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ERPs Reveal How Semantic and Syntactic Processing Unfold across Parafoveal and Foveal Vision during Sentence Comprehension

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Abstract

We examined how readers process content and function words in sentence comprehension with ERPs. Participants read simple declarative sentences using a rapid serial visual presentation (RSVP) with flankers paradigm. Sentences contained either an unexpected semantically anomalous content word, an unexpected syntactically anomalous function word or were well formed with no anomalies. ERPs were examined when target words were in the parafoveal or foveal vision. Unexpected content words elicited a typically distributed N400 when displayed in the parafovea, followed by a longer-lasting, widely distributed positivity starting around 300 ms once foveated. Unexpected function words elicited a left lateralized LAN-like component when presented in the parafovea, followed by a left lateralized, posteriorly distributed P600 when foveated. These results suggested that both semantic and syntactic processing involve two stages—the initial, fast process that can be completed in parafovea, followed by a more in depth attentionally mediated assessment that occurs with direct attention.

Keywords

Reading; ERPs; Parafoveal and foveal processing; Semantic and syntactic anomaly

Introduction

Readers process both semantic and syntactic information to comprehend sentences, and content versus function words are two classes of words that differ in the degree to which they carry semantic versus syntactic information. Content words like nouns (e.g., dog), lexical verbs (e.g., eat), or adjectives (e.g., red) have rich semantic information. In contrast, function words like determiners (e.g., the), pronouns (e.g., he), or prepositions (e.g., in) carry little substantive meaning but reveal grammatical relationships between content words (e.g., Neville, Mills, & Lawson, 1992). This difference might explain why patients with impaired grammatical analysis abilities due to Broca's aphasia typically report difficulties

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Declaration of Interest Statement
None

in processing function words (e.g., Caramazza & Zurif, 1976; Berndt & Caramazza, 1980; Bradley et al., 1980; Swinney et al., 1980; Friederici, 1983, 1985; Goodglass & Menn, 1985; Rosenberg et al., 1985; Friederici & Kilborn, 1989; Friederici et al., 1991; Pulvermüller, 1995; Biassou et al., 1997). The investigation of neurological differences in processing these two classes of words has been conducted since the 1980s (e.g., Bradley & Garrett, 1983; Friederici, 1985; Friederici, Opitz, & von Cramon, 2000; Nobre, Price, Turner, & Friston, 1997; Nobre & McCarthy, 1994). The present study addressed this issue from a new perspective — instead of directly comparing the processing of these two word classes, we instead examined differences during sentence processing between expected and unexpected content and function words using a modified rapid visual presentation (RSVP) paradigm. Importantly, using the event-related potential (ERP) methods, we examined how readers process content and function words not only when these words were presented in the fovea but also just prior to foveation while they were presented in the parafovea. This latter feature of the modified RSVP paradigm (henceforth RSVP with flankers) more closely resembles natural reading.

Prior ERP studies have revealed how content and function words are processed differently via directly comparing them in reading tasks. When reading single words or sentences that were presented one word at a time in the standard RSVP paradigm, content words tend to elicit more negative-going deflections that are largest over central-parietal brain regions (Brown, Hagoort & ter Keurs, 1999; Neville et al., 1992; Nobre & McCarthy, 1994; ter Keurs et al., 1999, but see Münte, Wieringa, Weyerts, Szentkuti, Matzke, & Johannes, 2001; Van Petten & Kutas, 1991). These negativities typically peak between 300 and 500 ms (N400) after word onset. Because the N400 is generally larger in amplitude when content words are not supported by the semantic context of prior words in a sentence, this component has been argued to reflect lexico-semantic operations during sentence processing (Kutas & Hillyard, 1980, 1984). On the other hand, function words tend to elicit more negative-going deflections that are largest over left anterior brain regions between 250 and 500 ms. Neville et al. (1992) was the first to propose that such left-anterior negativities (LANs) that reflect syntactic operations specific to function words during sentence processing (a component they identified as the N280), although subsequent studies have questioned this interpretation (ter Keurs, Brown, Hagoort, & Stegemann, 1999; Brunelliere, Hoen, & Dominey, 2005; Osterhout, Bersick, & McKinnon, 1997). Other studies have reported similar LAN-like components in paradigms using word-category and agreement violations (e.g., Coulson et al., 1998; Kim & Sikos, 2011; O'Rourke & Van Petten, 2011; see Molinaro, Barber, & Carreiras, 2011 for a review; but see Tanner, Morgan-Short, & Luck, 2015). Such violations also tend to generate large posterior positivities referred to as the P600 (Osterhout & Holcomb, 1992). Subsequent studies have shown that the P600 is a positive going deflection that peaks around 600 ms post-stimulus onset and is sensitive to grammatical anomalies and/or syntactic processing difficulty (Osterhout, Holcomb & Swinney, 1994), such as subject–verb agreement violations (e.g., Hagoort, Brown, & Groothusen, 1993), inflection violations (e.g., Friederici, Pfeifer, & Hahne, 1993), or difficult syntactic integration even in grammatical sentences (e.g., Kaan, Harris, Gibson, & Holcomb, 2000). In summary, content and function words seem to engage, at least to some degree different neural systems, likely due to richer semantic features for the former (which contribute to the N400) and richer syntactic features for the latter (which contribute to the LAN and the P600).

The first aim of the present study was to examine how content versus function words contribute differently to semantic and syntactic processing during sentence processing. To accomplish this in some sentences (controls) all content and function words were consistent with the meaning and syntax of the sentence while in other (experimental) sentences, either a content or function word was replaced by another word belonging to the same word class which rendered these sentences difficult to process from this point on. This design allows for two important controls over potentially confounding factors. First, the same sentence frames are used in experimental and control sentences allowing for the investigation of differences in ERP patterns elicited by unexpected content or function words while holding sentence context constant. Second, by only contrasting control and experimental items within a word-class variables such as word length and frequency are controlled.

We focused on three ERP components, N400, LAN, and P600. The N400, as described earlier, is a negative shift that usually peaks around 400 ms after word onset and sensitive to semantic anomalies. The LAN and P600 are two ERP components that have been shown to be sensitive to syntactic processing difficulties. While an unexpected content word should elicit an N400, an unexpected function word should elicit both a LAN and a P600 given these two components increased involvement in syntactic processing.

A second aim was to examine semantic and syntactic violation effects in a more realistic sentence reading task. Most of the research using ERPs to examine semantic and syntactic processing in sentences have adopted the word-by-word RSVP paradigm where individual words are presented at fixation. This approach is used in order to minimize the role of saccadic artifacts during natural sentence reading but also to provide an unambiguous time-lock point (word onset) to assess differences between conditions. However, the artificiality of this method of sentence reading leaves many questions about the interpretation of differences between conditions. In particular there is ample evidence that during normal reading information from words to the right of fixation influence processing prior to their being fixated in central (foveal) vision (e.g., Briihl & Inhoff, 1995; Gordon, Plummer, & Choi, 2013; Inhoff, 1989a, 1989b, 1990; Inhoff & Tousman, 1990; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1998; but see Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner, Balota, & Pollatsek, 1986; Rayner & Morris, 1992; Mirault, Yeaton, Broqua, Dufau, Holcomb, & Grainger, 2020). In particular, readers benefited from the preview of a semantically plausible word, suggesting early processing of parafoveal words regarding whether they semantically fit previous context (Schotter & Jia, 2016; Veldre & Andrews, 2016, 2018). A limitation of the boundary change paradigm used in the above studies was that there might be some confounding of eye-movements and/or the presentation of parafoveal words (e.g., the inclusion of both valid and invalid preview). Although the traditional word-by-word RSVP paradigm in ERP studies may address the confounding issue, parafoveal information is not available in that paradigm.

Some recent ERP studies support concerns about the lack of parafoveal information in the traditional RSVP paradigm. These studies strongly suggest that words presented in parafoveal vision are not only processed at a sub-lexical level but also receive some degree of semantic analysis as evidenced by parafoveal N400 effects (Barber, Doñamayor, Kutas, & Münte, 2010; Barber, van der Meij, & Kutas, 2013; Li, Niefind, Wang, Sommer, & Dimigen, 2015; Payne & Federmeier, 2017; Payne, Stites, & Federmeier, 2019; Stites, Payne & Federmeier, 2017; Snell, Meade, Meeter, Holcomb, & Grainger, 2019; Meade, Declerck, Holcomb, & Grainger, 2021; Mirault, et al., 2020; but see Dimigen, Kliegl, & Sommer, 2012). Barber and colleagues (2010, 2013) developed the RSVP with flankers paradigm to examine ERPs that are elicited by targets in the parafovea. In this paradigm, sentences are presented serially in triads. Participants are instructed to fixate on the target word at the center, which is flanked by the upcoming word in the sentence to the right, and the preceding word to the left. Adopting this paradigm, previous research has found N400 effects that can be elicited by unexpected content words while they are still in the parafovea – moreover these effects have been found in multiple languages (e.g., English and Hebrew in Barber et al., 2010; Chinese in Li et al., 2015). Note that in Hebrew the reading direction is from the right to the left, so that the upcoming words that elicited parafoveal N400s were on the left of the central word. Stites et al. (2017) further showed that this parafoveal N400 was continuously graded with increasing cloze probability, replicating the graded foveal N400 pattern that is typically found in studies using the typical RSVP paradigm (e.g., Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007; Kutas & Hillyard, 1984; Wlotko & Federmeier, 2012). Curiously, Stites et al. found that the presence of a parafoveal N400 mitigated or even eliminated the N400 when the unexpected word was subsequently foveated. This seems to suggest that readers did not only access the semantic information of the target word when it is in the parafovea, but also largely completed this semantic analysis before the target is foveated. The influence of words in the parafovea has also been shown to influence the N400 in word-pair tasks. Using a trans-saccadic priming paradigm, Grainger, Midgley, and Holcomb (2016) found foveal-to-parafoveal lexical priming effects on the N400.

Although semantic information has been processed when the target word is in the parafovea, there is evidence that there is a second step that engages readers' foveal attention on the target word to complete target word processing in a sentence context. Using the RSVP with flankers paradigm, Payne et al. (2019) found a posteriorly distributed late positive component (LPC or P600-like component), when an anomalous content word was fixated in the fovea. This effect was not seen when these words were in the parafovea. Importantly, this P600-like component was only observed when participants were asked to judge the plausibility of sentences and was not seen when sentences were read passively for comprehension. This latter finding is consistent with Stites et al. (2017) where participants completed a memory task after sentence comprehension, in which a P600-like effect was not observed when the target was foveated. Payne et al. suggested that the foveal P600-like component reflects a higher-order and task-dependent integrative process that engages foveal attention, i.e., a result of plausibility-related integration failures (Brouwer, Crocker, Vanhuizen, & Hoeks, 2017; DeLong, Quante, & Kutas, 2014; Van Petten & Luka, 2012).

To date ERP studies that adopted the RSVP with flankers paradigm have focused on unexpected content words that result in semantic anomalies. However, none of this work has examined unexpected function words that elicit syntactic anomalies, although results from eye-tracking studies have shown some evidence of parafoveal syntactic processing in normal reading (Brothers & Traxler, 2016; Veldre & Andrews, 2018). Accordingly, adopting the RSVP with flankers paradigm, the present study focused on ERPs recorded to expected and unexpected function words, first presented in the parafovea followed by presentation to the fovea. These function word effects were then contrasted with comparable expected and unexpected content word processing. Given that the difference between expected and unexpected function words should involve greater differential syntactic processing we aimed to determine whether such effects would be apparent when the target function words are in the parafovea. Moreover, we were interested in examining whether processing function words might also involve a two-step process as reported for content words by Payne et al. In other words, might we see a first effect of unexpected function words when they are presented in the parafovea followed by a second effect when these words are presented at fixation and engage foveal attention.

Following previous studies, we predicted a robust parafoveal N400 and a foveal P600-like component on unexpected content words. Furthermore, if readers also process syntactic information of the previewed targets, we predicted we would observe parafoveal LAN or P600 effects on unexpected function words when they are still in the parafovea. Lastly, if the syntactic analysis of function words is completed during parafoveal presentation (i.e., one-step processing), we predicted that there should be little to no foveal LAN or P600 effects on unexpected function words. However, if as suggested by Payne et al. for content word processing, there are also two steps involved in function word processing when a plausibility judgment is required, then unexpected function words might also elicit an enhanced foveal LAN or P600.

Methods

Participants

Twenty-four right-handed, native English speakers (10 males, mean age = 22.0 years, ranging from 19 to 27) received compensation for their participation. All participants reported normal or corrected-to-normal visual acuity with no history of neurological impairment or language disability. All participants reported that they had learned no other language before the age of six, and that they were not proficient in any languages other than English.

Stimuli & Design

The critical stimuli for this study were 120 sentences ranging from 7 to 17 words. There were three versions of each sentence: a) the normal version without semantic or syntactic errors and containing a control content word and a control function word (see sentences “a1” and “a2” below); b) a semantic violation version where the appropriate control content word was replaced by an unexpected content word which produced a semantic anomaly (see sentences “b1” and “b2” below); and c) a syntactic violation version where the appropriate control function word was replaced by an unexpected function word which produced a syntactic anomaly (see sentence “c1” and “c2” below). None of the target words were sentence final words. The target content and function words were at most one word away from each other to ensure the context around the replaced words were similar. For example, in the sentences

a1) The employee needs to prepare the document for his boss this morning.

a2) The old man was asleep in the chair when I came back.

The word *boss/chair* served as the control content words, and *his/the* served as the control function words. While *boss/chair* was replaced by *water/cherry* in the unexpected content word condition, *his/the* was replaced by *on/of* in the unexpected function word condition. As a result, the sentences in these two conditions were

b1) The employee needs to prepare the document for his water this morning.

b2) The old man was asleep in the cherry when I came back.

c1) *The employee needs to prepare the document for on* boss *this morning.*

c2) The old man was asleep in of chair when I came back.

Though we included sentences with various types of semantic and syntactic anomalies we did not control the number of sentences of each subtype, which was not the focus of the present study. For example, for sentences with semantic anomalies, 12 out of the 120 were due to animacy violations (but none were role-reversed sentences), while others were implausible events. For sentences with syntactic anomalies, in 29 out of the 120 sentences an article was replaced by a preposition or vice versa (like *c2*); in 27 a preposition was replaced by a pronoun or vice versa (like *c1*); in 21 a preposition was replaced by another preposition (e.g., *of-for*); in nine a conjunction was replaced by a pronoun or vice versa (e.g., *and-us*); in seven a conjunction was replaced by a preposition or vice versa (e.g., *and-of*); in six an article was replaced by a pronoun or vice versa (e.g., *the-he*), in five a quantifier was replaced by a preposition or vice versa (e.g., *some-in*); in five a preposition was replaced by an auxiliary verb (e.g., *on-will*); and the remaining 11 between other types of function word substitution.

We pre-tested each sentence in a group of six native English speakers that did not participate in the ERP study to determine if readers would be aware of the anomalies produced by the critical words at the point these words are presented in an RSVP format. On a 7-point scale they rated the acceptability of each sentence through the point of the critical words (1 not acceptable, and 7 completely acceptable). The ends of the sentences after the critical word were not presented. For example,

- The employee needs to prepare the document for on
- The old man was asleep in the cherry

Raters made their judgment based on whether it's acceptable to have the word *on* after the context *The employee needs to prepare the document for*. See Table 1 for detailed characteristics of critical words in each condition. We also recruited a different group of English monolinguals (n = 26) to complete a cloze task in order to assess the predictability of the critical sentences (e.g., they saw the incomplete sentence frame *The employee needs to prepare the document for*___ and completed it with whatever words or phrases came into their minds first). Predictability is indicated by the number of responses in which target words in the normal version (i.e., the control condition) were entered as the first words of their responses (e.g., ***his*** *boss* and ***his*** *job* both counted in function words, as in the control condition ***his*** was the target word in the sentence *The employee needs to prepare the document for* ***his*** *boss*). No participant used the target words from the unexpected conditions (i.e., the semantic violation and syntactic violation versions) in any sentences. Although function words were slightly more predictable than content words ($M = 6.45$ vs. 5.30; meaning that for each critical sentence, out of 26 responses in each word class, 6.45 were target function words vs. 5.30 were target content words), this difference was not significant ($t = 1.42$, $p = .16$).

In the ERP experiment the 120 critical sentences were evenly distributed in three experimental lists in a Latin-square design. In this way, each list contained 40 critical sentences in each condition, and no sentence repeated within a list. Stimuli were randomized once within each list and then presented in the same order for each participant. Participants were randomly assigned to a list. To elicit the higher-order and task-dependent P600-like effect that engages foveal attention, we instructed participants to judge whether a sentence makes sense after they finished reading each sentence. Their task was to press one button on a gamepad labeled "yes" for good sentences and another labeled "no" for bad sentences. In order to balance yes/no decisions 40 filler sentences without semantic/syntactic errors were included in each list. Each participant read 160 sentences in total.

Procedure

All stimuli were presented on a 24-inch LCD gaming monitor set to a refresh rate of 100 Hz and located 145 cm directly in front of the participant. The testing began with 10 practice sentences to acclimate participants to the paradigm and experimental conditions.

A visual hemi-field RSVP with flankers paradigm was adopted in which each sentence was presented three words at a time, with the target word at central fixation (foveal target), the upcoming word on the right (parafoveal target), and the preceding word on the left. For every triad, participants were instructed to fixate on the centered word throughout the experiment (i.e., the foveal target word). To facilitate attention to the central foveal target this item was displayed as white letters on a black background. The other two flanking words were displaced as slightly dimmer grey letters. In addition to the color difference, we also added two yellow vertical bars, one above and one below the foveal target to help participants maintain fixation on the center of the screen. All words were presented in a fixed width font (New Courier) with each character occupying a 20 × 40 pixel matrix. Each triad was presented for 400ms, following which the parafoveal target became the foveal target in the following 400 ms epoch (see Figure 1 – note this method of display makes the sentence seem to "slide" one word at a time from right to left). Each sentence presentation started with a fixation mark ("+") at the center of the screen (i.e., where the foveal target would be presented), and ended with a purple question mark ("?") at the center that indicating it was time to make the acceptability judgment. Participants were asked to maintain fixation on the central stimulus and to minimize blinking during sentence presentation, but were encouraged to make movements/blinks during the presentation of the fixation and question mark, which did not disappear until participants pressed a continue button at which point the fixation mark of the next trial was displayed. There were three longer rest breaks every 40 sentences.

EEG Recording

Participants were seated in a comfortable chair in a sound attenuated darkened room. An electro-cap fitted with tin electrodes was used to record continuous EEG from scalp 29 sites (See Figure 2). Four additional electrodes were used: one over the left mastoid bone that served as the reference site for all scalp electrodes; one over the right mastoid that was used to monitor for differential mastoid activity; one below the left eye which together with the FP1 electrode was used to monitor for vertical eye movement (i.e., blinks), and one at the outer canthus of the right eye to monitor for horizontal eye movements. Impedances were kept below 2.5 kΩ for all electrodes. EEG signals were amplified using Neuroscan Synamp RT amplifiers with a bandpass of DC to 100 Hz. The signals were digitally sampled at 500 Hz throughout the experiment.

EEG Analysis

Separate ERPs from four types of critical words (control content vs. unexpected content, control function vs. unexpected function) at two sentence positions (foveal target, parafoveal target) were calculated time-locked to the onset of the target triad. Averaging began 100 ms prior to stimulus onset and continued 1,000 ms thereafter. The resulting data were baselined to the mean voltage in a period from −100 to 0 ms pre-target onset for parafoveal and foveal targets, respectively. Trials with muscle artifact or eye movements (less than 5% of trials in total) were excluded. We were especially careful to monitor for and reject trials with any evidence of horizontal eye movements.

Repeated measures analyses of variance (ANOVAs) were used to analyze the ERP data. We analyzed the critical content and function words at each sentence position (foveal vs. parafoveal) separately. For both content and function words, for each position, the analysis included within participant factors of Word Type (control vs. unexpected), and two electrode position factors, Laterality (left vs. midline vs. right) and Ant-post (anterior-posterior, FP vs. F vs. C vs. P vs. O – see Figure 2 for a diagram of the sites used). For all statistical analyses Geisser-Greenhouse correction was used for all repeated measures factors with greater than 1 degree of freedom in the numerator (Geisser & Greenhouse,1959).

Results

Behavioral Results

Participants judged an average of 88.9% of the sentences correctly (SD = 3.0%). The accuracy rates in conditions with a *no* response (unexpected function words: M = 91.5%, SD = 9.1%; unexpected content words: M = 93.2%, SD = 5.1%) were higher than sentences with a *yes* response (control: M = 85.4%, SD = 7.3%; fillers: 85.3%, SD = 6.1%; $ps < .05$). This was probably due a high threshold for yes responses. The > 85% accuracy rate in all conditions confirmed attentive reading.

Visual Inspection of ERPs

The parafoveal results are plotted in Figures 3 and 4 and are the grand mean ERP waveforms for content and function words time-locked to the onset of the parafoveal targets. In these figures, the epoch starts with two broadly distributed components peaking at around 100 ms (N1) and 250 ms (P2). Neither of these components appears to be influenced by the Word Type variable. Starting at around 300 ms and continuing through 700 ms there was a larger negative-going component that appears to be larger for unexpected words compared to expected words.

The foveal results are shown in Figures 5 and 6 and are the grand mean ERPs for content and function words time-locked to the onset of words in foveal target position. Just as in the parafoveal plots (Figures 3 & 4) the ERPs in these figures start with broadly distributed N1 and P2 components. Following these, for content words, the first visible component that appears to differ between Word Types was a negative-going deflection between 0 and 150 ms after stimulus onset that was followed by a larger positive-going deflection starting from 300 ms post stimulus onset. For function words, the first and only visible difference for unexpected words compared to expected words was a positive-going deflection starting from 650 ms after stimulus onset. Figure 7A shows voltage maps at the 350 – 550 ms and 650 – 950 ms time windows for parafoveal targets, while Figure 7B shows voltage maps at the same time windows for foveal targets.

Epoch Analysis of ERPs

Parafoveal Targets 350 – 550 ms—For content words, an omnibus ANOVA on the mean amplitude values in this epoch revealed significant main effects of Word Type ($F(1, 23) = 9.14$, $p = .006$), indicating that unexpected content words elicited more negative-going ERPs than control words. There was also a significant interaction between Word Type and Laterality ($F(2,46) = 4.22$, $p = .021$) with the Word Type effect size at the midline ($F(1, 23) = 11.62$, $p = .002$) and the right column ($F(1, 23) = 7.96$, $p = .010$) being stronger than that at the left column ($F(1, 23) = 7.09$, $p = .014$). There was also a marginally significant Word Type × Ant-post interaction ($F(4, 92) = 3.76$, $p = .051$), further analyses of which showed that the Word Type effect was significant at F sites ($F(1, 23) = 5.0$, $p = .035$), C sites ($F(1, 23) = 18.95$, $p < .001$), P sites ($F(1, 23) = 12.2$, $p < .001$) and O sites ($F(1, 23) = 9.31$, $p = .006$), but not at FP sites ($F(1, 23) < 1$, $p = .83$).

For function words, the omnibus ANOVA showed a significant Word Type × Laterality interaction ($F(2, 46) = 6.11$, $p = .011$). Further analyses showed that the Word Type effect was only significant at the left hemisphere column ($F(1, 23) = 5.25$, $p = .031$) and the midline ($F(1, 23) = 5.11$, $p = .033$), but not at the right hemisphere column ($F(1, 23) = 1.35$, $p = .26$).

Parafoveal Targets 650 – 950 ms—In this epoch, for both content and function words, Word Type did not show a significant main effect or interaction with the two electrode position factors (ps > .37).

Foveal Targets 350 – 550 ms—Analyses of this epoch showed that unexpected content words produced more positive-going ERPs than control words (Word Type main effect: $F(1, 23) = 7.97$, $p = .010$). In addition, Word Type showed a significant interaction with both Laterality ($F(2, 46) = 3.72$, $p = .047$) and Ant-post ($F(4, 92) = 8.11$, $p = .001$). Follow-up analyses showed that the positivity was significant in all three columns (left: $F(1, 23) = 5.30$, $p = .030$; midline: $F(1, 23) = 7.85$, $p = .010$; and right: $F(1, 23) = 10.08$, $p = .004$), although numerically it was largest over the right hemisphere ($M = 0.92$, 1.21, and 1.31 on the left, midline, and right, respectively). In addition, the positivity was significant at C sites ($F(1, 23) = 7.84$, $p = .010$), P sites ($F(1, 23) = 13.06$, $p = .001$), and O sites ($F(1, 23) = 16.36$; $p < .001$), but was not significant at FP and F sites (ps > .10).

For function words, the omnibus ANOVA showed a significant interaction between Word Type and Laterality ($F(2, 46) = 7.36$, $p = .007$). Follow-up analyses suggested that unexpected function words had a trend to elicit more positive-going deflections at the left column and more negative-going deflections at the right column than control words, but none of the three lines (i.e., left, midline, and right) showed a significant Word Type effect (ps > .10).

Foveal Targets 650 – 950 ms—For content words, the omnibus ANOVA revealed significant main effects of Word Type ($F(1, 23) = 9.14$, $p < .001$), indicating that unexpected content words elicited more positive-going ERPs than control words. There was also a significant interaction between Word Type and Ant-post ($F(2, 46) = 4.22$, $p = .021$). Follow-up analyses showed that the difference between unexpected vs. control words was significant at C sites ($F(1, 23) = 18.84$, $p < .001$), P cites ($F(1, 23) = 27.77$, $p < .001$), and O sites ($F(1, 23) = 29.71$, $p < .001$), marginally significant at F sites ($F(1, 23) = 4.08$, $p = .055$), but was not significant at FP sites ($F < 1$).

For function words, although the main effect of Word Type was not significant ($F(1, 23) = 2.12$, $p = .16$), there was a significant interaction between Word Type and Laterality ($F(2, 46) = 7.88$, $p = .007$). The Word Type effect was only significant at the left column ($F(1, 23) = 5.12$, $p = .033$), marginally significant at the midline ($F(1, 23) = 3.57$, $p = .071$), and was not significant at the right column ($F < 1$). There was also a significant interaction between Word Type and Ant-post ($F(4, 92) = 14.32$, $p = < .001$). Follow-up analyses showed that the difference between unexpected and control function words was significant at P sites ($F(1, 23) = 19.32$, $p < .001$) and O sites ($F(1, 23) = 11.26$, $p = .003$), but was not significant FP, F, and C sites (ps > .12).

Word Class Difference Wave Analyses—We further calculated difference between waves of unexpected and control words in each critical time window and then analyzed this difference as a function of Word Class (content vs. function)[1], Laterality (left vs. midline vs. right) and Ant-post (FP vs. F vs. C vs. P vs. O) as three independent variables. These analyses showed that the distribution of the above word type effects was significantly different between content and function words as follows. The analyses of parafoveal target

[1]Note that using difference waves computed in this manner removes any word category specific differences prior to analysis of differences in the anomaly effects (i.e., word type effects) as a function of word class.

words between 350 and 550 ms showed a significant interaction between Word Class and Laterality ($F(2, 46) = 5.68$, $p = .012$). Combining the findings in separate analyses for content and function words, the negativity was right lateralized for unexpected content words but left lateralized for unexpected function words. See Figure 7A for the spatial distribution that illustrates these interactions.

The analyses of foveal targets between 350 and 550 ms showed a significant interaction between Word Class and Laterality ($F(2, 46) = 12.28$, $p < .001$), a marginally significant interaction Word Class and Ant-post ($F(4, 92) = 3.36$, $p = .062$), and a significant three-way interaction ($F(8, 184) = 2.61$, $p = .032$). As shown above, while unexpected content words elicited a right lateralized positivity at posterior sites, unexpected function words did not elicit any significant effects. See Figure 7B for the spatial distribution that illustrates these interactions.

The analyses of foveal targets between 650 and 950 ms showed a significant interaction between Word Class and Laterality ($F(2, 46) = 7.31$, $p = .006$) and a significant three-way interaction ($F(8, 184) = 3.56$, $p = .007$). While unexpected words in both classes showed a positivity in this time window, the effect elicited by unexpected function words was more left lateralized and posteriorly distributed. See Figure 7B for the spatial distribution that illustrates these interactions.

Discussion

In the present study we used the RSVP with flankers paradigm combined with ERP recording to compare parafoveal-foveal content versus function word processing during sentence comprehension. The first notable finding was that we replicated previous studies, whereby an unexpected semantically anomalous content word elicited a widely distributed parafoveal N400 (e.g., Barber, et al., 2010, 2013; Li, et al., 2015; Payne & Federmeier, 2017; Payne, et al. 2019; Stites, et al., 2017). In addition, a broadly distributed positivity but no N400 was shown when the unexpected content word was foveated. A novel finding of the current study was that unexpected function words in the parafovea also elicited a negativity around 400 ms. At first blush this finding would seem to suggest that unexpected function words, like content words produce an N400 effect. However, careful examination of the negativity produced by unexpected function words suggests this effect was more left lateralized compared to the comparable effect seen for content words. Therefore, we cautiously suggest this effect might better be classified as a parafoveal LAN. Interestingly, function words did not elicit a parafoveal P600 effect but did show a clear P600 when they were foveated. In summary, for both content and function words, different ERP components were shown when the targets were presented in the parafovea versus in the fovea. Consistent with the results of Payne et al (2019), these results indicate there are two stages that differently engages attention in sentence comprehension, regardless of the part of speech of target words.

Content Words

As mentioned above, the parafoveal N400 elicited by unexpected content words is consistent with previous studies with similar manipulations. Because these words only moved to the fovea after 400ms, this result strongly suggests that the effect cannot be due to foveal processing. One potential caveat is that participants might have on some trials made rightward saccades during the presentation of the critical word in the parafovea, thus allowing foveal processing of the critical items. To guard against this possibility, we carefully monitored horizontal eye movements and rejected all trials containing such movements.

When target words were foveated, unexpected content words no longer elicited an N400 effect, consistent with previous findings that a parafoveal N400 mitigated or even eliminated the following foveal N400 (Stites et al., 2017). Instead, a broadly distributed positivity was seen starting around 300 ms after targets were foveated. It seems likely that this positivity reflects the same process that the late positivity reported by Payne et al. (2019), namely, a failure of sentence level integration for foveated unexpected content words. An alternative possibility is that the foveal content word effect is a member of the semantic P600. Semantic P600s had been observed in sentences with semantic anomalies with a plausible non-surface interpretation, typically in role-reversed sentences (e.g., *The mouse is chasing the cat*) or sentences with animacy violation (e.g., *The hearty meal was devouring*) in which the error could be attributed to syntactic properties like word order or the characteristics of the agent/patient of a verb (e.g., Chow & Phillips, 2013; Herten, Kolk, & Chwilla, 2005; Kim & Osterhout, 2005; Kuperberg, 2007). Although none of our sentences involved role reversals and only 13 out of 120 sentences with semantic anomalies involved animacy violation, other factors may also elicit semantic P600s, such as the severity of the conflict between expected words and the presented words. For example, van de Meerendonk, Kolk, Vissers, and Chwilla (2010) found that deeply implausible sentences (e.g., The eye consisting of among other things a pupil, iris, *sticker*…) elicited a larger P600 than mildly implausible sentences (e.g., The eye consisting of among other things a pupil, iris, *eyebrow*….). We suggested that the positivities shown in the present study were less likely to be semantic P600 though, considering that the semantic P600 has been observed in both active and passive comprehension tasks in previous research, while our effects, according to Payne et al. (2019), were likely only present in tasks that required participants to make an overt judgment (see Leckey & Federmeier, 2020 for review). Nevertheless, either a result of plausibility-relevant integration failures or a semantic P600, our suggestion is that the component elicited by unexpected content words engages foveal attention. Both interpretations suggest difficulty in sentence-level re-analysis.

One interesting difference between the current foveal P600-like effects and the positivities reported by Payne et al (2019) is that the current effects seem to have a somewhat earlier time course. One possible explanation of this difference might be that Payne et al (2019) used the same baseline for parafoveal and foveal targets, while in the present study we reset the baseline for foveal targets. However, our foveal P600-like effects were already robust in the foveal N400 time window. Although additional analyses showed that the effects were no longer significant if we used the baseline for parafoveal targets (ps > .13), unexpected content words still elicited numerically more positive waves in this time window. In contrast, previous studies using the baseline for parafoveal targets showed negativities in the foveal N400 time window (Payne et al., 2019; Stites et al., 2017). The opposite direction suggested that different baseline at least was not the only reason. Importantly, this difference does not affect our most critical comparison between content versus function words, given the baselines of the two word classes were the same. Another factor that may contribute to this different P600 time course might be the experimental procedure. In the present study, each trial was presented for 400 ms with no blank screen between words. In Payne et al.'s (2019) study each word was presented for 100 ms but was followed by a 350 ms blank screen. It is possible that the 50 ms shorter SOA or the 300 ms longer presentation duration of each parafoveal target in our study contributed to the earlier target P600 onset. Although more research is needed to confirm this speculation, neither of the above possibilities affected our critical claims. That is, our results showed evidence that initial semantic processing occurs early in parafovea, while the later stage semantic processing at the higher order sentence level engages foveal attention, overall consistent with previous findings.

Function Words

The novel manipulation in the present study was on function words. Unexpected function words elicited a negativity between 350 and 550 ms when presented in the parafovea. However, the distribution of this effect was greater over midline and left-hemisphere sites, whereas the comparable content word N400 effect was larger over midline and right hemisphere sites. Moreover, while the parafoveal N400 effect for content words had a focus at central to posterior electrodes, the effect for function words showed a flatter distribution along the anterior-posterior axis, an absence of Word Type × Ant-post interaction. Therefore, the negativity was relatively more anterior on function than content words. Given the difference in spatial distribution, the parafoveal negativity elicited by unexpected function words seems more likely to related to previous reports of LAN effects for syntactic violations. Although the LAN is typically distributed more anteriorly while our effect shows a broad distribution across anterior and posterior sites, this could be because the LAN and N400 are not categorically distinct ERP components; instead, the distribution reflects a continuum about agreement errors on semantic and syntactic processing (Molinaro, Barber, Caffarra, & Carreiras, 2015; also see Barber & Carreiras, 2005; Tanner & Van Hell, 2014). Namely, the more semantic information processed, the more N400-like are the effects; the more syntactic information processed, the more LAN-like are the effects. Therefore, this different N400 versus relatively more LAN-like distribution elicited by content versus function words did indicate more semantic process versus relatively more syntactic processing in parafovea, respectively. In addition, the absence of foveal LAN further suggested that initial syntactic processing of function words was completed before targets are foveated, similar to the initial semantic processing of content words.

Interestingly we did not observe any P600-like activity when function words were in peripheral vision. The presence of parafoveal LAN and absence of parafoveal P600 supported the claim that the LAN and the P600 are two functionally dissociable components (Mancini, Molinaro, Rizzi, & Garreiras, 2011). While the LAN reflects earlier and more automatic syntactic processing, the P600 seems more likely to reflect a higher-order/ sentence level structural repair or reanalysis process that occurs at a later stage (Friederici, 2002). This difference was also consistent with previous research that adopted the co-registration approach of eye movements and fixation-related-potentials (FRPs), which showed that regressions were strongly associated with the P600 effect in natural reading (i.e., when the whole sentence was available to readers in each trial; Metzner, Von Der Malsburg, Vasishth, & Rösler, 2017; also see Degno & Liversedge, 2020 for a review of this co-registration approach). According to Metzner et al. (2017), regressions reflect readers' attempt to find alternative interpretations in response to words that do not match built-up expectations, thus eliciting P600 effects which reflect sentence level reanalysis. In addition, P600 effects were triggered by both semantic and syntactic anomalies in Metzner et al. (2017), although in that study both types of anomalies were elicited by unexpected content words. This result was consistent with the present study, that both unexpected content and function words in fovea elicited P600 effects, supporting the claim that P600 might not be specific to syntactic processing, but reflect a general process of reanalysis. The present study further suggested that the reanalysis process might involve direct/foveal attention to the words that elicit anomalies.

The foveal P600 elicited by function words appeared later, was more left lateralized, and more posteriorly distributed than the foveal P600-like effects elicited by content words. These differences seemed consistent with early findings in Kutas and Hillyard (1983), which directly compared content versus function words using the word-by-word RSVP paradigm — in sentence comprehension, ERPs elicited by content words were overall more positive than those elicited by function words from 200–700 ms over most scalp sites. The word class effects on foveal targets probably reflect general different mechanisms of content versus function words processing at the sentence level, although the exact mechanism(s) is not clear. It is possible that the foveal P600 elicited by unexpected content words was more about plausibility-relevant integration failures, while the foveal P600 elicited by unexpected function words was more relevant to syntactic re-analysis at the sentence level. While future research is needed to examine the exact mechanism(s), one factor that is unlikely to be the cause of the different distribution and time course in the present study are differences in expectancy, as our rating results showed that unexpected content and function words were less acceptable than their controls to the similar extent before the context after the critical words are presented. One conclusion that does seem warranted is that the processes involved in both P600-like effects likely include foveal attention. In other tasks such as passive reading or memory tasks, unexpected content words have not been shown to elicit the foveal positive component, and while no RSVP passive reading studies have looked at function word anomalies it seems reasonable that the function word P600 effect seen here also resulted in part from the attentional demands of the task. Future research is needed to verify this speculation.

Limitations and Future Research

Like most studies of complex cognitive/linguistic questions, the present study had several limitations. First, while the RSVP with flankers paradigm is a clear improvement over the word-by-word RSVP task in terms of approximating the stimulus conditions encountered in natural reading, it is still possible that participants in this task use a less than natural reading strategy that impacted the pattern of ERP anomaly effects reported. One possibility is that despite instructions to fixate the highlighted word at fixation, participants nevertheless consistently biased their attention to the right of the central word allowing the word to the right to receive more in-depth processing than occurs in natural reading. This might make the reported parafoveal effects reported here and in previous RSVP with flankers studies more akin to typical foveal effects in RSVP studies. This might happen because of a longish SOA (400 ms in our study) which results in a slightly slower than typical reading rate thus encouraging rightward shifts of attention. However, because we carefully monitored participants' horizontal eye movements to guard against the possibility of saccades to and from the rightward parafoveal words, one thing that we can be sure of is that any such attentional bias occurred in the absence of accompanying eye movements. If participants were consistently covertly attending to the word to the right of fixation, they were doing so without moving their eyes. Importantly, even if participants in the RSVP with flankers task consistently covertly attend to the parafoveal word, the ERP results obtained clearly demonstrate that it is *possible* for words in the parafovea to influence both semantic and syntactic processing, a process followed by a second step engages foveal attention.

Second, the results of the present study might be dependent on requirements to make plausibility judgments to each sentence. As suggested in Payne et al. (2019), the foveal P600 effect elicited by semantic anomalies was only present in their experiment requiring plausibility judgments but was not present in passive comprehension. Therefore, some effects reported here for function words might also be selectively present in the plausibility judgment task.

Third, although we did not directly compare content versus function words, these two word classes typically appear alternately in a sentence. As a result, parafoveal content words might have, on average, been closer to foveal vision than parafoveal function words which could account for some of the differences between word classes we are reporting.

Fourth, given the 400 ms presentation duration of each triad, what we are reporting as a foveal P600 effects might alternatively be a somewhat delayed parafoveal P600 (see Risse & Kliegl, 2012 for the similar argument in eye-tracking studies).

Lastly, in the present study we showed P600-like effects in both semantically and syntactically anomalous sentences. While we argued that both effects reflect sentence-level integration and re-analysis difficulties, there were differences in terms of time course and scalp distribution suggesting that semantics and syntax may affect the family of late positivities differently.

To address these limitations, future research with more diverse paradigms (e.g., FRPs, passive comprehension), other languages (e.g., Chinese in which word length difference is less salient across content versus function words, so that visual angle of flanker words can be better controlled), and more factors controlled (e.g., orthographic similarity between target words and unexpected words, sub-word class within content and function words such as the comparison between nouns vs. verbs, preposition vs. conjunctions) are needed to provide a more comprehensive picture. Future research should also include more detailed manipulations of semantic and syntactic variables such as role-reversed sentences, morphosyntactic violations and agreement violations to elicit semantic P600 versus syntactic P600 via different components to shed light on the meaning of late positivities in sentence comprehension. Despite the above limitations and the clear need for additional studies, we would argue that our results and those of previous RSVP with flankers studies (e.g., Payne & Federmeier, 2017; Payne, et al., 2019; Stites, et al., 2017) provide important additional information beyond that gleaned from the traditional RSVP paradigm about the neural mechanisms involved in semantic and syntactic processing during sentence comprehension.

Conclusion

In summary, the present study suggested that in sentence comprehension content versus function words elicit more semantic versus syntactic processing, respectively. More importantly, similar to content words, the processing of function words also appears to include two stages that rely on attention to different extents. In sentence comprehension in natural settings, readers are able to first perform an initial semantic and syntactic assessment of the upcoming word when it is presented in the parafovea. At this stage, semantic and syntactic processing is fast, perhaps automatic, and does not have to rely on direct attention. In contrast, at the second stage readers seem to perform a more in depth attentional mediated assessment. Both semantic and syntactic processing at this stage seems to be about sentence-level integration or re-analysis, which engages foveal attention.

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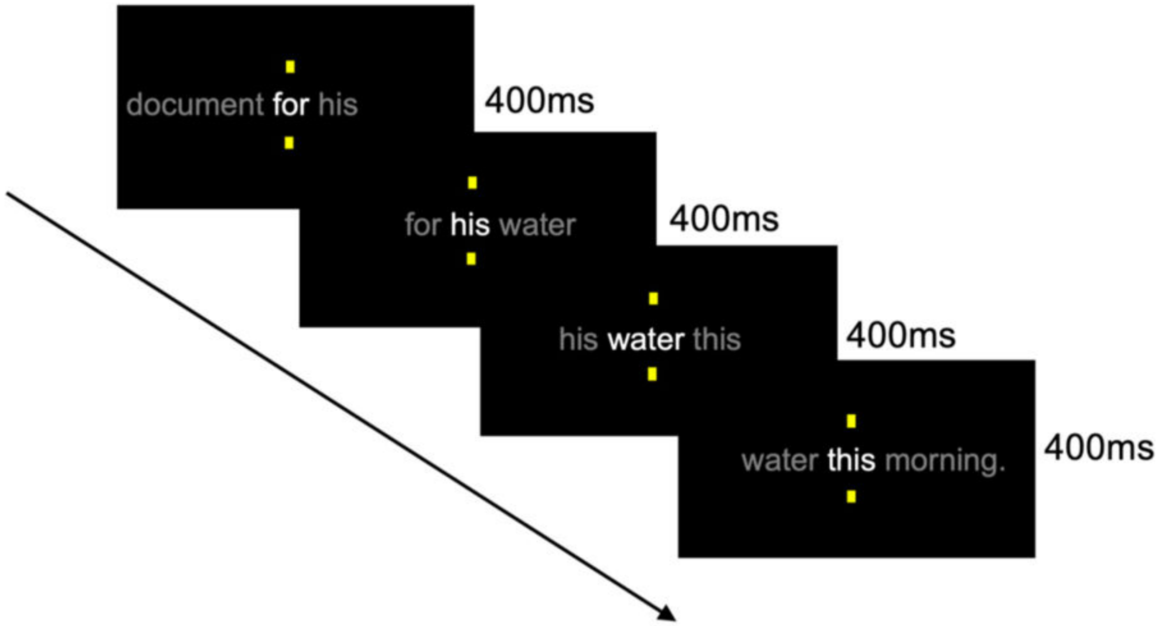

Figure 1.
The visual hemi-field RSVP-flanker paradigm. The foveal target of each triad is presented centered in white.

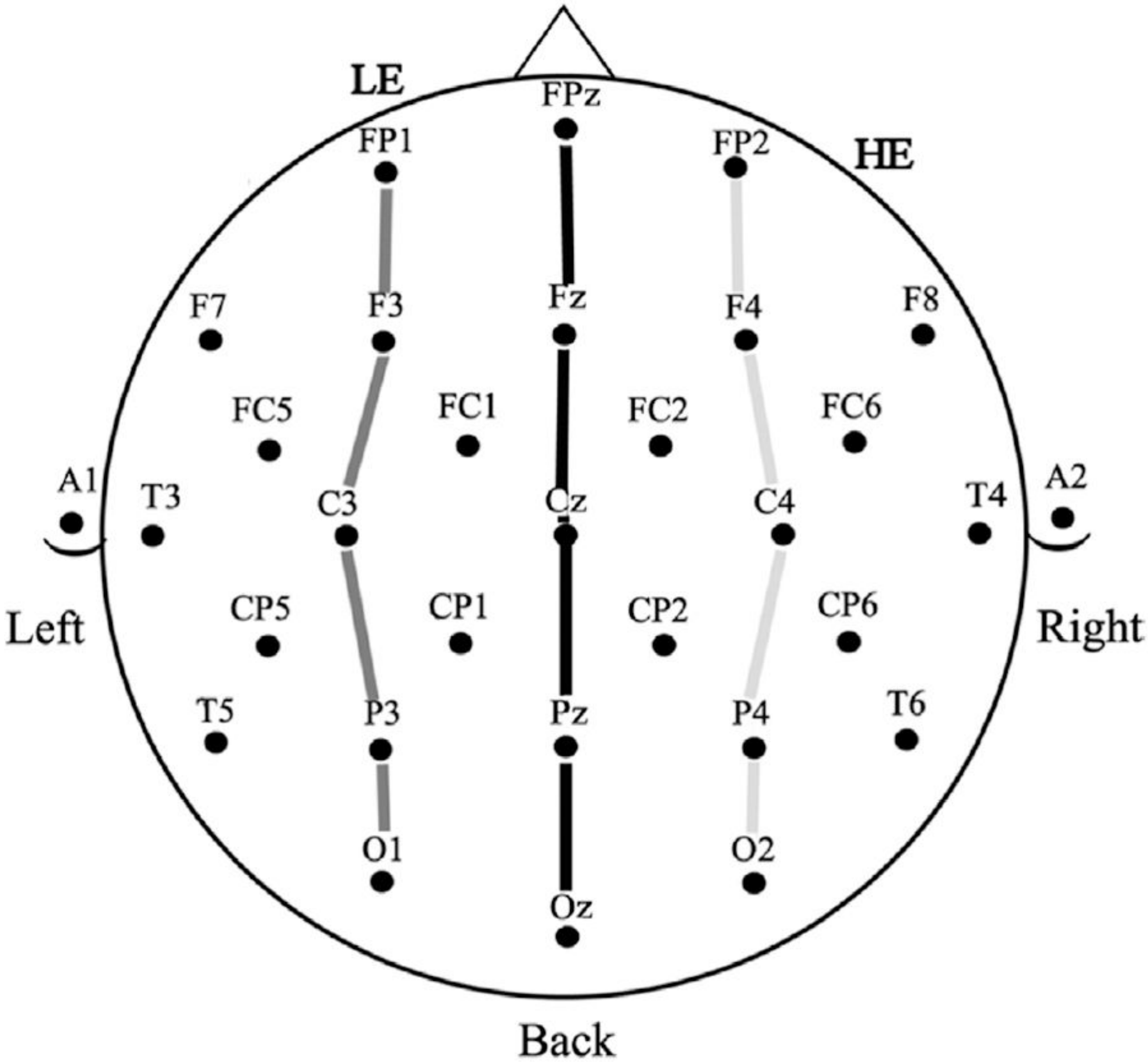

Figure 2.

Electrode montage and the 15 analysis sites used for ANOVAs. The Ant-post factor is defined by the five sites (FP, F, C, P, O) in each of the three Laterality columns, which are indicated with connecting lines. The four additional electrodes were A1 (the reference site over the left mastoid bone), A2 (the other reference cite to monitor for differential mastoid activity); LE (the eye electrode to monitor for blinks), and HE (the eye electrode to monitor for horizontal eye movements).

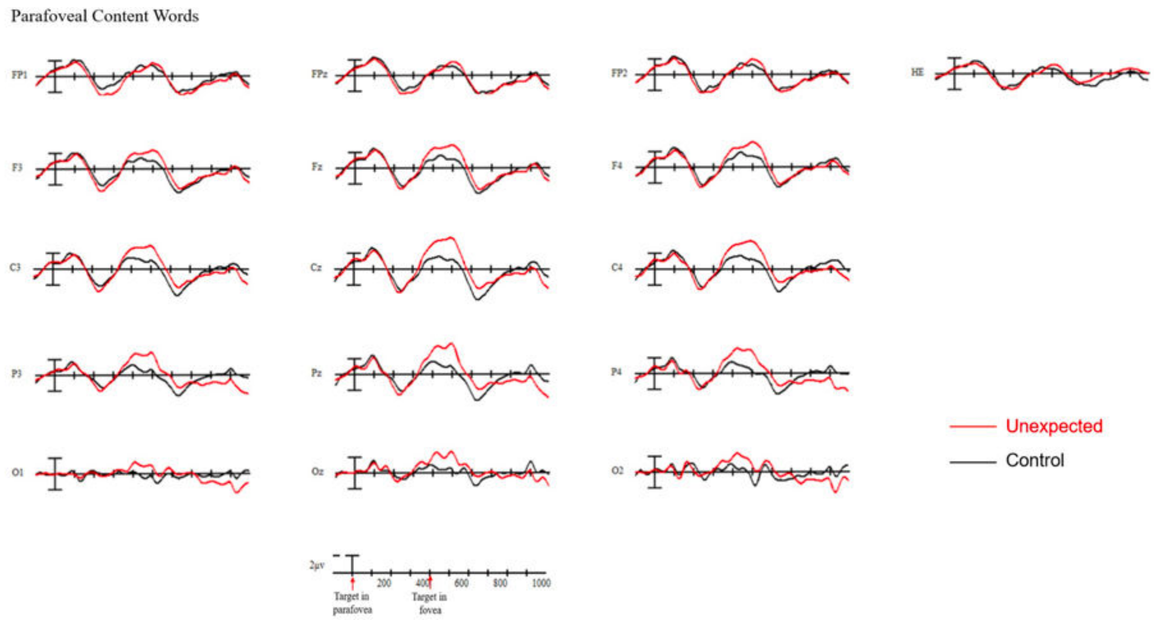

Figure 3.
ERPs time locked to parafoveal target onset from the 15 sites that were included in analyses, comparing unexpected vs. control content targets. The black line is from the control content targets, while the red line is from the unexpected content targets. We also plotted the ERPs from the channels that monitor horizontal eye movements (HE). While 0 ms refers to the parafoveal target onset, the targets moved to the foveal position at 400 ms.

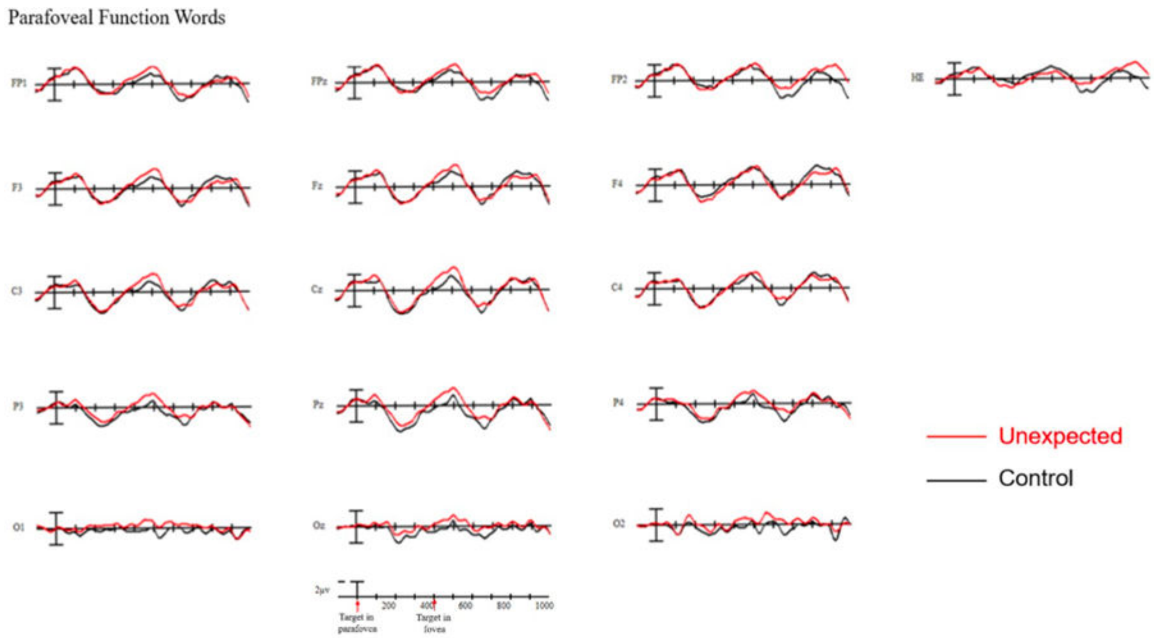

Figure 4.

ERPs time locked to parafoveal target onset from the 15 sites that were included in analyses, comparing unexpected vs. control function targets. The black line is from the control function targets, while the red line is from the unexpected function targets. We also plotted the ERPs from the channels that monitor horizontal eye movements (HE). While 0 ms refers to the parafoveal target onset, the targets moved to the foveal position at 400 ms.

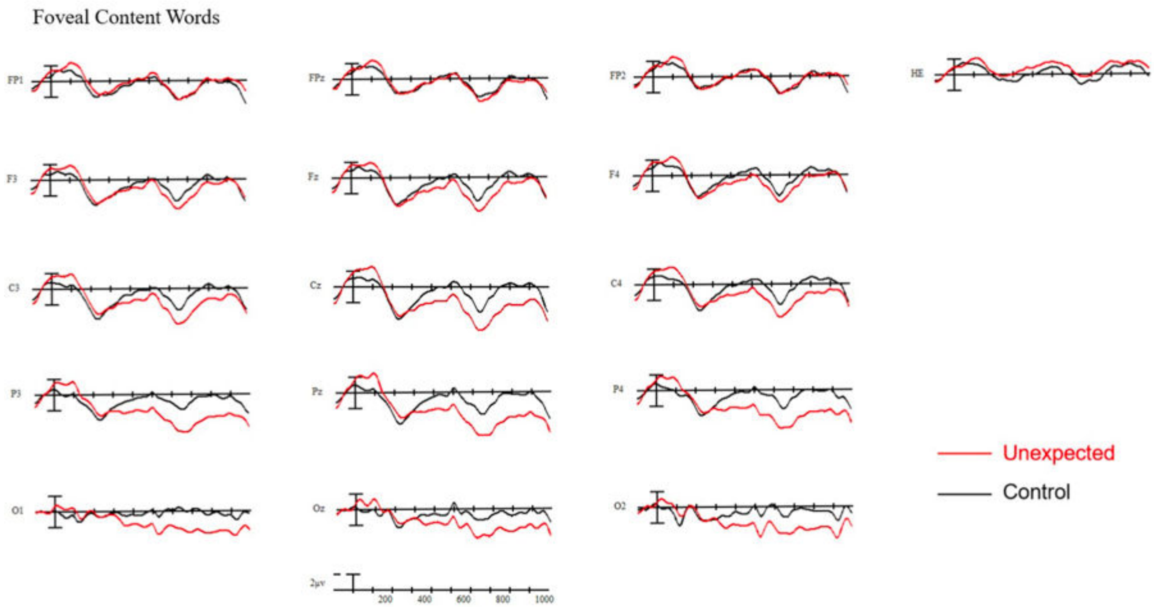

Figure 5.

ERPs time locked to foveal target onset from the 15 sites that were included in analyses, comparing unexpected vs. control content targets. The black line is from the control content targets, while the red line is from the unexpected content targets. We also plotted the ERPs from the channels that monitor horizontal eye movements (HE). While 0 ms refers to the foveal target onset, the targets moved to the left position (i.e., being the preceding word) at 400 ms.

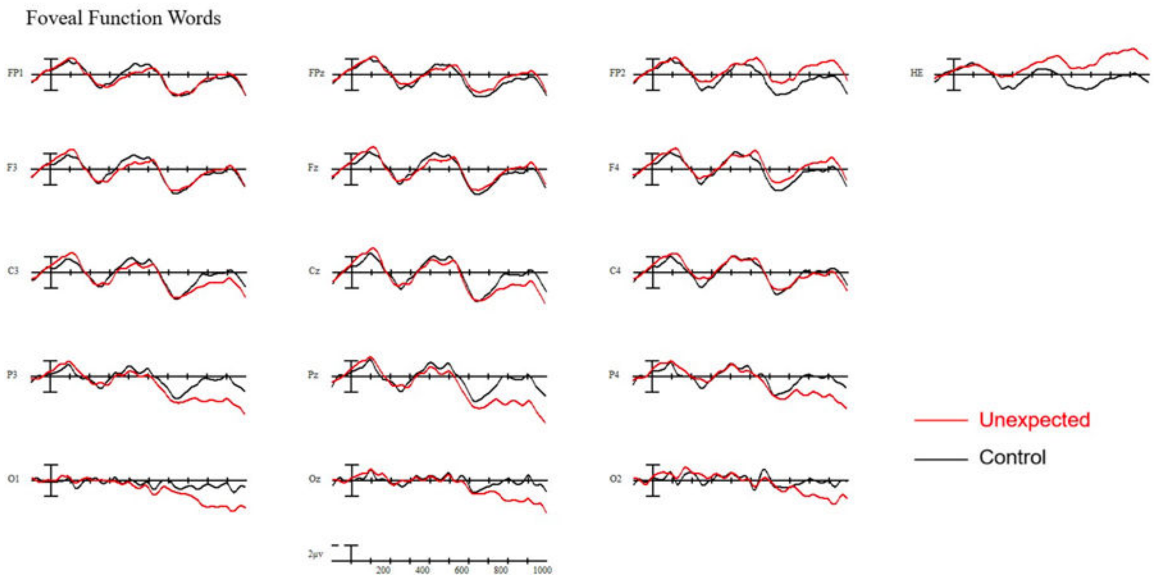

Figure 6.
ERPs time locked to foveal target onset from the 15 sites that were included in analyses, comparing unexpected vs. control function targets. The black line is from the control function targets, while the red line is from the unexpected function targets. We also plotted the ERPs from the channels that monitor horizontal eye movements (HE). While 0 ms refers to the foveal target onset, the targets moved to the left position (i.e., being the preceding word) at 400 ms.

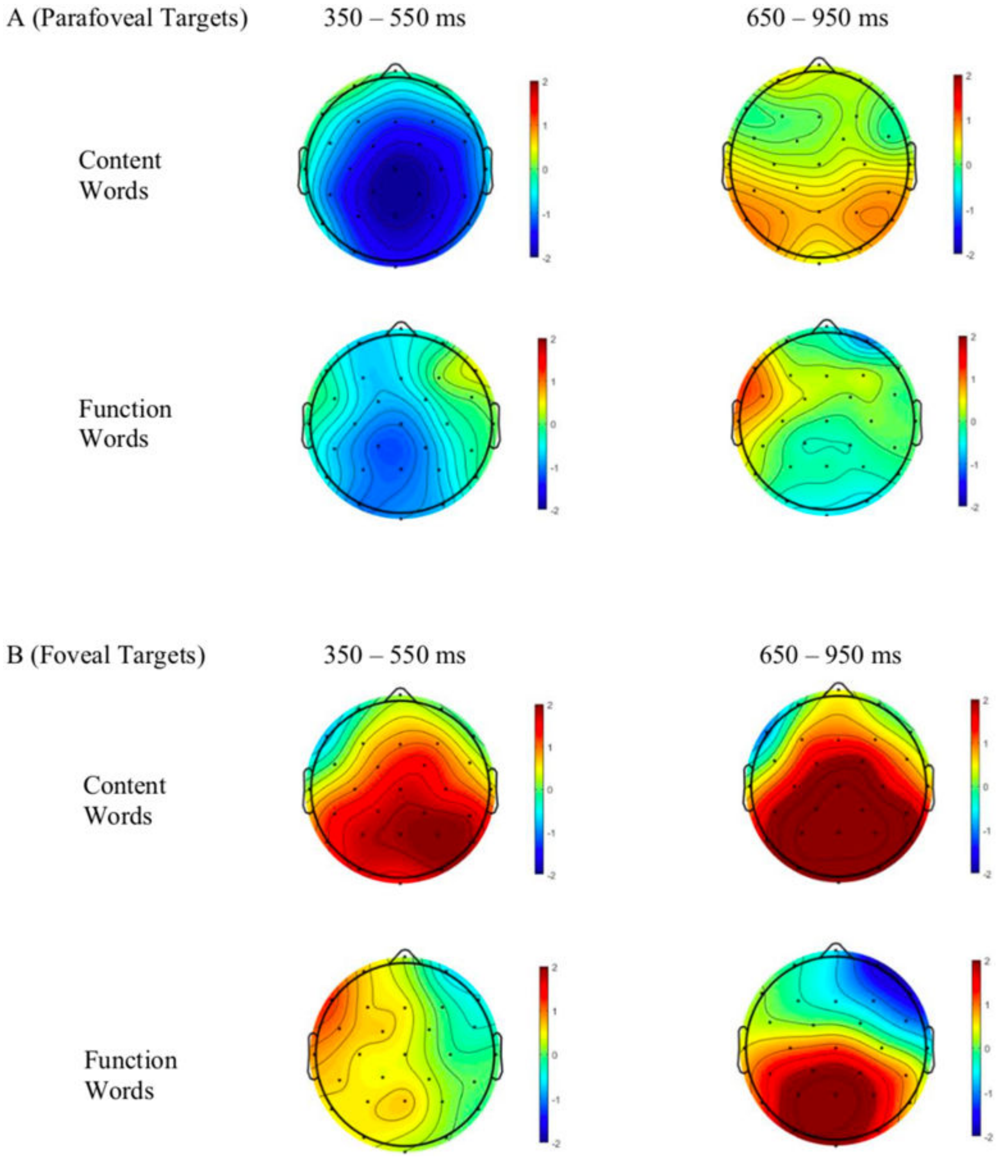

Figure 7.

Voltage maps calculated from the mean difference (in microvolts) between unexpected words and control words at 29 scalp sites at the 350 – 550 ms (left column) and 650 – 950 ms (right column) time windows. Panel A shows the maps for parafoveal targets, while Panel B shows the maps for foveal targets.

Table 1.

Mean word frequency, length, and acceptability judgment scores (standard deviation in the parentheses) across conditions.

		Frequency[a]	**Length**	**Acceptability**[b]
	Unexpected	84.34 (201.34)	5.46 (1.49)	1.33 (.24)
Content Words	Control	108.37 (216.22)	5.67 (1.83)	6.74 (.17)
	Difference	$p = 0.37$	$p = 0.29$	$p <.001$
	Unexpected	7347.07 (8504.04)	3.07 (1.16)	1.69 (.42)
Function Words	Control	11752.85 (9397.60)	2.84 (1.06)	6.56 (.55)
	Difference	$p < .001$	$p = 0.13$	$p <.001$

[a]The frequency refers to the number per million based on SUBTLEX_US (Brysbaert & New, 2009).

[b]The difference score between unexpected and control words for the content vs. function words were also compared ($p = .16$), indicating that the unexpected content vs. function words were equally unexpected compared to their corresponding control words.