kornrumpf, Niefind, Sommer, & Dimigen, 2016). It may be possible that this mixed evidence in eye movements literature is partly explained by the parafoveal conditions used in the experiment, being the interaction of foveal load and parafoveal preview commonly found with visual or non-word parafoveal manipulations, while modulation of foveal load over semantic parafoveal words has not been supported (Veldre & Andrews, 2018).

Electrophysiological measures, such as Event-Related Potentials (ERPs), have been shown to be a sensitive technique for studying semantic parafoveal word processing. Some evidence coming from flanker-RSVP-ERPs (Barber, Doñamayor, Kutas, & Münte, 2010; Li, Niefind, Wang, Sommer, & Dimigen, 2015) and Fixation-Related Potentials (Antúnez, Mancini, et al., 2021; Antúnez, Milligan, Hernandez-Cabrera, Barber, & Schotter, 2021; Kretzschmar, Bornkessel-Schlesewsky, & Schlesewsky, 2009; López-Pérez, Dampuré, Hernández-Cabrera, & Barber, 2016) suggest that semantic information from words in the parafovea can be activated and quickly integrated under some specific circumstances. Flanker tasks allow studying parafoveal word perception asking participants to read words (isolated or embedded in sentences) that are flanked by other words. In the flanker-RSVP, sentences are sequentially presented word by word at the centre of the screen with the next word of the sentence on the right and the previous word on the left. A flanker-RSVP-ERP study addressed the question of how the availability of cognitive resources may modulate the amount of parafoveal processing. Barber, van der Meij, and Kutas (2013) manipulated the contextual predictability of the critical words that were either congruent or incongruent with the sentential context. Additionally, they used different stimulus presentation rates, which could be similar to that of natural reading (SOA = 250 ms) or much slower (SOA = 450 ms). The authors found that the extraction of semantic parafoveal information was altered by the different contextual and temporal constraints of the task. Specifically, the smaller parafoveal effects with the faster presentation rate compared to the slower one showed that cognitive load can modulate parafoveal processing. This was reflected in the amplitude of the N400 component, which has been classically linked with semantic processing in language (Kutas & Federmeier, 2011). In another ERP experiment, Payne, Stites, and Federmeier (2016) studied the influence of foveal load over parafoveal processing by manipulating the semantic expectancy and congruity of the currently fixated word in a flanker-RSVP-ERP experiment, by using orthographically illegal invalid previews. They found that a greater foveal load reduced the processing of parafoveal words at the orthographic level, through disruption of attentional resources allocated onto the parafoveal region. Therefore, even though there is ERP evidence that the availability of cognitive resources may modulate semantic parafoveal processing (Barber et al., 2013), the effect of foveal load over parafoveal processing has only been demonstrated at the orthographic level in the electrophysiological record (Payne et al., 2016).

To our knowledge, no study has provided evidence of how foveal load variations may modulate semantic parafoveal processing. In this experiment, our aim was to test if a frequency-based foveal load could modulate semantic parafoveal-on-foveal effects. Considering that the frequency-based foveal load effect may be small, leading to mixed evidence (Drieghe, Fitzsimmons, & Liversedge, 2017), Findelsberger et al. (2019), as well as Veldre and Andrews (2018), suggested that frequency-based foveal load may impact parafoveal processing differently, depending on the sensibility of preview manipulations. Therefore, by following this approach, we wanted to test if semantic parafoveal-on-foveal effects can be influenced by foveal load based on word frequency. The impact over semantic parafoveal processing may be tracked through N400 amplitude modulations, which are extremely sensitive measures for semantic access (Kutas & Federmeier, 2011).

In this experiment, participants performed a Go-noGo semantic categorization task where they had to attend to a central word and press a button each time the word was referred to an animal (Go). The central word could vary in its lexical frequency and it was flanked by parafoveal words that could vary according to its semantic relationship with the central word. By choosing this experimental approach, we try to isolate parafoveal and foveal load variables that we assume would interact with other variables in a more complex situation, such as unconstrained, natural reading. Snell, Meade, Meeter, Holcomb, and Grainger (2019) previously used parafoveal flankers in a similar experimental situation to assess sub-lexical parafoveal processing, where the flankers could be identical or unrelated to the foveal word. In contrast to that study, the present experiment focuses on parafoveal word processing at the semantic level. Consequently, our design also included an experimental condition in which flanker words varied on their semantic relatedness with the foveal word, with the right flankers of each triad therefore being either identical, semantically related or entirely unrelated to the foveal word. The identical condition acted as a control condition because in this case, the parafoveal word does not only share the same semantic representation with the foveal word, but also the sub-lexical and perceptual information. In order to test the foveal load hypothesis, parafoveal flanker words were presented in combination with a foveal word that could have either a low or a high lexical frequency. We paid special attention to the N400 component because previous Fixation-Related Potential studies of word pair reading have shown that semantic manipulations of parafoveally perceived words can result in modulations of the N400 amplitudes (Antúnez, Mancini, et al., 2021; López-Pérez et al., 2016).

We expected to find semantic parafoveal-on-foveal effects when comparing the related and unrelated conditions, and we expected this effect to be larger for the identical than for the semantically related condition. Additionally, the foveal load could interact with the semantic manipulation of the flankers. According to the foveal load hypothesis, the frequency of the central words should modulate the semantic parafoveal processing, with high-frequency words producing larger parafoveal-on-foveal effects than low-frequency words.

2. Methods

2.1. Participants

Twenty-nine students between 18 and 32 years of age (M = 21) of the University of La Laguna participated in the experiment in exchange for course credits. They all were Spanish native speakers, had no neurological history and were right-handed, according to the Spanish version of the Edinburgh Handedness Inventory (LQ > 50) (Oldfield, 1971).

2.2. Stimuli and experimental paradigm

450 triads of words were used for the experiment. 384 of these trials had a pair of words that could be identical, semantically related or semantically unrelated based on the corpus "Normas de Asociación Libre en Español", of the University of Salamanca (Fernández, Díaz, Alonso, & Beato, 2004). The other 66 trials had pairs of unrelated words and the words in the central position where composed by names of animals, which acted as fillers in the task. In the experiment, a central word in the screen was flanked by two words located in the right and left parafoveal field and participants performed a Go/no-Go task (Donders, 1868, 1969), where they had to press a button each time the central word referred to an animal (Go). Only trials where no responses were registered (no-Go) were analyzed.

The experiment followed a 2 (foveal load) x 3 (parafoveal word) repeated measures design. The manipulation of the foveal load was controlled through the lexical frequency of the central word, with two levels: low foveal load (high lexical frequency) and high foveal load (low lexical frequency). This foveal load factor was manipulated according to the logarithm lexical frequency parameter (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013). Considering the word of each pair presented on the central position, half of the pairs were of high lexical frequency (M = 2.1, SD = 0.3), while the other half were of low lexical frequency (M = 0.5, SD = 0.2). No participant saw any word more than once. Each word had a length between four and seven letters (M = 5.6 letters of the high lexical frequency words and M = 5.7 for the low lexical frequency words). Left words had the same length as the foveal words, low orthographic proximity (Levenshtein distance below 0.35; M = 0.1, SD = 0.1) and a similar lexical frequency across conditions (M = 1.2, SD = 0.4).

While there was always an unrelated word in the left visual field, the parafoveal word in the right field could vary according to its semantic relationship with the central word. Hence, the parafoveal word factor had three different levels: identical word, semantically related word and semantically unrelated word, according to the corpus of Fernández, Díez, Alonso, and Beato (2004). The lexical frequency, length and orthographic proximity were controlled for the three conditions of the parafoveal word factor, considering each level of the foveal load factor. As in the left word, the words on the right field always had the same length, a Levenshtein distance below 0.35 (M = 0.1, SD = 0.1) and a similar lexical frequency (M = 0.9, SD = 0.6) across conditions.

2.3. Apparatus and procedure

The EEG was registered through 27 electrodes AG/AgCl following the 10–20 system (EasyCap, www.easycap.de) with the left mastoid electrode as online reference. Four additional electrodes, two in the external canthus of each eye and two in the infraorbital and supraorbital regions of the right eye, were allocated in order to obtain a bipolar record of the horizontal and vertical electro-oculogram. The electrical activity was recorded, amplified and processed with the BrainVision system (www.brainproducts.com) with a bandwidth of 0.01–100 Hz, and a sampling rate of 500 Hz. The impedances were kept under 5 kΩ (electro-oculogram < 10 kΩ). Raw data were filtered offline with a band pass filter of 0.1–30 Hz, referencing an algebraic mean of the activity of the two mastoids. The eye movements were registered with an eye-tracker EyeLink 1000 (SR Research Ltd., Ontario, Canada), with a sampling rate of 1000 Hz and a spatial resolution of 0.01°. For each sampling rate, the SR Research EyeLink algorithm, which also compared the results with the system threshold criteria (30 deg/s and 8000 deg/s), calculated the speed and acceleration of the saccades. The distance threshold for the saccade identification was of 0.1°. The calibration was performed through a standardized template of 9 points. Both systems were synchronized through TTL (transistor-transistor-logic) pulses, which were sent from the presentation computer to the eye tracker through a network wire and a parallel port to the EEG recording system. The eye-tracker allowed a trial presentation only when a fixation was detected in the center of the screen, so that parafoveal perception of flanker words was guaranteed. The invisible boundaries were allocated at 1.8° away from the fixation point.

After electrode preparation, each participant performed the task at 60 cm distance of a monitor of 23 inches with a 1024 × 768 resolution and a vertical refresh rate of 120 Hz. The words were presented in Courier New format in black color over a white screen by using the Experiment Builder software (SR Research Ltd., Canada). The triads were presented in lower case with a size of 14 points. The distance between the center of the foveal world and the beginning of the right word was of 2° of the visual angle. The sequence of the events in each trial continued as follows (see Fig. 1): 1) A fixation cross appeared in the center of the screen. 2) After the fixation was detected by the eye-tracker, the cross reduced its size to announce the beginning of the trial. 3) The trial was presented during 225 ms. 4) In the case that the participant looked at one of the flanker words, the trial ended and a message appeared in the screen indicating that the participant should look at the center of the screen. Simultaneously, a TTL pulse was sent through the parallel port to dismiss the trial (trials dismissed this way during the recording of the experiment were minimal, below 1%). 5) If the participants looked at the center of the screen for the 225 ms of presentation, the trial was considered valid. The presentation time of 225 ms emulated the average duration time of the first fixation in the sentence and text reading context (Rayner, 1998). **6)** After that time, a blank screen was presented for 775 ms and the participant could answer during this period. After response or after 775 ms, the trial ended. The trials that were valid for the analysis were those that included no answer (No-Go trials) and no saccades.

All parafoveal word conditions were counterbalanced so a specific foveal word would be paired with an identical, related or unrelated word depending on the counterbalancing list. Additionally, each pair of words was randomly presented to each participant. The presentation of the 450 triads of words per participant lasted approximately 90 min.

2.4. Data analysis

Before performing the statistical analysis, all EEG recordings from trials where participants executed saccades were dismissed. The data were segmented and pre-processed with the BrainAnalyser 2.0 software (www.brainproducts.com). Ocular artefacts were removed through an Independent Component Analysis (ICA) considering the data from the ocular electrodes in order to detect which components were linked with eye movements, removing between 2 and 4 components per participant. Other artefacts were removed semi-automatically. First, a moving window peak to peak threshold with a voltage threshold of 100 μV, a moving window width of 200 ms and a window step of 50 ms was performed for the epoch length and a visual inspection of the data allowed to reject artefacts undetected automatically. For each subject, no more than 10% of the data were rejected and each subject had at least 20 trials per condition. For the EEG data segmentation, the epochs of interest were from −100 to 600 ms time-locked to the triad presentation. The correction on the baseline was performed considering 100 ms before the presentation of the triads.

The average amplitude of the ERP of the segmented area was analyzed through a 3 (parafoveal word: related, unrelated and identical word) x 2 (foveal load: high lexical frequency and low lexical frequency) ANOVA, considering the "Electrode" as a topographic factor. For this factor, 9 different groups composed of 3 electrodes each were calculated: anterior-left group (Fp1, F7, F3), central-left (FC5, T7, C3), posterior-left (CP5, P7, P3), anterior-right (Fp2, F8, F4), central-right (T8, C4, FC6), posterior-right (CP6, P8,

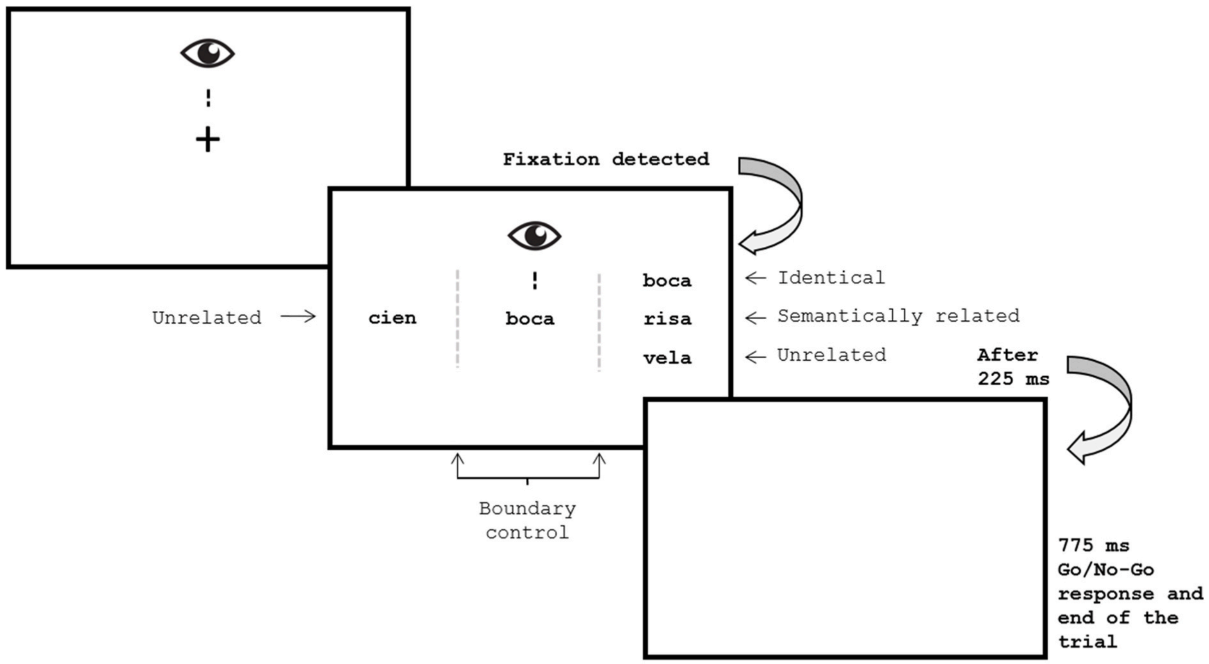

Fig. 1. Presentation procedure. After fixating the cross in the center of the screen the triad of words was presented. Participants could then make a saccade to the word in the center of the screen and then to the word on the right of the screen. When the eyes crossed the invisible boundary, the preview word was replaced by the target word. After 400 ms, a question mark appeared indicating that participants could respond.

P4), anterior-central (Fz, FC1, FC2), medium-central (Cz, CP1, CP2) and medial-posterior (Pz, O1, O2). The analyzed time windows were selected following an inductive approach, which consisted in a point-by-point *t*-test analysis using the Guthrie-Buchwald procedure (Guthrie & Buchwald, 1991). The analyses showed that effects were located between 300 and 600 ms after the stimulus onset presentation. Since we aimed to explore the N400 component, which is theoretically found between the 300–500 ms, we chose a 300–500 ms temporal window plus a 500–600 ms temporal window to conduct our analyses.

The statistical analyses were performed with the R programming software (http://www.r-project.org), and the ULLRToolbox system (https://sites.google.com/site/ullrtoolbox/). Each analysis was performed considering Mauchly's sphericity test (Mauchly, 1940). Thus, sphericity violations were corrected for each time the test showed significant results. The alpha value was corrected considering the Greenhouse-Geisser epsilon value since it was the most conservative one.

3. Results

The grand averages for the identical, related and unrelated conditions are shown for the low and high foveal load conditions in Fig. 2. Visually, it is noticeable that the parafoveal word factor modulates the N400 component in the low foveal load condition. More specifically, the unrelated condition seems to show a greatest negativity around the N400 temporal window, followed by the related and identical condition. However, no differences between parafoveal word conditions seem to be present when the foveal load was high. The following analyses confirm these preliminary examinations.

3.1. 300–500 ms window: N400

Table 1 shows t values, degrees of freedom and p values of significant post-hoc contrasts while Table 2 shows the mean voltage values for the three repeated measures factors. In both tables, it can be appreciated that the main differences related to the parafoveal word factor in the N400 temporal window occur in left frontal and left central electrodes in the low foveal load condition. These differences are due to a greater negativity for the unrelated preview word than for the related and identical words.

The ANOVA showed a main effect of the foveal load factor, $F(1, 28) = 18.32$, $p < 0.001$, $\eta_p^2 = 0.39$; with a greater negativity on the high foveal load condition (−2.38 vs −1.64), a main marginal effect of the parafoveal word factor, $F(2, 56) = 2.75$, $p = 0.07$, $\eta_p^2 = 0.08$; where the unrelated condition had the greatest negativity, followed by the semantically related and the identical condition (−1.6 vs −1.3 vs −1.2 μV). Considering the marginal main effect of the parafoveal word factor, there was only a significant difference when contrasting the identical condition against the unrelated condition $t(28) = 2.36$, $p < 0.02$ and comparisons of the semantically related preview condition with the identical and unrelated preview conditions were not found statistically significant ($p > 0.05$). We found a

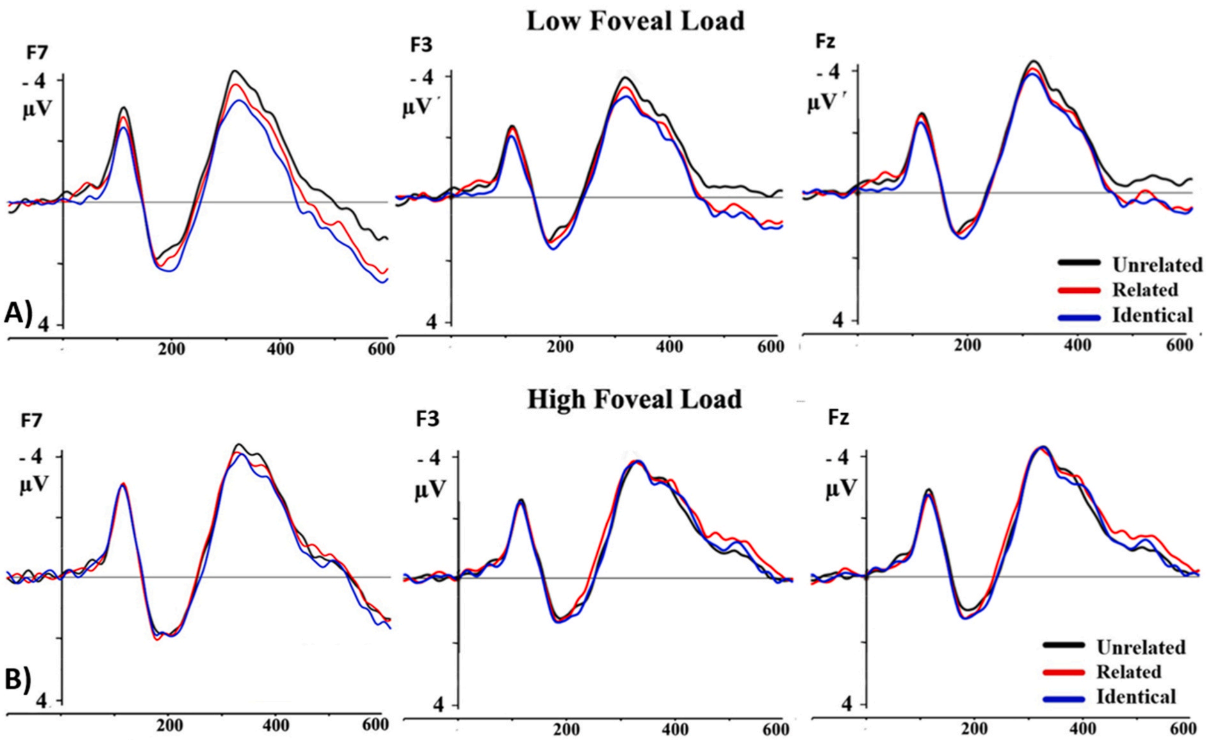

Fig. 2. ERP obtained during the task. **A.** The three parafoveal word conditions showed differences for the low foveal load condition, exhibiting a N400 component. **B.** No differences between the foveal word conditions were visible for the high foveal load condition.

Table 1
Significant post-hoc contrasts in the N400 temporal window for the Foveal Load x Parafoveal Word x Electrode factors. The table displays t values, degrees of freedom and p values.

Electrodes	Contrast	t values	df	p.hocberg
Anterior-left	Related-Unrelated	2.38	28	0.02
	Identical-Unrelated	3.05	28	0.01
Anterior-central	Related-Unrelated	1.83	28	0.07
	Identical-Unrelated	2.24	28	0.03
Anterior-right	Identical-Unrelated	2.65	28	0.01
Central-left	Related-Unrelated	2.04	28	0.05
	Identical-Unrelated	2.74	28	0.01
Central-medial	Related-Unrelated	1.72	28	0.09
Posterior-left	Related-Unrelated	1.98	28	0.05

Table 2
Voltage measures on the different parafoveal word conditions considering each electrode factor on the 300–500 ms temporal window.

	Parafoveal word	Anterior-left	Anterior-central	Anterior-right	Central-left	Central-medial	Central-right	Posterior-left	Posterior-central	Posterior-right
Low	Unrelated	−2.88	−3.05	−2.63	−1.63	−1.32	−1.03	0.04	0.36	0.94
Foveal	Related	−2.2	−2.37	−2.11	−1.14	−0.73	−0.77	0.5	0.73	1.08
Load	Identical	−1.99	−2.26	−1.88	−0.92	−0.85	−0.79	0.42	0.65	0.97
High	Unrelated	−3.3	−4.07	−3.07	−2.27	−2.48	−1.92	−0.53	−0.22	0.03
Foveal	Related	−2.97	−3.59	−2.66	−2.03	−2.11	−1.63	−0.5	−0.12	0.15
Load	Identical	−3.05	−3.66	−2.96	−2.3	−2.53	−1.93	−0.68	−0.52	−0.23

two-way interaction between the foveal load x electrode factors, $F(8, 224) = 3.22$, $p < 0.001$, $\eta_p^2 = 0.10$; maintaining significant differences on each level of the topographic factor ($t > 3$ for each pair to pair comparison), and showing greater negativity on central and posterior electrodes of the left hemisphere on the high foveal load condition. Additionally, we found a significant three-way interaction between the foveal load x parafoveal word x electrode factors, $F(16, 448) = 1.75$, $p < 0.01$, $\eta_p^2 = 0.05$, $\varepsilon = 0.05$. The post-hoc comparisons on each topographic area showed that, at a low foveal load, the unrelated parafoveal word condition was significantly more negative than the related and identical conditions and that these differences were on the frontal-left and the central-left electrodes. The central anterior, rather than central-posterior distribution of RSVP paradigms, agrees with previous semantic evidence from flanker tasks (e.g. Payne, Stites, & Federmeier, 2019).

3.2. 500–600 ms window

The ANOVA showed a main effect of the foveal load factor, $F(1, 28) = 40.24$, $p < 0.01$, $\eta_p^2 = 0.58$, where the high foveal load showed the greatest negativity (0.34 μV vs 1.79 μV). It also showed a main effect of parafoveal word, $F(2, 56) = 5.61$, $p < 0.01$, $\eta_p^2 = 0.16$, where the voltage values were more negative for the unrelated condition, than for the related $t(28) = 2.44$, $p < 0.02$, and identical one $t(28) = 3.36$, $p < 0.01$. Similarly to the N400 component window, there was a three-way interaction among the foveal load x parafoveal word x electrode factors, $F(8, 352) = 3.4$, $p < 0.002$, $\eta_p^2 = 0.07$. The post-hoc comparisons showed effects on the anterior-left, central-medial and central-left topographic areas at a low foveal load and when comparing the unrelated parafoveal word against the related $t(28) = 3.38$, $p < 0.01$ and identical parafoveal word $t(28) = 4.56$, $p < 0.001$. Those differences were still significant and in the same direction on the anterior-central and the central-left group for both comparisons.

4. Discussion

Our aim was to explore the effect of frequency-based foveal load effect on semantic parafoveal processing. Consequently, the N400 was particularly targeted to investigate any variations related to parafoveal-on-foveal effects since this component is classically linked with semantic processing (Kutas & Federmeier, 2011). We hypothesized that variations in the foveal load would interact with the semantic manipulation of the flankers located in the parafoveal region, providing more solid evidence of the foveal load hypothesis (Henderson & Ferreira, 1990).

In line with our expectations, we found that the semantic parafoveal word manipulation modulated the processing of the fixated word, reflected in variations of the amplitude of the N400 component, mainly in frontal-left and central-left topographic areas. The semantically unrelated condition showed a greater negativity for this window, than the related and identical conditions, which reflects greater difficulty in processing such words. While this semantic modulation contrasts with previous Fixation-Related Potentials research (FRPs) evidence that failed on finding semantic parafoveal-on-foveal effects (Antúnez, Mancini, et al., 2021, Dimigen, Kliegl, & Sommer, 2012), our findings are consistent with previous electrophysiological evidence from the literature. For instance, similar semantic parafoveal-on-foveal effects have been previously reported in a FRP study of word pair reading using the boundary paradigm (López-Pérez et al., 2016), a ERP study with triads (Snell et al., 2019), sentence reading experiments with flanker-RSVP presentation

(Barber, Ben-Zvi, Bentin, & Kutas, 2011; Barber, Doñamayor, Kutas, & Münte, 2010; Li et al., 2015), and more recently in a FRPs experiment with natural reading: Antúnez, Milligan, et al., 2021). However, it has to be acknowledged that the N400 modulation found in these studies (including the present one) can be a summation of foveal and parafoveal word processing and not exclusively a modulation of parafoveal word over the fixated word. However, considering the current design where the main manipulation was the semantic relationship between foveal and parafoveal words, therefore emulating previous research who reported similar effects (e.g. López-Pérez et al., 2016), we believe the most likely (but not exclusively) explanation is that the meaning of the parafoveal word interacted with the meaning of the foveal word. This opens a new window for future research. For instance, in our study we avoided RT to ensure that the EEG signal was not contaminated by response events. However, future research may use designs allowing the collection of both RT and ERPs using methodological approaches such as the deconvolution technique and collecting regression-ERPs (e.g. Ehinger & Dimigen, 2019), which could allow the researcher to confirm that the foveal word processing was impacted by the meaning of the parafoveal word. Nevertheless, taking into account the variations within the N400 component found here, the meaning of parafoveal words were fully activated and most likely integrated with the word allocated in the foveal region i.e. a semantic parafoveal-on-foveal effect.

Supporting our main hypothesis, the frequency-based foveal load manipulation modulated semantic parafoveal processing, by interaction with the found variations in the N400 component. For instance, when the foveal load was low, readers were able to extract and process the meaning of parafoveal words, reflected on a variation in the N400 component. These effects continued in the later time window, where unrelated parafoveal words still showed a greater negativity than related and identical words. However, in a high foveal load scenario, these effects disappeared, meaning that they were not able to access parafoveal information. More specifically, when a low-lexical frequency word was presented, there were no differences between any conditions, indicating that neither semantic nor low-level parafoveal information was accessed. Citing again the classical foveal load hypothesis (Henderson & Ferreira, 1990), when the word located in the center of the visual field was difficult to process, not enough attentional resources were allocated to the parafoveal word, and so, the semantic information could not be accessed. On the other hand, having a low foveal load, attentional resources were spatially distributed across the visual field, including the parafoveal region, allowing processing of all words in the visual field. The finding that a semantic preview manipulation can be sensitive to lexical frequency foveal load variations helps the debate about possible previews that could be used to test foveal load effects and which parafoveal information can be modulated by foveal load. Here, we decided to use a more commonly used foveal load manipulation (i.e. a frequency-based foveal load), in order to resemble the original work of Henderson and Ferreira (1990), providing a more solid evidence of the foveal load hypothesis. By recording electrophysiological measures, future parafoveal research could use word frequency to manipulate foveal load, since this proved to be a suitable approach to explore how the distribution of attentional resources modulates more subtle parafoveal effects i.e. high-order parafoveal information such as the meaning of words.

These findings are not limited to reading research. Foveal load, as well as working memory load, modulates the efficiency of attention guidance and parafoveal processing during visual search for words, according to the Load Theory (Lavie & De Fockert, 2005). Our findings are in line with results from Dampuré, Benraiss, and Vibert (2019), who manipulated the foveal load in a visual search task by modifying the relevance of the foveal stimuli for the task. They found that, only when there was enough availability of cognitive resources, defined by low foveal and task-related loads, participants were able to access orthographic and semantic properties of parafoveal words. Considering the importance of knowing which foveal load manipulations may modulate semantic parafoveal processing in different scenarios, future research exploring visual search should test if foveal load can modulate the availability of attentional resources, attention guidance, and semantic parafoveal processing.

Additionally, our findings might have implications for the classic parallel vs serial lexical processing debate. Serial processing models of ocular control in reading (e.g. E-Z Reader, see Reichle, Pollatsek, Fisher, & Rayner, 1998) postulate that, after partially processing the fixated word, attention moves to the next word, located away from the fixation point, allowing then the processing of parafoveal words. Therefore, lexical processing would be concluded on only one word at a time. On the other hand, parallel processing model perspectives (e.g. SWIFT, see Engbert, Nuthmann, Richter, & Kliegl, 2005), suggest that attention is distributed across multiple words in the visual field and that lexical access of foveal and parafoveal words occur simultaneously. These models from eye movements' research during sentence reading have played a major role in the current serial vs parallel debate. In this scenario, Snell and Grainger (2019b) argued that the debate could not be resolved with only natural reading paradigms since these describe reading behavior but not the implicit mechanisms behind it. In line with their claim, while serialism would arise from mere observation of ocular behavior, the patterns observed in EEG research related with the different stages of visual word recognition suggest parallel word processing, e.g., semantic parafoveal-on-fovea effects in word-pair (López-Pérez et al., 2016) or sentence reading (Barber et al., 2010). Schotter and Payne (2019) have defended the validity of natural reading paradigms and raised a concern that while some processes may be taking place in parallel (e.g. sub-lexical features), other processes like word identification involve the serial allocation of attention. White, Boynton, and Yeatman (2019) also joined Schotter and Payne (2019), arguing that lexical access of words would take place serially, based on previous evidence from their laboratory where they presented pairs of words for a short time to readers, which could not consciously recognize both words (White, Palmer, & Boynton, 2018). Snell and Grainger (2019a) replied that the parallel word recognition process should not be caged into sub-lexical processing and conscious identification, because semantic, high-order features, may take place in parallel during word identification without conscious identification. Looking for bridging such different theoretical perspectives, Snell and Grainger (2019a, 2019b) suggested that the parallel OB1-reader model might connect the processes of word recognition and eye movements during reading. The OB1-reader model (Snell, van Leipsig, Grainger, & Meeter, 2018; see also; Meeter, Marzouki, Avramiea, Snell, & Grainger, 2020), as a parallel model, posits a widespread attentional distribution and a spatiotopic sentence-level representation, implementing mechanisms of word recognition, position coding and letter identity, which may attempt to bring some insight into the reading process and to bridge traditionally isolated pieces of literature (Schotter &

Payne, 2019; Snell & Grainger, 2019b; see).

Both the parafoveal-on-foveal and foveal-processing-load effects tested in the present experiment have been at the core of the parallel vs. serial debate. Although our experiment was not designed to address this debate, we believe that our results have some implications that deserve to be considered. Semantic parafoveal-on-foveal effects in natural reading cannot be incorporated in the serial models (see Reichle, 2011), and are easily explained in the context of parallel word processing. By contrast, the reduction in parafoveal processing when foveal processing load increases has been traditionally taken as evidence of serial processing. From a serial perspective, readers may not have had enough time to access the meaning of the parafoveal words in the high foveal load condition, since it took longer for them to lexically access the fixated word so they could not switch their attention to the parafoveal region. However, parallel models make similar predictions implementing lexical processing as a function of eccentricity, and some of these models, like the SWIFT model, understand the perceptual span as a dynamic attentional window that is modulated by foveal load (Schad & Engbert, 2012). In principle, the foveal load effect reported here is compatible with both views, but there are some characteristics of our design that are worth to keep in mind: 1) Our task prevents ocular movements, which can be an adequate way to isolate the question of parallel word processing, because several previous controversies have been related to potential confounds at the level of sentence reading (e.g. spillover effects). 2) E-Z proposes that attention do not shift until sufficient degree of lexical processing is achieved, and on average this should happen around 250 ms after the presentation of a word without a preview (Sereno, Rayner, & Posner, 1998). Considering the stimulus duration in our experiment (225 ms), it is highly improbable that the meaning activation of foveal and parafoveal words take place in a serial way (even when some initial visual processing before the attentional shift can be accepted by the model; Drieghe, 2011). 3) Most of previous data supporting the alternative views have used behavioral measures that show the effects of lexical processing, meanwhile ERP measures are direct measures of the ongoing neural activity that additionally allow to track the time course of different sub-processes. In this sense, it could hypothesize that serial processing of different words should be reflected in the morphology and/or latency of the ERP components associated to the visual word recognition process. Although this was not directly manipulated in our experiment, the latency and morphology of the ERP components triggered by triad presentation do not seem to differ from previous descriptions in the literature with single words (Barber & Kutas, 2007).

To summarize, resolving the serial-parallel debate is out of the scope of the present study but we believe that our findings show that the used design and task can be a suitable tool to test more specific hypothesis in future research. By way of illustration, the flanker task can be used to test the effects of parafoveal processing load, which would lead to different predictions from the different models. As a case in point, if it happens for the parafoveal load to have similar effects to the foveal load ones presented here, we may provide solid evidence in favour of the parallel perspective, since the greater cognitive constraints may take place after we process all words across the visual field simultaneously. Moreover, the presentation times may also be manipulated to get a better description of the latency and morphology of the ERP components associated to serial or parallel processing.

Finally, it would be important to take into account some research questions related to the nature of the task. The flanker paradigm has been classically used in the study of visual word recognition (Schaffer & La Berge, 1979) and, more specifically, flanker-ERPs paradigms had been particularly successful in finding semantic parafoveal effects (Antúnez, Mancini, et al., 2021; Barber et al., 2013; Li et al., 2015; López-Pérez et al., 2016). Future research should explore how foveal load interacts with other variables in more complex reading situations (i.e. sentence reading). This is an important question since attentional resources may be differently distributed in a flanker paradigm compared to normal reading (Kornrumpf et al., 2016; Niefind & Dimigen, 2016). In fact, it has been suggested that higher-order parafoveal-on-foveal effects would be present in single-word reading paradigms, but not during sentence reading where sentence-level feedback to individual word positions may constrain the recognition of parafoveal words (Snell, Meeter, & Grainger, 2017). A more recent line of research has tackled these issues by obtaining Fixation-Related potentials (FRPs) in natural sentence reading situations. In this context, some authors have already explored semantic parafoveal effects in highly predictive sentence constructions (Kretzschmar et al., 2009), as well as foveal load effects (Kornrumpf et al., 2016). Furthermore, in a recent experiment, Antúnez and colleagues (Antúnez, Milligan et al., 2021), have reported plausibility parafoveal processing evidence, consistent with parafoveal-on-foveal semantic effects, in a FRP experiment in natural reading. In such experiment, participants read low-constraint sentences, and the plausibility of previews was manipulated with the boundary technique, similarly to how the plausibility of previews was manipulated in flanker-ERPs studies (e.g. Barber et al., 2013). These results suggest that findings from visual word recognition paradigms may still be present in natural reading. However, for the time being, the influence of foveal load over semantic parafoveal processing has not been explored yet in this context. FRPs in sentence reading may explore these questions to extend our findings to less controlled experimental designs, closer to more ecological situations, and therefore delving into the common mechanisms of parafoveal processing during single word recognition and sentence reading.

5. Conclusion

In summary, we have provided evidence that a frequency-based foveal load modulates semantic parafoveal processing and that a semantic preview manipulation is a suitable baseline to test the foveal load hypothesis. This paper contributes to the investigation of the relationship between frequency-based foveal load and semantic parafoveal processing, delving into how we process multiple words by distributing our attention spatially across the visual field.

CRediT authorship contribution statement

M. Antúnez: Investigation, Visualization, Writing – original draft, Writing – review & editing. **P.J. López-Pérez:** Conceptualization, Formal analysis, Investigation. **J. Dampuré:** Conceptualization, Investigation, Supervision. **H.A. Barber:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

None.

The authors declare that they have no interest to declare that could influence the work reported in this paper.

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