Parallel semantic processing in the flankers task: Evidence from the N400

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ABSTRACT

The extent to which higher-order representations can be extracted from more than one word in parallel remains an unresolved issue with theoretical import. Here, we used ERPs to investigate the timing with which semantic information is extracted from parafoveal words. Participants saw animal and non-animal targets paired with response congruent or incongruent flankers in a semantic categorization task. Animal targets elicited smaller amplitude negativities when they were paired with semantically related and response congruent animal flankers (e.g., *wolf coyote wolf*) compared to unrelated and response incongruent flankers (e.g., *sock coyote sock*) in the N400 window and a post-N400 window. We interpret the N400 effect in terms of facilitated processing from the joint activation of shared semantic features (e.g., animal, furry) across target and flanker words and the later effect in terms of post-lexical decision-making. Thus, semantic information can be extracted from flankers in parallel and impacts various stages of processing.

1. Introduction

Recent evidence has rekindled a debate regarding a question of fundamental importance to our conception of reading: Can multiple words be processed in parallel or is the human brain limited to serial processing of individual words (see, e.g., Schotter & Payne, 2019; Snell & Grainger, 2019a; Snell & Grainger, 2019b; White, Boynton, & Yeatman, 2019)? Here, we focused specifically on semantics, since parallel processing of higher order representations is the crux of this debate (see, e.g., Schotter, Angele, & Rayner, 2012, for a review). We used the reading version of the flankers task as a particularly effective way of investigating parallel processing when the task only requires processing of a single word. Central targets were briefly presented with a flanker word in the parafovea on either side (e.g., *sock coyote sock*) and participants performed a semantic categorization decision made to central target words (i.e., is it an animal?). We manipulated the semantic relatedness and response congruency between the target and flankers across conditions and used the precise temporal acuity of event-related potentials (ERPs) to track the relative contributions of these two variables.

Much of the early evidence pertaining to access of parafoveal semantic information came from eye-tracking studies employing the gaze-contingent boundary paradigm (Rayner, 1975). This paradigm relies on an invisible boundary in a sentence. When participants are fixating to the left of the boundary, the preview word immediately to the right of the boundary can either be semantically related to the intended word or unrelated. As participants' gaze crosses the boundary, the preview word is replaced with a target word that fits within the sentence frame. Some authors have reported that having a semantically related preview word decreased the gaze duration for the target word relative to unrelated preview words (e.g. Hohenstein & Kliegl, 2014; Veldre & Andrews, 2016). However, these effects are far from ubiquitous; others have been unable to find a semantic preview effect or have only found it in certain conditions (e.g., Angele, Tran, & Rayner, 2013; Rayner & Schotter, 2014; Rayner, Schotter, & Drieghe, 2014; Snell, Declerck, & Grainger, 2018). One factor that might determine the presence of a semantic preview effect is strength of the semantic relationship between the related preview word and the target word. For example, Schotter (2013) found a semantic preview effect for synonyms, but not for semantically related words (see also Schotter, Lee, Reiderman, & Rayner, 2015). When found, such effects indicate that semantic information can be extracted from the preview words in the parafovea.

The interpretation of these parafoveal preview effects differs across theoretical models of reading. Serial attention shift models, such as E-Z

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Table 1
Stimulus Characteristics [mean (SD)]

		Length	Frequency	Concreteness	NLD Response Congruent Flanker	NLD ResponseIncongruent Flanker
Targets	Animal	4.88 (1.00)	13.27 (30.21)	4.84 (0.14)	0.90 (0.12)	0.90 (0.11)
	Non-Animal	4.88 (1.00)	13.26 (29.49)	4.84 (0.15)	0.90 (0.10)	0.90 (0.13)
Flankers	Animal	4.42 (1.05)	15.89 (19.66)	4.86 (0.16)	——	——
	Non-Animal	4.42 (1.05)	15.83 (19.84)	4.83 (0.13)	——	——

Note: NLD = Normalized Levenshtein Distance.

Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998), assume that attention has already shifted to the parafoveal location while the foveal word is still being fixated (Schotter, 2018). That is, semantic information can be extracted from the parafovea as long as attention has moved to that location in preparation for an eye movement. On the other hand, parallel models such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005) and OB1-reader (Snell, van Leipsig, Grainger, & Meeter, 2018) allow for parallel processing across multiple words prior to any eye movement or shift in attention. The key issue, therefore, is the extent to which semantic information can be extracted from the parafovea prior to attention shifting to that location in preparation for an eye movement.

The temporal precision of ERPs has been exploited to address this issue of the simultaneity of semantic processing across multiple words in a sentence. Traditionally, the rapid serial visual presentation (RSVP) paradigm has been used to investigate the electrophysiological correlates of sentence processing in the absence of eye movement artifacts. In this paradigm, each word in a sentence is presented one at a time at fixation for a constant duration. The semantic fit between the word and the preceding sentential context reliably modulates amplitude of the N400, a peak in the ERP waveform that occurs approximately 400 ms after word onset and is associated with lexico-semantic processing (see, e.g., Kutas & Federmeier, 2011, for a review). These modulations of N400 amplitude are graded; for example, expected words generate the smallest negativities, anomalous words generate the largest negativities, and unexpected but plausible words fall somewhere in between (e.g., Kutas & Hillyard, 1983; Meyer & Federmeier, 2007). In the flanker-RSVP paradigm, words are displayed together with the words that occur immediately to the left and right in the sentence. The critical ERPs are time-locked to presentation of the word in position N with the semantic manipulation to the right of fixation in position N + 1. If processing is limited to the foveal word in position N, then there should be no differences across conditions because the information up to and including that word is identical. However, the semantic fit of the word in parafoveal position N + 1 has been found to modulate N400 amplitude in a similarly graded fashion as the classic findings from foveal words in the standard RSVP paradigm (e.g., Barber, Doñamayor, Kutas, & Münte, 2010; Barber, van der Meij, & Kutas, 2013; Payne, Stites, & Federmeier, 2019; Stites, Payne, & Federmeier, 2017). These results suggest that the semantics of words in the parafovea can be accessed; the "fit" between the word in the parafovea and the sentence frame that precedes it impacts how the triad of words is processed. The simplest explanation for these findings is that words N and N + 1 are processed in parallel and simultaneously contribute to the construction of a sentence-level representation. It is the nature of this sentence-level representation that appears to be modulating N400 amplitude.

Both the gaze-contingent boundary and the flanker-RSVP ERP paradigms involve processing of sentences, a context in which extracting meaning from upcoming words is advantageous. Evidence from the flankers task suggests that parallel processing of semantics might also hold in a more minimal context where parafoveal words are irrelevant for the task at hand. Moreover, compared with the flanker-RSVP paradigm, the flankers task has the advantage of not providing a preview of semantically related words before they are fixated, hence providing an even stronger test of parallel semantic processing. Snell, Declerck, et al. (2018) presented English target words to French-English bilinguals in the context of a semantic categorization task (i.e., is this word natural or

artifactual?). When target words were flanked by their French translations (e.g., *loup wolf loup*), they elicited faster and more accurate responses compared to when they were flanked by unrelated French words (e.g., *loge wolf loge*). These results suggest that semantic information can be extracted from the parafovea, but it is unclear what was driving these behavioral effects. The semantics of the translation equivalent flankers could have facilitated target word processing by joint activation of a subset of the same semantic features. Alternatively, given that target and flanker words belonged to the same response category in the translation equivalent condition, but not in the unrelated condition, post-lexical decision-making level may have been facilitated (e.g., Eriksen, 1995; Shaffer & LaBerge, 1979). These mechanisms are not mutually exclusive; a final possibility is that semantic facilitation was followed by a response congruency effect.

The present study was designed as a further investigation of semantic effects in the flankers task. We aimed to capitalize on the precise temporal resolution of ERPs to dissociate the effects of flanker semantics on lexico-semantic processing of the target versus post-lexical decision-related processes. Participants saw animal and non-animal target words and were asked to decide whether or not they were animals. Each target was paired with response congruent and incongruent parafoveal flankers. The response congruent flankers paired with animal words were also semantically related. Our first prediction was that processing of animal targets would be facilitated when presented with semantically related and response congruent animal flankers (e.g., *wolf coyote wolf*) relative to unrelated non-animal flankers (e.g., *sock coyote sock*), as reflected by faster and more accurate behavioral responses. If this facilitation arises from joint activation of semantic features that are shared by target and flanker words, then we would expect it to be accompanied by smaller amplitude N400s (i.e., less effortful processing for animal targets presented with related animal flankers compared to those with non-animal flankers). If, on the other hand, the behavioral facilitation is driven uniquely by response congruency during decision-level processing, then the electrophysiological counterpart should arise in a post-N400 window. A sustained effect that begins in the N400 window and continues through the late positivity would be consistent with both mechanisms. Non-animal targets allow for further examination of response congruency effects in the absence of semantic relatedness. Here too, we expect that responses to non-animal targets should be facilitated in the presence of response congruent non-animal flankers (e.g., *sock carrot sock*) relative to response incongruent animal flankers (e.g., *wolf carrot wolf*) and that any modulation in the ERP waveform should come in a post-N400 window.

2. Methods

2.1. Participants

Data are reported from 24 participants (15 females; mean age 21.25 years, *SD* 2.94 years). By self-report all participants were right-handed and did not have a history of neurological disorders or disorders that affect language and/or reading. All participants were functionally monolingual, which we defined as not having exposure to a language other than English before the age of six and not being fluent in another language. They provided informed consent in accordance with the Institutional Review Board at San Diego State University and received

Table 2
Stimulus Examples.

Target	Animal	Flanker	
		Response Congruent *newt gecko newt, wolf coyote wolf*	Response Incongruent *twig gecko twig, sock coyote sock*
_____	Non-Animal	*twig braid twig, sock carrot sock*	*newt braid newt, wolf carrot wolf*

monetary compensation for their time. Data from an additional two participants were excluded because they misunderstood the task (e.g., pressed "yes" when both the target and flankers were animal words).

2.2. Stimuli

All of the stimuli were concrete English nouns that were 3–6 letters long. There were 100 targets, half of which were animals. Animal and non-animal targets had the same number of letters and similar frequencies in the SUBTLEX database (Brysbaert & New, 2009, see Table 1). Each target was presented twice, once with a response congruent flanker and once with a response incongruent flanker. Animal targets were paired with response congruent animal flankers that had a strong semantic relationship (see Table 2 for examples and https://osf.io/uwzvn/ for the full set of stimuli). The non-animal flankers were chosen to match the animal flankers in terms of number of letters, frequency, and concreteness (Brysbaert & New, 2009; Brysbaert, Warriner, & Kuperman, 2014). Moreover, there was no overt semantic relationship between the non-animal targets and either the response congruent or incongruent flankers with which they were paired. Orthographic similarity between targets and flankers was controlled by calculating Levenshtein distances normalized by the longer of the two words. The mean normalized Levenshtein distance was similar between each type of target and the corresponding flanker conditions (see Table 1).

2.3. Procedure

Each of the 200 trials consisted of a white fixation cross that was presented at the center of the black screen for 500 ms followed by simultaneous presentation of the central target and parafoveal flankers for 170 ms. This short duration has been used in previous flanker experiments (e.g., Snell, Declerck, et al., 2018) and was used here to minimize eye artifacts related to saccades to the flanker stimuli. The longest target word subtended a horizontal visual angle of 2.13 degrees and the longest possible stimulus (i.e., flanker target flanker) subtended a horizontal visual angle of 5.76 degrees. The same flanker word was presented on either side of the target. Participants pressed one trigger button on a videogame response box for animal targets and the other trigger button for non-animal targets. Response hand was counterbalanced across participants and lists. Eight hundred ms after a response was registered, a purple fixation was presented at the center of the screen as an indication to participants that they could blink. A longer break was also offered at the halfway point.

Stimuli were presented in one of four pseudorandomized lists. Each target was presented once in each half of each list, with a response congruent flanker in the first half of two of the lists and with a response incongruent flanker in the first half of the other two lists. No more than three consecutive trials belonged to the same target category. The experiment began with a practice list that contained eight trials, four of which had animal targets.

2.4. EEG recording and analysis

Participants wore an elastic cap (Electro-Cap) with a standard montage of 29 electrodes. Impedances for all electrodes were maintained below 2.5 kΩ. EEG was amplified with SynAmps RT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100 Hz and was
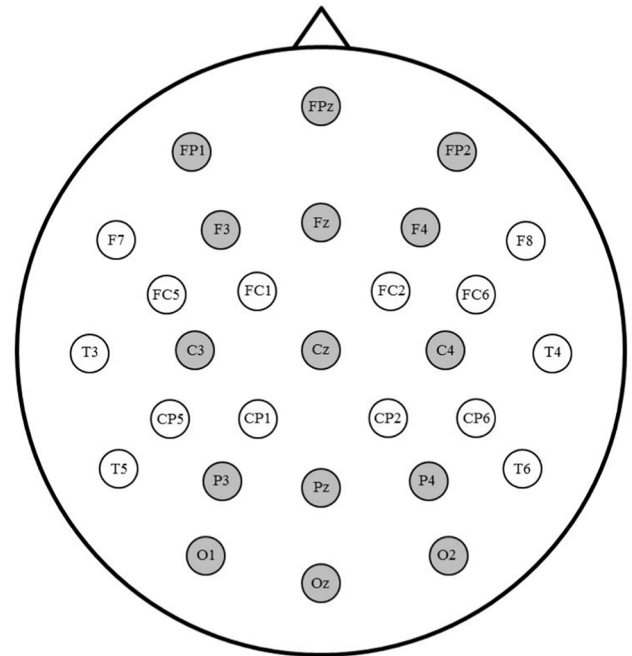
Fig. 1. Electrode montage. Sites highlighted in grey were included in analyses.

sampled continuously at 500 Hz. One electrode was placed on each mastoid bone; the electrode on the left mastoid was used as a reference during recording and for subsequent analyses. Epochs were time-locked to target onset and extended 1000 ms, including a 100 ms pre-stimulus baseline. All trials with artifacts during this epoch of interest were excluded from analyses. An electrode next to the right eye was used to detect horizontal eye movements and another electrode below the left eye was used to identify blinks in conjunction with the recording from FP1. Artifacts were identified through automatic algorithms with thresholds set for each ocular parameter followed by manual verification for each participant. In total, an average of 10 trials (5%) per participant were identified as containing artifacts. An ANOVA with within-participant factors Target (Animal, Non-Animal) and Flanker (Response Congruent, Response Incongruent) confirmed that a similar number of trials were excluded from each condition, all $ps > 0.52$.

Artifact-free trials that had correct responses between 200 and 2000 ms after stimulus onset were averaged separately for animal and non-animal targets in each flanker condition and low-pass filtered at 15 Hz.[1] For each participant, mean N400 amplitude was calculated between 300 and 500 ms after stimulus onset. Since the effects appear to extend beyond the N400 window and we were interested in the effects of flanker congruency on post-lexical decision processes, we also report

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[1] The exact same pattern of results is obtained using a 0.1–15 Hz bandpass filter.

Table 3
Behavioral results [mean (SD)]

		Response Congruent Flankers	Response Incongruent Flankers
Animal Targets	RTs (ms)	630 (88)	635 (79)
	Accuracy (%)	95.4 (3.9)	94.5 (4.5)
Non-Animal Targets	RTs (ms)	669 (76)	697 (79)
	Accuracy (%)	96.0 (3.5)	94.5 (5.6)

3. Results

3.1. Behavior

Only trials with correct responses between 200 and 2000 ms were included in the RT analyses. Mean RTs and accuracy for each condition are reported in Table 3.[3] Response congruency with the flankers did not significantly affect RTs to the animal targets, $F(1,23) = 1.03$, $p = .321$, $\eta_p^2 = 0.04$. In contrast, non-animal targets elicited faster RTs when paired with response congruent non-animal flankers compared to response
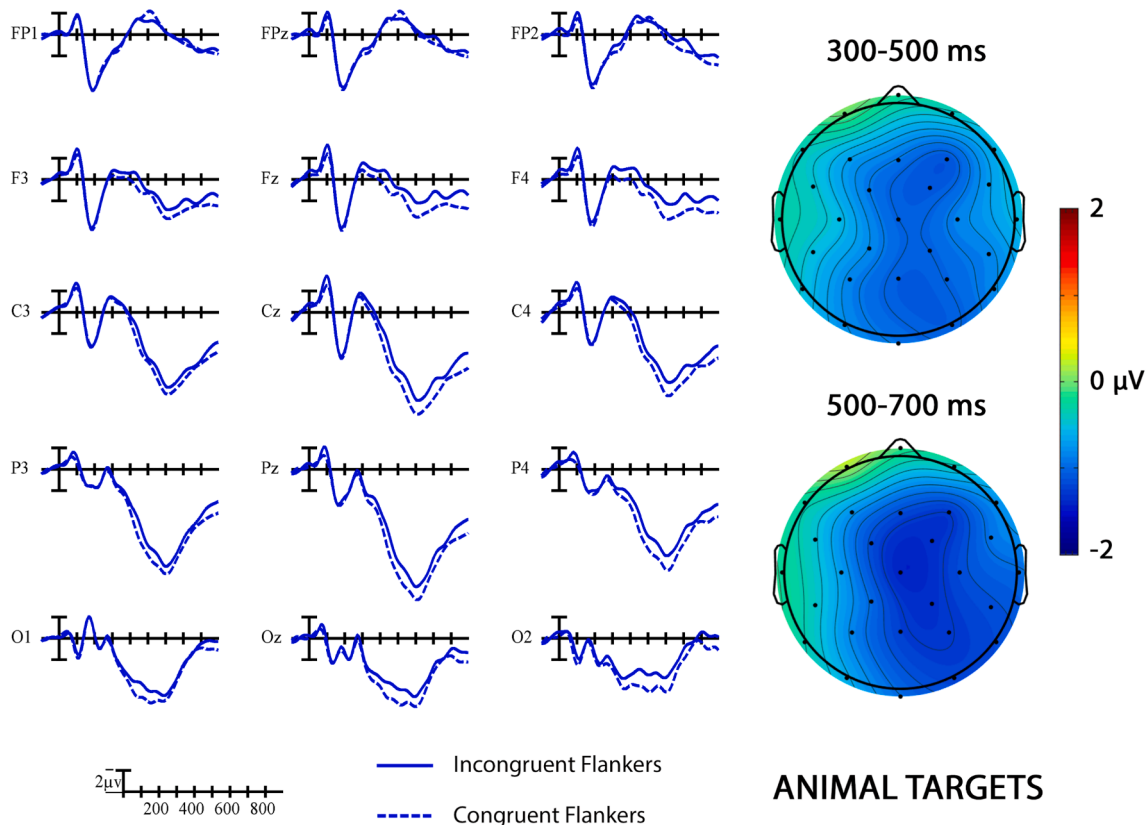
Fig. 2. Flanker effect for animal targets. Grand average ERP waveforms elicited by animal targets paired with response incongruent non-animal (solid line) and response congruent animal (dotted line) flankers. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 μV. The scalp voltage maps on the right show the distribution of the flanker semantic effects (incongruent-congruent) for the animal targets in the two windows that were analyzed.

mean amplitude between 500 and 700 ms.[2] Analyses were conducted on the grid of 15 electrodes illustrated in Fig. 1 that was determined prior to data inspection. Separate omnibus ANOVAs were used for each type of target and time window with factors Flanker (Response Congruent, Response Incongruent), Laterality (Left, Midline, Right), and Anterior/ Posterior (Prefrontal, Frontal, Central, Parietal, Occipital). Greenhouse-Geisser correction was applied for all within-subject measures with more than one degree of freedom in the numerator. Partial eta squared (η_p^2) is reported as a measure of effect size.

incongruent animal flankers, $F(1,23) = 31.11$, $p < .001$, $\eta_p^2 = 0.57$. In accuracy analyses, the effect of flanker response congruency was not significant for either type of target, both $ps > 0.10$.

3.2. ERPs

Animal targets. Animal targets elicited smaller amplitude N400s when presented with response congruent animal flankers versus with response incongruent non-animal flankers (i.e., N400 priming), $F(1,23) = 6.95$, $p = .015$, $\eta_p^2 = 0.23$ (see Fig. 2). In the subsequent window, the effect of flanker response congruency continued to be significant and was strongest at right hemisphere sites, Flanker, $F(1,23) = 7.37$, $p = .012$, $\eta_p^2 = 0.24$, Flanker × Laterality, $F(2,46) = 4.59$, $p = .037$, $\eta_p^2 = 0.17$.

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[2] Following Luck and Gaspelin (2017), we analyzed several other time windows to ensure the robustness of this effect. The same pattern of significant results held for the following windows: 500–750 ms, 500–800 ms, 550–700 ms, 550–750 ms.

[3] Information regarding the distribution of the RT effects, which are consistent with the effects reported here, can be found in Supplementary Materials. Behavioral and ERP data from individual participants can also be found at https://osf.io/uwzvn/.
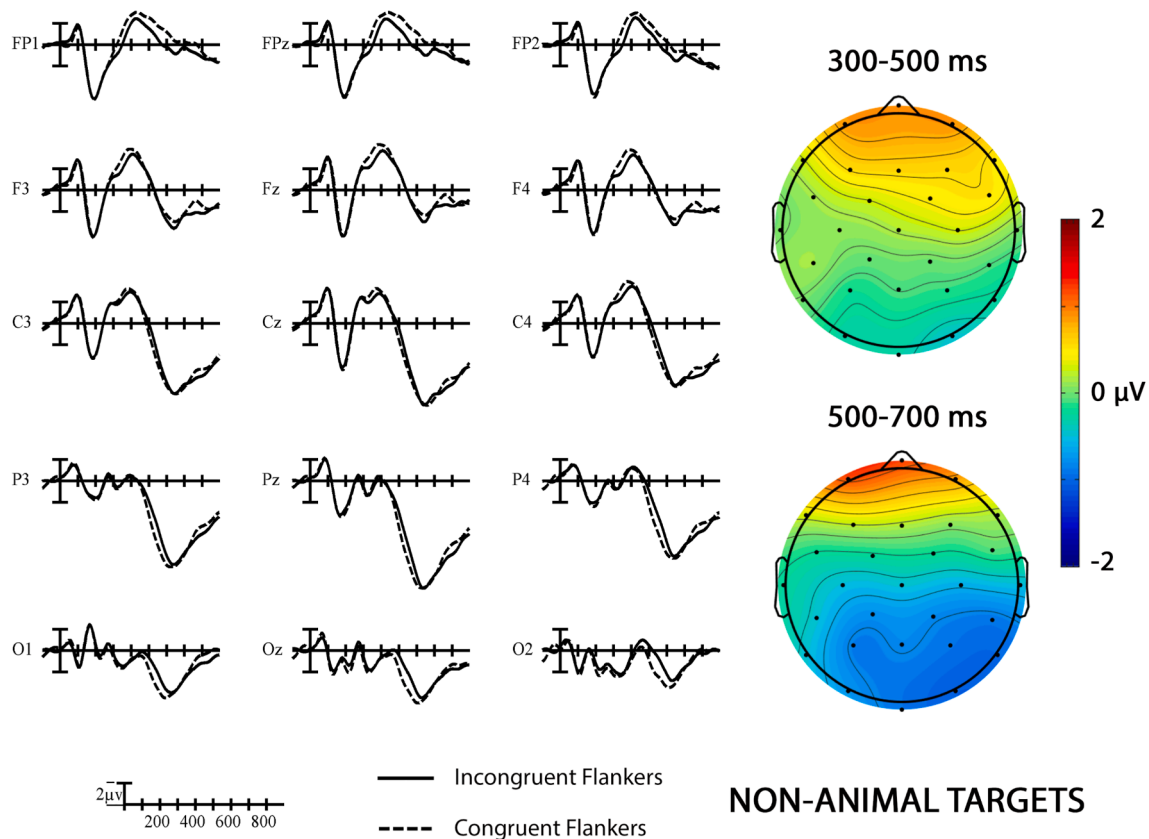
Fig. 3. Flanker effect for non-animal targets. Grand average ERP waveforms elicited by non-animal targets paired with response incongruent animal (solid line) and response congruent non-animal (dotted line) flankers. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 μV. The scalp voltage maps on the right show the distribution of the flanker semantic effects (incongruent-congruent) for the non-animal targets in the two windows that were analyzed.

Non-animal targets. Response congruency with the flankers did not have a reliable effect on the amplitude of the N400s elicited by non-animal targets, all $ps > 0.09$. However, an effect emerged across posterior sites in the subsequent post-N400 window such that non-animal targets paired with response congruent flankers elicited smaller negativities (i.e., larger positivities) than those paired with response incongruent flankers, Flanker × Anterior/Posterior, $F(4,92) = 9.18$, $p = .001$, $\eta_p^2 = 0.28$ (see Fig. 3).

4. Discussion

At issue here was the extent to which semantic information is extracted in parallel from parafoveal words in a paradigm that directs participants' attention to the central target word, hence providing a strong test of parallel semantic processing. In order to examine this hotly debated issue in reading research, we combined the high temporal resolution of EEG recordings with a manipulation of the semantic relatedness of flanker words in the flankers task. If flanker semantics are extracted in parallel, then effects of semantic relatedness should appear as modulations of N400 amplitude (i.e., during the time window in which target semantics are being processed). Our manipulations also allowed us to examine effects of response congruency in the flankers task, which we expected to be visible in a post-N400 time window. Both manipulations revealed the expected pattern, with animal targets showing effects of flanker semantic relatedness on the N400, and both types of targets showing effects of response congruency in a later time window.

The key finding of the present study is that semantic information can be extracted from parafoveal words in time to modulate ERP activity in the N400 window. Given that the N400 component is also associated

with semantic manipulations when single words are presented (see, e.g., Kutas & Federmeier, 2011, for a review), this pattern strongly suggests that lexico-semantic processing of the targets and flankers occurred with at least some degree of simultaneity.[4] We would argue that this facilitated processing is driven by the increased proportion of semantic feature representations that were shared across targets and flankers in the related condition; animal targets share more semantic features with other animals than with unrelated non-animal words. Otherwise stated, N400 amplitude would appear to reflect the aggregate semantic processing across the three words. Slight variations in the timing with which each of these words is processed and overlap with the subsequent positivity might contribute to a less pronounced peak than is typical for this component. This N400 effect mirrors previous results from the flanker-RSVP paradigm, in which semantic violations in the parafovea yielded larger amplitude N400s (e.g., Barber et al., 2010; Barber et al., 2013; Payne et al., 2019; Stites et al., 2017). The critical difference is that the flanker-RSVP paradigm encourages participants to extract meaning from the parafovea in order to build a sentence-level representation, whereas the flankers in the current study were irrelevant for the task at hand. Thus, it would appear that extraction of semantic information from the parafovea is subject to some degree of automaticity; a stricter test of this automaticity would be to find a comparable N400 effect in a task that does not require any degree of overt semantic decision.

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[4] Of course, a very fast serial processor could also account for these results. In the limit, a serial processor cannot be distinguished from a parallel processor. What is at stake here is just how fast can be considered reasonable for a serial model given the constraints associated with eye movement and attention shifts.

The N400 effect was specific to the animal targets. This was to be expected since the non-animal targets were never paired with semantically related flankers. In the subsequent time window, which was largely dominated by a P300-like positivity, we found response congruency effects for both types of targets. In this post-lexical window, targets also elicited larger amplitude negativities (i.e., smaller amplitude positivities) when paired with response incongruent flankers relative to response congruent flankers. We interpret this pattern in terms of the relative increase in difficulty making a semantic categorization judgment when the responses required by the target and flanker conflict. Given that the posterior distribution of this effect bears some similarity with the N400 effect observed for animal targets, it might be tempting to conclude that the two ERP effects reflect similar underlying processes for the two types of targets. That is, either the effect reflects semantic processing or response congruity, and the timing of the effect is shifted earlier for animal targets relative to non-animal targets. This account receives some support from the findings that the P300 appeared to peak earlier and RTs were faster for animal targets relative to non-animal targets, presumably reflecting a faster processing sequence. However, we find this explanation unlikely given that there is a distinct post-lexical effect for the animal targets and the delay between the onset of the ERP effects for the two types of targets (~200 ms) is not compatible with the delay in RTs or P300 peaks between the two (~50 ms). Overall then, we would argue that the pattern across the two windows is most consistent with a dissociation between semantic influences operating during parallel word processing and decision-level processing that is sensitive to response congruency across target and flankers.

Given this pattern in the post-N400 window, it may seem surprising at first that we did not find a behavioral response congruency effect for animal targets. We suggest that this is likely due to the nature of the semantic categorization task used in the current study, where there was a well-specified target category (i.e., animals) that was contrasted with a non-animal category rather than an equally well-defined category (e.g., plants) or two equally vague categories (e.g., natural vs. artifactual; Snell, Declerck, et al., 2018). Given the considerably faster RTs for animal targets compared to non-animal targets, it seems that words in the target category had special status; that is, participants may have been looking for animal target words and may have had a lower response criterion for this specific category of words. This reasoning awaits empirical confirmation.

This line of reasoning also accounts for why we did find a significant behavioral congruency effect for the non-animal targets, which would not have benefitted from this same privileged status. Non-animal targets elicited slower responses when paired with response incongruent flankers versus paired with response congruent flankers. We interpret this interference in terms of response competition at the decision level, which is supported by the post-N400 congruency effect. Animal flankers provide evidence in favor of the "yes" response when the non-animal target ultimately requires a "no" response in the semantic categorization task. This is further evidence that the semantics of the flankers were being processed, even though this information did not influence non-animal target processing until post-lexical decision-making.

Taken together, the current electrophysiological investigation of the extraction of higher-order representations from parafoveal words indicates that semantic information is extracted early enough to have an influence at multiple levels of processing. These findings consolidate recent behavioral evidence suggesting that the flankers task is a particularly useful paradigm for investigating parallel processing of linguistic information at varying levels of complexity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2021.104965.

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