Parallel word reading revealed by fixation-related brain potentials

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Abstract

During reading, the brain is confronted with many relevant objects at once. But does lexical processing occur for multiple words simultaneously? Cognitive science has yet to answer this prominent question. Recently it has been argued that the issue warrants supplementing the field's traditional toolbox (response times, eye-tracking) with neuroscientific techniques (EEG, fMRI). Indeed, according to the OB1-reader model, upcoming words need not impact oculomotor behavior per se, but parallel processing of these words must nonetheless be reflected in neural activity. Here we combined eye-tracking with EEG, time-locking the neural window of interest to the fixation on target words in sentence reading. During these fixations, we manipulated the identity of the subsequent word so that it posed either a syntactically legal or illegal continuation of the sentence. In line with previous research, oculomotor measures were unaffected. Yet, syntax impacted brain potentials as early as 350 ms after the target fixation onset. Given the EEG literature on syntax processing, the presently observed timings suggest parallel word reading. We reckon that parallel word processing typifies reading, and that OB1-reader offers a good platform for theorizing about the reading brain.

Keywords: reading, parallel processing, fixation-related potentials, EEG, syntax

1. Introduction

No visual task requires such systematicity as the act of reading. Imagine we were to relay some eye-tracking data of humans viewing natural scenes to an extraterrestial intelligent lifeform. The alien would discern scanpaths determined by salience, goals and perhaps a dose of randomness. Overall, the scanpaths would seem 'organically shaped' and possibly even akin to those of the lifeform's own species. Imagine we'd now send along data which, unbeknownst to the alien, is from humans reading a book. The alien now observes neat grid-shaped scanpaths, with many, fairly consistently timed fixations, intermitted by saccades with fairly consistent short amplitudes. The alien would logically be puzzled: compared to the previous data, which seemed to reflect natural oculomotor behavior, the new data appears very artificial and must perhaps stem from a different species altogether. And yet, it is this artificial behavior upon which modern humans depend so much.

Knowledge about the reading process is not only practically important, but also fundamentally interesting: due to the systematicity, the burden that is imposed on various cognitive components (visual perception, attentional selection, memory, oculomotor planning) may be heavier than any of those components were evolved to bear. With respect to vision and attention, we may note that text offers a far more homogeneous visual than do natural scenes. No single location is more salient, in terms of luminance, color or contrast, than its surroundings. Moreover, information is very densely packed and evenly distributed across the visual field, meaning each bit of the visual field *must* be pro-actively processed, and it must be done in a specific, conventionalized fashion (e.g., left-to-right and top-to-bottom). Finally, all those bits—that is, all words—must be approached as individually interpretable units. Had natural scene viewing been analogous to reading, then recognizing a tree would have involved counting its branches and leaves. How does the brain cope with these extreme conditions on a daily basis?

No visual task requires such systematicity as the act of reading; and no cognitive component is so important for maintaining that systematicity as attentional selection. In the present paper we continue a prominent and as of yet unresolved debate about the potential limits of attention in reading. Evidently attentional selection exists; but is that selection so fine-grained that the system can discretely attend to single words while our eyes are darting across oceans of squiggly lines? And if attentional selection is not so fine-grained, and the brain is indeed continuously kept busy by more than one word, how does it succeed? This particular aspect of the reading process is looking to play a crucial role in the adjudication among theories, and here we aim to contribute to its understanding. We do so by focusing on syntactic processing, which is assumed, in recent and ongoing modeling work (Snell, van Leipsig, Grainger, & Meeter, 2018a; Snell & Grainger, 2019a; 2019b; Meeter, Marzouki, Avramiea, Snell, & Grainger, 2020), to play a key role in the brain's ability to deal with multiple words simultaneously. As will be seen in due course, we will probe parallel syntactic processing during sentence reading with a combination of eye-tracking and electro-encephalography (EEG).

1.1 The serial versus parallel processing debate

In the past few decades, various researchers have expressed the view that attention is in fact, without failure, directed to strictly one word at a time (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Liversedge, Pollatsek, & Rayner, 2009; Schotter, Angele, & Rayner, 2012; Brothers, Hoversten, & Traxler, 2017; Cutter, Drieghe, & Liversedge, 2017; Schotter & Payne, 2019). The main argument for serialism has been the apparent lack of certain influences from upcoming (parafoveal) words[1] on current or subsequent fixations of the eye during sentence reading. This lack of influences has largely pertained to oculomotor behavior (as observed with eye-tracking apparatus) and is typically registered upon manipulating the lexico-semantic properties of the upcoming word during the fixation on a target word (e.g., Rayner & Morris, 1992; Rayner, White, Kambe, Miller, & Liversedge, 2003; Angele, Tran, & Rayner, 2013; Snell, Declerck, & Grainger, 2018b). One assumption has been that, if parallel word processing were true, processing of a target word should be quicker if the upcoming word is semantically related (e.g., '*dog cat*') than if it is unrelated ('*dog mat*'); and quicker processing should translate into briefer fixation durations. The lack of such an effect, then, is taken as evidence against parallel word processing (e.g., Angele et al., 2013). This rationale implies that parallel processed semantic information must be integrated so that multiple words contribute to the activation of a single lexical representation. Let us refer to this line of reasoning as the semantic integration assumption.

Other lines of research have tested influences of word frequency. How often a word appears on average in everyday life is a good predictor of how quickly that word is recognized (e.g., Brysbaert, Mandera, & Keuleers, 2018), with high-frequency words typically warranting briefer fixation durations than low-frequency words. In a set of corpus analyses, Kennedy and Pynte (2005) established that fixation durations were modulated not just by the frequency of the fixated word, but also by that of the subsequent word. This led the authors to conclude that the upcoming word must be occupying the mind simultaneously with the fixated word. However, while these effects can be established in large corpora, they are rather elusive in controlled experimental settings (e.g., Brothers et al., 2017). The absence of upcoming word frequency effects may be regarded as evidence against parallel processing if one reasons that, under parallel processing, any modulation of the average difficulty of all words in view (as might be effectuated by manipulating the upcoming word's frequency) should affect all individual fixations along the way. Let us refer to this line of reasoning as the frequency assumption.

It is our view that a parallel processing model has to adhere neither to the semantic integration assumption, nor to the frequency assumption. With respect to the former, Snell, Meeter and Grainger (2017a) argued that a parallel processing system can only be successful if it does *not* mix up information from multiple word locations. Instead, a successful system would have to allow independent activation of multiple lexical representations; and additionally, it should have a mechanism in place to associate each representation with its respective location in the visual field. It is, after all, a reader's aim to recognize all individual words—rather than to mix everything into a single hodgepodge—given that each word makes a unique contribution to context comprehension. To further illustrate this point: the classic take on parallel processing would allow the sequence '*lion, elephant, fence, otter*' to be recognized as '*zoo*', whereas the alternative scenario would not.

The new take on parallel processing is formalized in the OB1-reader model (Snell et al., 2018a). In line, with the above rationale, the model contains no semantics-based lateral connections among word nodes (e.g., there is no direct connection between '*dog*' and '*cat*'). Rather, each word node's activation depends, firstly, on the activation of sub-lexical letter nodes, and secondly, on top-down constraint from a spatiotopic sentence-level representation on the basis of words' expected lengths and grammatical categories (Figure 1). Crucially then, when multiple words are viewed simultaneously, OB1 does *not* predict faster lexical activation in the

[1] Throughout this paper we will use the term 'upcoming word' to refer to word *n+1* when the eyes are fixating word *n*.

case of semantic relatedness to upcoming words. Semantic features (not modeled in OB1) would be activated post-lexically and would therefore impact processing of *subsequently* viewed words rather than *simultaneously* viewed words.

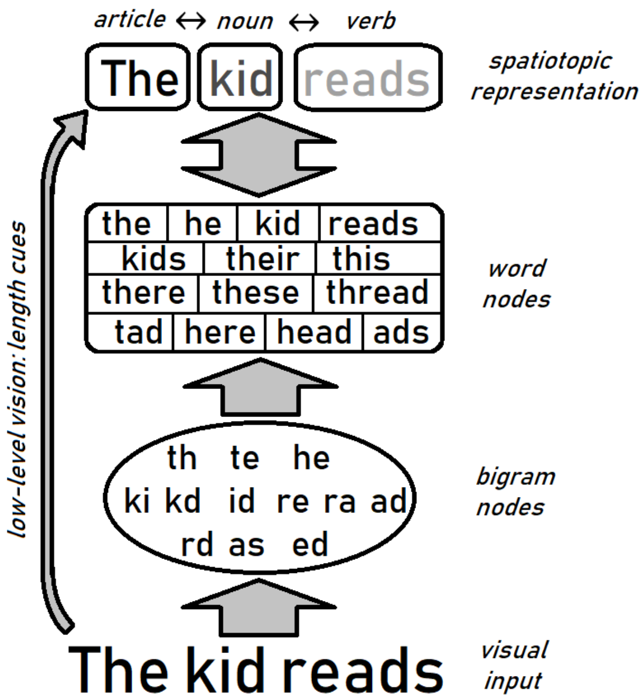

Figure 1. OB1-reader. The model employs representations at the level of letters (bigrams), words and sentence structures. Bigram nodes, which convey information about the identities and relative positions of letters, are activated by corresponding letters within the perceptual span (weighted by attention and acuity). Each bigram node activates all word nodes that it is connected to (e.g., the bigram '*th*' is connected to words '*the', 'them', 'there', 'other',* et cetera). A first glance at the visual input prompts the activation of a spatiotopic sentence-level representation that comprises information about the number of to-be-recognized words and their approximate lengths. Activated words are mapped onto plausible locations on the basis of length and syntax (e.g., having mapped a verb onto position 3, OB1 may expect a noun for position 2).

Like semantics, the frequencies of upcoming words do not influence fixation durations either in OB1. Indeed, generally the frequency of one word does not in any way modulate the speed of processing another word; (instead, fixation durations largely depend on the time it takes OB1 to mark the fixated word as "recognized"). Hence, even if the so-called successor frequency effects were to be established experimentally, OB1 would not have a clear means of accounting for them.

1.2 The syntactic constraint hypothesis

If not for effects of semantics or lexical frequency, how can parallel processing be falsified? The focus of the debate has somewhat shifted recently from semantics and frequency to syntax. This is because OB1's spatiotopic representation sparks the prediction that ongoing word recognition may be aided by knowledge of the grammatical categories of surrounding words. For instance, when having associated a verb with position 3 and an article with position 1, this would boost activation for noun words at position 2. Recognition of the noun should be slowed, then, if it is surrounded by syntactically incompatible words (e.g., a verb at position 1 and an article at position 3). These so-called sentence superiority effects have indeed been established (e.g., Snell & Grainger, 2017; Wen, Snell & Grainger, 2019; Vandendaele, Declerck, Grainger, & Snell, 2020). When presenting four-word sequences briefly (200 ms) and asking readers to report a post-cued word (tested *at the same location* in a grammatically correct sequence versus a scrambled version of the same words; e.g., 'the man *can* run' vs. 'the run *can* man'), performance is better when the target word was surrounded by syntactically compatible words. Moreover, the size of this sentence superiority effect is not modulated by target word location (e.g., Snell & Grainger, 2017). The latter finding suggests that the amount of syntactic information that is extracted from the visual field is evenly distributed across the four words.

Another syntax-related phenomenon that is predicted by OB1 is the transposed word effect. In sequences such as '*Do love you me?*', many readers do not notice the fact that the positions of '*love*' and '*you*' are incorrect. This phenomenon is robustly revealed in experimental settings with many different types of sentences (Mirault, Snell, & Grainger, 2018; Snell & Grainger, 2019c; Wen, Mirault, & Grainger, 2021; Liu, Li, & Wang, 2021). The typical finding is that grammatical judgments ('*Is the sequence grammatically correct or not?*') for incorrect sequences are slower and less accurate when the sequence can be corrected with a transposition (e.g. '*The can man run'*) than when the sequence cannot be corrected ('*The fan man run*'). This aligns with the idea that activated words are flexibly associated with locations based on grammatical constraints. Another important result is that these effects are not modulated by the critical point of ungrammaticality (Snell & Grainger, 2019c). Had words been processed in a serial fashion from left to right, then leftward anomalies should have been detected faster than rightward anomalies.

Against the above results we may pit the sentence reading experiments of Snell et al. (2017a) and Brothers and Traxler (2016). These experiments tested so-called parafoveal preview effects, whereby upcoming word identities were manipulated so that these were either syntactically valid or invalid. Normal reading—from the participant's perspective—was maintained by employing the boundary technique (Rayner, 1975), whereby the upcoming word is replaced by a logical continuation of the sentence precisely during the saccade towards that word. In all experiments syntactic violations led to fewer skipping of the upcoming word (i.e., readers were more likely inclined to spend time fixating the word), and the word was viewed longer. Since the word was no longer syntactically invalid upon being fixated, the fact that reading was nevertheless hampered suggested that information from that location was processed prior to its fixation. But what happened during the fixation preceding it? OB1 would have predicted that the syntactically invalid preview (location *n+1*) must negatively impact processing of the word preceding it (location *n*): for instance, '*dog*' should be recognized faster in '*the dog walks*' than in '*the dog phone*'. But such effects were not found.

Thus, hitherto the findings do not speak unequivocally for OB1's syntactic constraint hypothesis. Yet, with respect to the oculomotor data of Brothers and Traxler (2016) and Snell et al. (2017a), a few more things must be considered. Even if syntactic recognition of '*dog*' were constrained by '*walks*', the amount of constraint provided by '*walks*' may be relatively small compared to that provided by the context *preceding* the word (given that the context preceding '*dog*' has already been foveated). As has been argued by Snell and Grainger (2019a), eye-tracking data alone might not provide a sufficiently clear window onto the mind for revealing such subtle word-to-word influences.

Additionally, although it is traditionally assumed that the boundary technique in itself does not hamper reading, it is not inconceivable that the parafoveal anomaly (i.e., the syntactic violation) impacted the ongoing fixation in multiple ways. While OB1 would indeed predict slowed word processing (which would normally cause a longer fixation), in addition there may have been extra-lexical factors at play: for instance, the anomaly may have captured attention, prompting a fast eye movement in disregard for the fact that word processing has been slowed. These two effects—a longer fixation due to slowed word processing, but a shorter fixation because attention is captured by a parafoveal anomaly—would cancel each other out, hence resulting in a null effect. The problem is that oculomotor data alone does not allow us to tease apart these scenario's.

1.3 Fixation-related potentials

Despite the developments discussed above, the theoretical impasse has endured for several reasons. The opposition's largest concern has been that many of OB1-reader's directly testable consequences lie outside the realm of ('natural') text reading (e.g., Schotter & Payne, 2019; Snell & Grainger, 2019b). For instance, one might invoke the possibility that visuo-spatial attention is directed to multiple words in the semantic categorization task of Snell et al. (2018b), while being focused on single words during sentence reading. In studies revealing the '*Do love you me*' phenomenon, readers are instructed to make grammaticality judgments, which may prompt them to process the materials differently than under normal reading conditions. Finally, in studies revealing sentence superiority effects, readers only have a limited amount of time to view words before receiving a cue for partial report, and so may be incentivised to adopt a more parallel processing strategy than they would have done under normal reading conditions.

Here we hope to break the impasse, by returning to sentence reading—in the spirit of the studies of Brothers and Traxler (2016) and Snell et al. (2017a)—but this time employing EEG in addition to eye-tracking. Researchers have established various components in the event-related potential (ERP) triggered by visual words, that can be linked to various types of processing, such as the N150 (constructing letters from visual features), the N250 (mapping sub-lexical representations, such as bigrams, onto whole-word representations) and the N400 (lexical and semantic recognition) (Grainger & Holcomb, 2009, for a review). Particularly relevant for our purposes is the P600 component, associated with syntactic processing (e.g., Osterhout & Holcomb, 1992; Hagoort, Brown, & Groothusen, 1993; Hagoort, Brown & Osterhout, 2000). The typical finding is that syntactic violations induce a positive shift in the P600 amplitude (Hagoort et al., 1993; 2000) and possibly enhanced negativity in the earlier N400 (Kutas & Hillyard, 1983; Osterhout & Holcomb, 1992).

In order to probe processing of the upcoming word in sentence reading, the ERP will have to be carefully time-locked to the onset of the fixation on the preceding word (henceforth called the target word). Here we build upon the important work of our peers, who have applied the idea of using oculomotor markers for ERP onsets (pioneered by Yagi and Ogata, 1995) to the realm of reading (Baccino & Manunta, 2005; Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Dimigen, Kliegl, & Sommer, 2012; Kliegl, Dambacher, Dimigen, Jacobs, & Sommer, 2012; Degno, Loberg, Zang, Zhang, Donnelly, & Liversedge, 2019; Mirault, Yeaton, Broqua, Dufau, Holcomb, & Grainger, 2020; Degno & Liversedge, 2020, for a review). We reason that if the syntax of word *n* is processed during processing of word *n-1* (our target word), then syntactic violations of word *n* should elicit deviations in the so-called fixation-related potential (FRP) well within 600 ms from the start of the fixation on *n-1.*

As in the studies of Brothers and Traxler (2016) and Snell et al. (2017a), the boundary technique (Rayner, 1975) plays an important role in the current experiment. Given that words are viewed 200—250 ms on average (e.g., Rayner, 1998), syntax-related deflections in the FRP would normally unfold when the eyes have already moved towards the word that is causing the deflections. Thus, normally it would be impossible to verify that syntactic information was extracted from the word prior to fixating it. However, with the boundary technique, the upcoming word will have been changed into a different (and always syntactically valid) word upon its fixation. Thus, any effects of syntactic compatibility that we register in the EEG signal must have been caused before the eyes moved towards the upcoming word—and the earlier the effect, the more difficult it would be to explain things from a serial processing perspective.

2. Methods

2.1 Participants

Twenty-nine native French students (age M = 25.0 years old) from the Aix-Marseille University (Marseille, France) received monetary compensation for participating in this experiment. All participants gave informed consent in accordance with the declaration of Helsinki. All participants declared to be non-dyslexic and to have normal vision.

2.2 Stimuli and design

We devised 128 French sentences that were between 7 and 12 words long. Sentences comprised a 4-, 5- or 6-letter word at the third or fourth position that we marked as the target word. Targets were pronoun, noun or verb. The word immediately following the target—the so-called post-target word—always had a length of 4—8 letters (M = 6.16 letters) and was a noun, verb or adjective. In each trial of the experiment, we manipulated the identity of the post-target prior to its fixation (i.e., pre-boundary), across two conditions. In the *Syntactically Compatible* condition, this so-called *preview* word was of the same syntactic category as the post-boundary word, and thus posed a syntactically valid continuation of the sentence. In the *Syntactically Incompatible* condition, the preview was of a different syntactic category and posed a violation of the grammatical structure. Within each trial, the length of both preview types was equal to that of the post-boundary word. We further made sure that the average frequency of the preview was approximately equal between the Compatible and Incompatible conditions, at 3.61 and 4.12 Zipf, respectively. An example stimulus is shown in Figure 2.

For each sentence we also created a question about the contents of the sentence, that was to be answered by means of two-alternative forced choice (2AFC) (e.g., in the example stimulus of Figure 2, a question might be: "*What does the girl love?*", to be answered by a left- or right-handed button press for '*candy*' or '*trees*' respectively). The questions were a means to motivate participants to read attentively.

The two experimental conditions were implemented as a Latin Square design, so that all 128 targets were tested in all conditions, but only once per participant. Each participant read the 128 sentences in a random order.

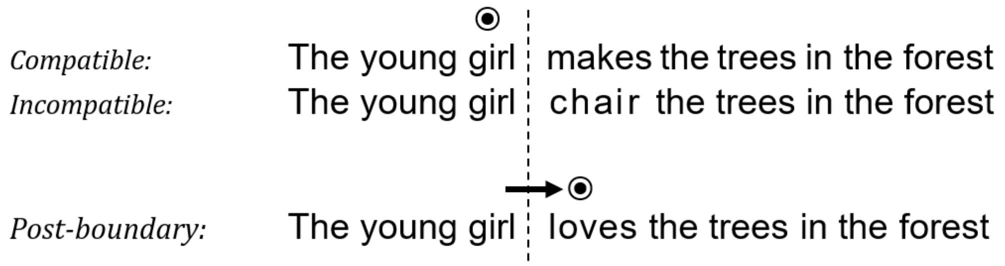

Figure 2. Example stimulus in both experimental conditions. The position of the eye is indicated with the ⦿ symbol. Although this example is in English, our experimental stimuli were in French.

2.3 Apparatus

The experiment was implemented with OpenSesame (Mathôt, Schreij, & Theeuwes, 2012). Stimuli were presented in monospaced font on a 1024×768 pixel 75 Hz CRT monitor about 100 cm from the participant's eyes, so that each letter in the display subtended 0.30 degrees of visual angle. The eye position was tracked from the right eye with an SR Research EyeLink 1000 eye-tracker. EEG was sampled at 512 Hz from 64 scalp electrodes and 6 facial electrodes with a Biosemi ActiveTwo system.

2.4 Procedure

Participants were seated in a comfortable office chair in a dimly lit room. After having signed informed consent, participants were fitted with a 64-electrode elastic cap. A reference signal was calculated by averaging recordings from two electrodes on the mastoids, while recordings from four electrodes below the eyes and on the outer canthi of the eyes were used to detect blinks and horizontal eye movements, respectively.

Each trial started with a fixation dot slightly to the left of where the start of the sentence would appear. Participants were instructed to look at the dot, which allowed us to correct potential drifts in the eye position. After the drift correction, the dot was removed and the sentence was presented at the center of the screen, with the first character of the sentence being located slightly to the right of where the dot had been shown before. At this point, the sentence comprised either the syntactically compatible or incompatible preview word. Participants were instructed to read the sentence as they normally would, though they were requested not to blink until they reached the end of the sentence. For each sentence, we determined the x-coordinate of the invisible boundary between the target and preview. As soon as the eyes crossed this boundary, the preview was replaced by the post-boundary word, so that, from the participant's perspective, normal reading was maintained. After having reached the end of the sentence, the sentence was removed and participants were shown a 2AFC question with the two response options shown in the left and right bottom corners of the screen. Participants responded with a left- or right-handed button press on a gamepad accordingly.

In total, the experiment lasted approximately 30 minutes. Participants were offered a break halfway through the experiment. Prior to the 128 experimental sentences, participants received 8 practice trials.

2.5 Oculomotor measures of interest

From the eye-tracking data we retrieved the following measures of interest for the target word: the First Fixation Duration (FFD; the duration of the first fixation on the word, reflective of early processing), the Gaze Duration (GD; the summed durations of all fixations on the word during the first pass, reflective of word recognition), the Skipping rate (with greater processing difficulty come fewer skips) and the Refixation rate (with greater processing difficulty come more fixations); (for more information about these measures, we refer to the review of Rayner, 1998).

2.6 Pre-processing of EEG data

We used the *EEGLAB* toolbox (Delorme & Makeig, 2004) to process the EEG data in Matlab (The MathWorks, 2010). The EEG data were time-aligned with the eye-tracking data using the EYE-EEG toolbox (Dimigen et al., 2011). Blink events detected by the eye-tracker were removed from the continuous data. The data were then re-referenced to the averaged mastoids and band-pass filtered between 2.5 and 100 Hz. As our main window of interest (the P600 component, and possibly the N400) would typically start only after the saccade from the target to the post-target, we filtered out oculomotor-related activity on the basis of an Independent Components Analysis (ICA) for each individual participant, using the automatic component rejection procedure from Plöchl, Ossandón and König (2012). Prior to ICA training, the data underwent pre-saccadic potential overweighting (Dimigen, 2020).

One participant was eliminated due to an anomalous number of components being identified for removal, and the remaining participants had an average of 2.2 oculomotor-related components removed. Data were then cut into 900 ms epochs between -100 and 800 ms, with the 0 ms timepoint aligning with the target fixation onset. Epochs were baseline corrected using the 100 ms pre-fixation baseline. A total of 5.2% of trials were removed due to remaining artifacts. In all, we analyzed 3.283 trials from 28 participants.

3. Results

Below, we report results for oculomotor data (Section 3.1) and electro-encephalographic data (Section 3.2) separately. As all our participants answered more than 85% of the questions correctly, we excluded no participants on the basis of task performance. To preview our results: in line with Brothers and Traxler (2016) and Snell et al. (2017a), syntactic compatibility was not found to have an influence on the oculomotor measures. However, we established a clear—and early—effect of syntactic compatibility on brain potentials.

3.1 Oculomotor analyses

Prior to all fixation duration analyses, we excluded datapoints beyond 2.5 SDs from the mean (~2.4% of trials) and words that were skipped (~23% of trials). Data were analyzed with linear mixed-effects models (LMMs) with Syntactic Compatibility (Compatible vs. Incompatible) as fixed effect and Participants and Items as random effects. Models included random intercepts as well as random slopes. We report b-values, Standard Errors (SEs) and t-values, with $|t| > 1.96$ deemed significant. The skipping rates were analyzed with a generalized LMM, for which we report z-values that we interpret in the same way as t-values. In all analyses, the syntactically compatible condition was selected as reference.

Condition averages are presented in Table 1. Neither the first fixation duration (FFD) nor the gaze duration (GD) was impacted by syntactic compatibility of the preview (FFD: b = -1.04, SE = 2.76, t = -0.38; GD: b = -3.21, SE = 4.74, t = -0.68). We also didn't observe an effect in the refixation rate (b = 0.00, SE = 0.04, t = 0.10), nor in the skipping rate (b = -0.16, SE = 0.11, z = -1.43).

Table 1. Condition averages. Durations are in milliseconds. Values in parentheses indicate SDs.

Condition	*FFD*	*GD*	*Refixation rate*	*Skipping rate*
Syn. Compatible	212 (66)	247 (110)	0.23	0.24
Syn. Incompatible	212 (66)	246 (102)	0.23	0.23

Note: abbreviations: Syn., syntactically; FFD, first fixation duration; GD, gaze duration.

3.2 EEG analyses

EEG data were analyzed with a cluster-mass permutation test using the Mass Univariate ERP Toolbox (Groppe, Urbach & Kutas, 2011) in Matlab. The mass-univariate approach yields a t-statistic over time (sampled at 500 Hz) that reflects whether our established condition difference deviates significantly from a distribution of condition differences sampled from 2500 random permutations of the same data.

We have plotted condition differences topographically in Figure 3, and FRPs per condition at representative electrode sites in Figure 4. The topographic plots show considerable differences in neural deflections between conditions as early as 350 ms after the target fixation onset. This is confirmed by the cluster-mass permutation test, which revealed a large significant cluster starting over frontal sites around this timepoint, and subsequently spreading across the scalp (Figure 6). The entire cluster reflects greater negativity in the Incompatible condition than in the Compatible condition, strongest over frontal sites in the N400 window and central sites in the P600 window.

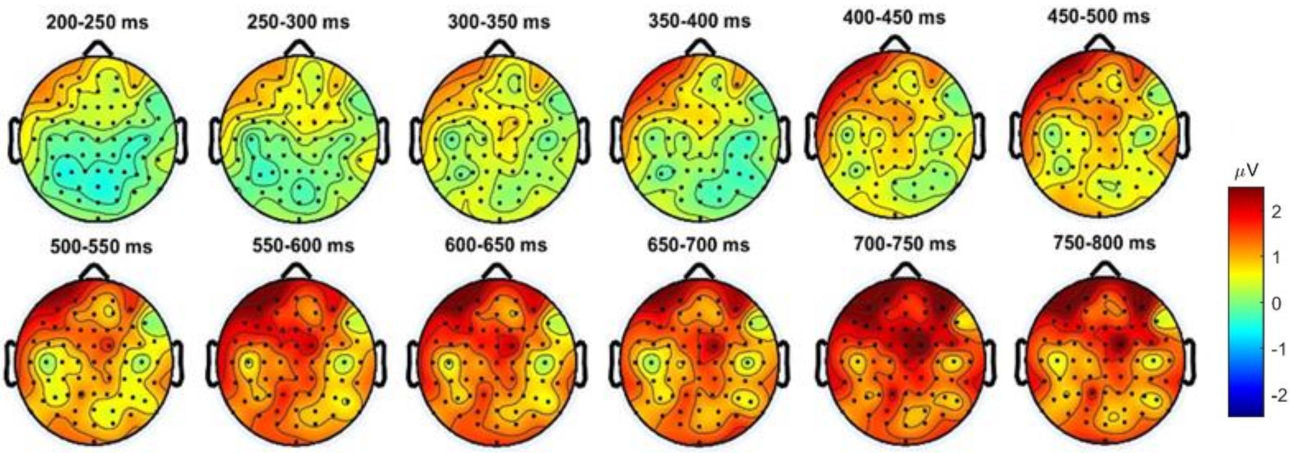

Figure 3. Deflection differences between the Incompatible (ref.) and Compatible condition within the interval 200—800 ms after the target fixation. Topographies are meaned over 50 ms intervals.

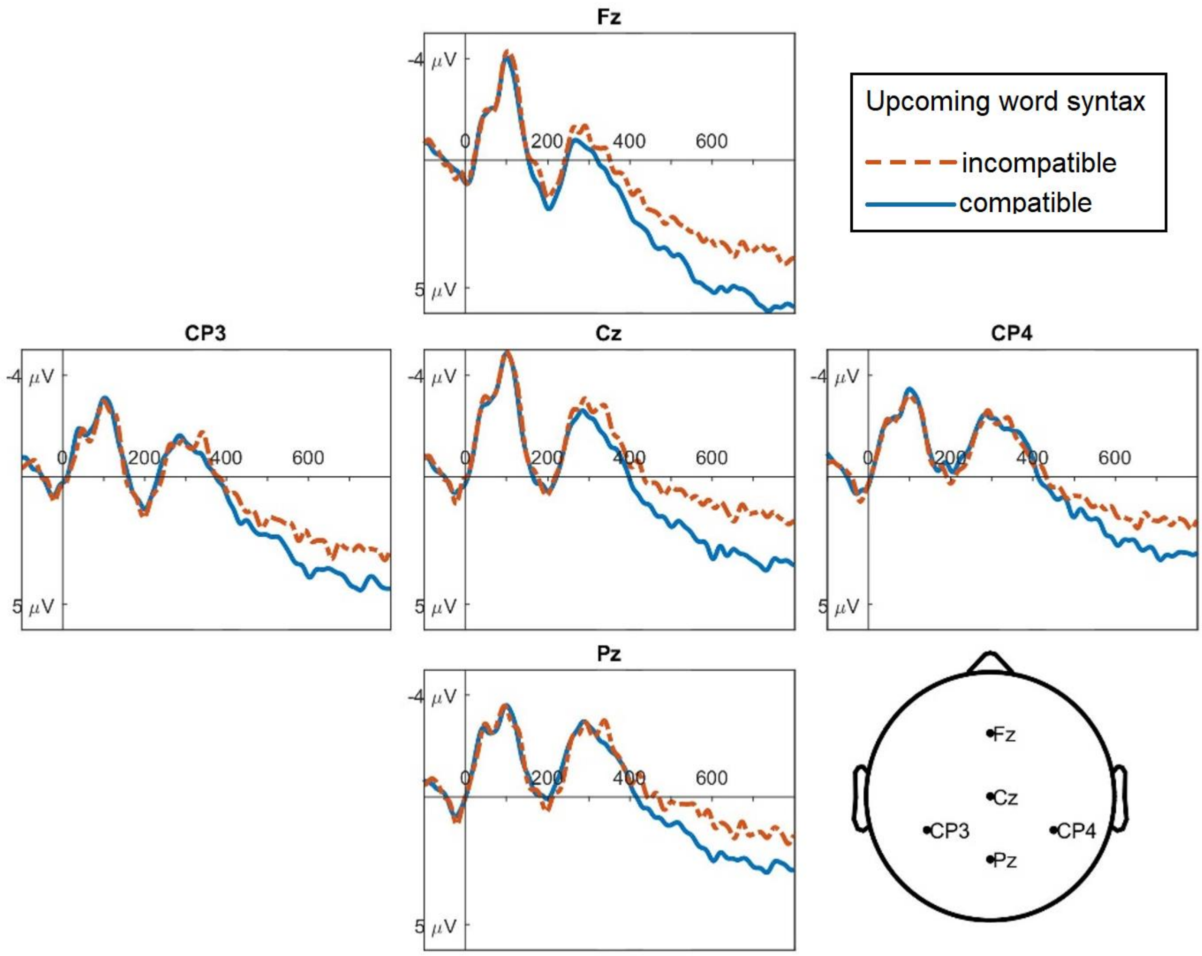

Figure 4. Fixation-Related Potentials (FRPs) for the Compatible (continuous line) and Incompatible (dashed line) conditions at representative electrode sites. FRPs are time-locked to onset of fixation on the target word (0 ms).

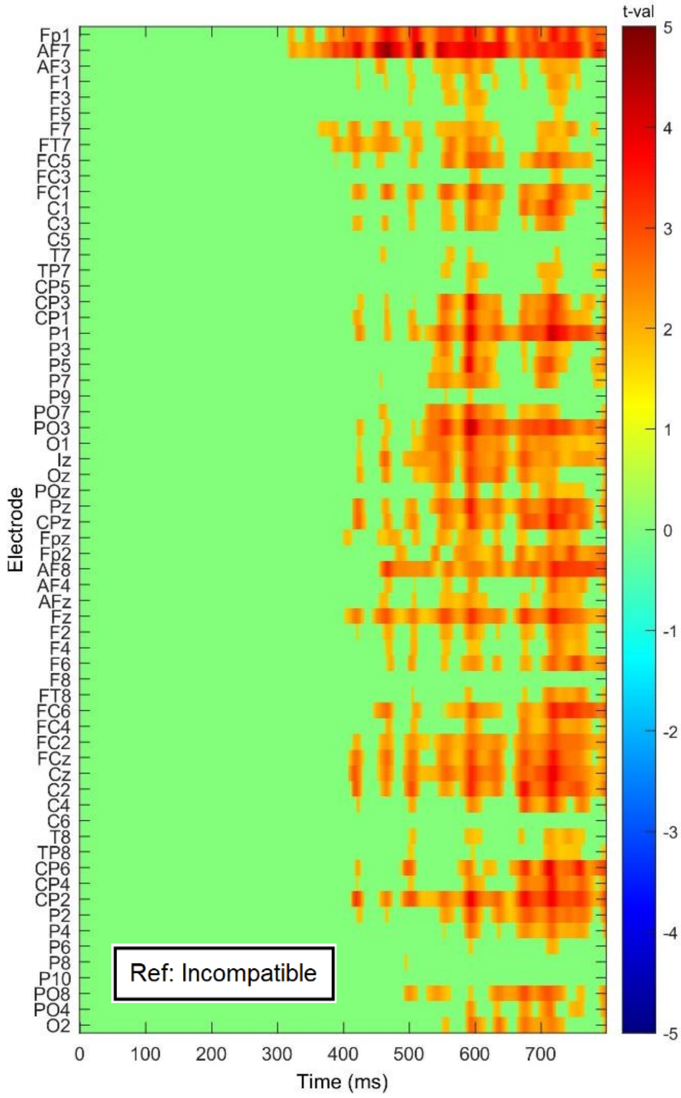

Figure 6. Results of the cluster-mass permutation test. Colors indicate *t*-values for electrode × timepoint pairs which are part of the effect. All values not part of the cluster are set to zero. The Incompatible syntax condition is taken as reference.

Discussion

The matter of parallel word processing has since a few decades been a point of considerable controversy (e.g., Reichle et al., 1998; 2009; Inhoff et al., 2000; Kennedy & Pynte, 2005; Engbert, Nuthmann, Richter, & Kliegl, 2005; Dare & Shillcock, 2013; Angele et al., 2013; Brothers et al., 2017; Snell et al., 2017a; Snell & Grainger, 2019a; Schotter & Payne, 2019; Zang, 2019). The issue bears not just on reading in specific, but also on the domains of vision and attention in general. As argued at the outset of this paper, there is no doubt that attentional selection exists; but given that text bombards the retina with so many relevant objects at once, one may wonder whether our attentional mechanisms can afford focusing on single objects (i.e., words) within this artificial environment as effectively as object selection in natural visual scenes. Is attentional selection so fine-grained that the brain can dedicate all of its lexical processing capacities to a single word while blocking-out surrounding words?

Though much of the evidence in support of strict serial (one-by-one) word processing stems from eye-tracking studies (e.g., Angele et al., 2013; Brothers et al., 2017), it has recently been argued that a definitive answer to the above question begs more than oculomotor data alone (e.g. Snell & Grainger, 2019a; Schotter & Payne, 2019). In the OB1-reader model (Snell et al., 2018a), for instance, the duration of a fixation predominantly depends on the speed of recognizing the fixated word, and this is not influenced by the lexico-semantic properties of the word following it. Thus, from OB1's perspective, one cannot probe parallel processing by measuring the impact of lexico-semantic manipulations of the upcoming word on oculomotor behavior.

Things are slightly different for syntax. In principle, recognition of the fixated word should be helped by a syntactically compatible adjacent word (or hampered by an incompatible word). But then again, syntactic violations might impact oculomotor behavior in multiple ways (e.g., attentional capture by the anomaly, triggering a fast saccade; Section 1.2). Hence, these premises do not spark a single clear prediction with a single clear direction of effects by which to test parallelism.

In an attempt to solve this theoretical and methodological stalemate, here we supplemented the traditional approach—employing the boundary technique and measuring the influence of word *n+1* on oculomotor measures for word *n*—with electro-encephalography (EEG). According to OB1, syntactic processing proceeds for all words in the perceptual span simultaneously, and therefore a syntactic violation at *n+1* during the fixation on *n* should impact neural deflections no later than the processing latencies established in the EEG literature (e.g., Osterhout & Holcomb, 1992; Hagoort et al., 1993; 2000). The present results align entirely with these hypotheses. While fixation durations were unaffected, the syntactic properties of the upcoming word caused deflection differences as early as 350 ms after fixating the target word. Given that the upcoming word was replaced, upon its fixation, by a logical continuation of the sentence in both conditions, these effects of syntax must have been caused at an earlier timepoint. More specifically, in order for syntactic processing of the upcoming word to be revealed at 350 ms post target fixation onset, processing of the upcoming word would have had to have commenced right at the start of the target fixation.

Importantly, the effect that we have reported here is well-established in the literature. Left Anterior Negativity (LAN) around 350 ms into viewing words (Figure 3) has been linked to difficulty in an early, seemingly automatic type of syntactic analysis (occurring prior to the more centrally distributed N400 component associated with the retrieval of semantics) and processing of morpho-syntactic structure (Gunter, Stowe, & Mulder, 1997; Friederici & Meyer, 2004; Friederici, Gunter, Hahne, & Mauth, 2004; Friederici & Weissenborn, 2007; Steinhauer & Drury, 2012). Crucial in the interpretation of the present results is the fact that these LAN effects are traditionally obtained by means of presenting sentences in a sequential word-by-word format. Thus, the 'traditional' LAN could not have been triggered prior to the onset of the syntactically anomalous word, and as such provides a benchmark for gauging the timepoint at which our own participants started higher-order processing of the post-target word. Given that our FRPs were time-locked to the onset of the fixation on the target word, and that the latency of deflection differences caused by anomalous post-targets matches the traditional LAN, the present data necessitate immediate processing of word *n+1* upon the fixation on word *n*.

While our findings align perfectly with parallel processing, they are quite difficult to reconcile with the serial processing perspective. Indeed, if processing of word *n+1* commenced right at the start of the fixation on *n,* and the two words could not be processed simultaneously, this would imply that attention and the eyes can never dwell on the same word concurrently. It is quite inconceivable that the mind wouldn't at least to some extent be occupied by the foveated word.

The remaining serial processing scenario is one wherein the syntactic categories are rapidly retrieved from multiple words in parallel, while detailed semantic information is still accessed in serial fashion. However, although such an approach may allow one to effectively explain a good deal of reading behaviors, it can be argued that a model of the sort should no longer be defined as being strictly serial. We reckon the degree of parallelism inherent to such a model would beg a 'hybrid' classification at best.

On a final note, the absence of effects in oculomotor behavior, combined with clear effects in neural activity, bolster the conception that parallel processing cannot be falsified on the basis of oculomotor data alone (Snell & Grainger, 2019a; Schotter & Payne, 2019). It is our view that OB1-reader has hitherto done a good job accounting for phenomena both in- and outside natural reading settings, and that the way forward is one that continues to appeal to both sides of the same theoretical coin.

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